

Policy Recommendation for Net-zero Technology in Taiwan

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Throughout the deliberation process for this policy recommendation report, the advisory committee and participating experts have taken part in discussions on net-zero emissions policy planning in many parts of the government. Many of the ideas and recommendations presented in this report have already been incorporated into Taiwan's net-zero policy framework.

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Executive Summary

In response to global warming, numerous countries have pledged to achieve net-zero emissions by 2050. As a key player in global economic activities, Taiwan must also act swiftly to meet this challenge. Given Taiwan's limited space and dense population, heavy reliance on imported energy, an isolated power grid, and an economy dominated by energy-intensive manufacturing, the path to net-zero for Taiwan will be particularly challenging.

Research conducted both within Taiwan and overseas indicates that relying solely on existing technology will be insufficient to meet the 2050 net-zero emissions target. This policy recommendation report, as a result, focuses on the feasibility of developing emerging net-zero technologies in Taiwan, aiming to drive Taiwan's energy and industrial transformation while easing societal adaptation pressures through successful technology development. However, the implementation of net-zero technologies must be supported by social science-based measures, including policy incentives, economic tools, public engagement, legal frameworks, and optimized governance mechanisms. Moreover, since unrestricted use of the Earth's resources is unsustainable, it is essential to also pursue a sustainable lifestyle that coexists with the environment. These social science perspectives have been discussed by various teams in other works; this report only briefly outlines aspects related to net-zero technology promotion. For further details, please refer to the other original publications.

This report asserts that net-zero technology research and development should be rooted in scientific principles but not limited by current engineering constraints. Setting achievable future engineering goals within the boundaries set by scientific laws and overcoming commercialization challenges are critical to research and development strategies. Additionally, net-zero technology development must consider the potential to reduce carbon specifically in Taiwan, along with the speed and scale of such research and development. A diverse, localized, and decentralized energy approach is also essential to moving beyond a reliance on limited energy options.

Currently, Taiwan's greenhouse gas emissions primarily stem from energy demand (>90%), with the power generation accounting for a significant portion (>48%). Given the advantages of electricity as a convenient, manageable, and efficient energy source, Taiwan's future energy supply is expected to become increasingly electrified. Consequently, the development of zero-carbon electricity is a primary focus of our net-zero technology R&D. Sectors less adaptable to electrification will need to rely on

hydrogen, bioenergy, and negative carbon technologies to achieve net-zero targets. In addition, close attention should be given to breakthrough technologies, supported by economic and social enablers, while strengthening the research management framework to integrate technology development with social, economic, and governance dimensions to jointly achieve Taiwan's net-zero emissions goal.

Summary of Key Recommendations:

- **Develop as fast as possible:** Decarbonized hydrogen electricity (using methane pyrolysis), geothermal energy, ocean energy, biomass carbon sinks, and high-efficiency photovoltaic (PV) systems
- **Expand:** Wind power, emerging bioenergy, power system support (smart grids, energy storage), as well as social and economic measures
- **Continue to Promote:** Traditional bioenergy, hydropower, conventional carbon capture, utilization, and storage (CCUS), and natural carbon sinks (agriculture and forestry)
- **Monitor:** Future nuclear technology, emerging CCUS technologies

Summary of Key Arguments:

1. Active Development of Hydrogen-Powered Electricity (using Methane Pyrolysis): This technology is compatible with natural gas power plants. Recently, the European Union approved low-carbon natural gas power generation (< 270 g/kWh) as a sustainable energy investment option by 2035. If hydrogen made from methane pyrolysis can continue reducing carbon emissions, it may potentially qualify as a “quasi-green energy” source, helping to address Taiwan's significant shortage of green energy. The solid carbon produced could also serve as an emergency backup energy source, alleviating Taiwan's energy reserve shortfalls. However, reliance on imported natural gas is a drawback, as only 55% of the gas's thermal value is utilized. Prerequisite technological developments include oxygen-free cracking of natural gas (pyrolysis), generating power from hydrogen blended with natural gas, and full-hydrogen power generation, along with technologies to use the solid carbon byproduct. This approach sidesteps traditional carbon capture, utilization, and storage (CCUS) concepts, advancing zero-carbon power solutions more suitable for Taiwan's needs.

2. Next-Generation High-Efficiency Photovoltaic Modules: Although PV technology is relatively mature, Taiwan's limited land area and high population density pose challenges to large-scale solar panel installations. Thus, advancing next-generation, high-efficiency PV modules (efficiency > 30%) is essential to optimize

land use through technological advancements. The primary focus should be on perovskite tandem silicon-based solar cells, alongside stronger economic and policy incentives to encourage wider adoption.

3. Expanding Geothermal Development: Taiwan, located in the "Pacific Ring of Fire," possesses abundant geothermal resources. Extensive exploration and actively expanding deep geothermal development is essential. Geothermal is one of the few energy sources that can be produced domestically and can serve as a baseload power source to stabilize the grid, making it a crucial renewable energy focus. The success of geothermal development hinges on advanced mapping and drilling techniques, both of which have seen significant advancements in recent years. In addition to shallow geothermal resources (within three kilometers underground), the focus should shift toward deep geothermal development. Regulatory frameworks should also be enhanced to provide policy incentives, and appropriate feeder line systems should be constructed to maximize the zero-carbon baseload power potential.

4. Ocean Energy Potential Along Taiwan's East Coast: Taiwan's eastern coast features deep ocean waters with a fast and stable *Kuroshio* current, making it highly suitable for ocean current and ocean thermal energy conversion (OTEC) power generation. Comprehensive hydrological and geological surveys of potential ocean energy sites should be conducted as soon as possible. Investment should be made in the development of ocean current and OTEC power generation technologies, and their integration with the power grid, along with the related marine engineering technologies.

5. Promoting Biomass Carbon Sinks: Utilizing Taiwan's non-arable land to grow short-cycle biomass crops, which can then be processed into hydrogen for power generation and converted into reusable or sequestered solid carbon through pyrolysis, is recommended. This approach not only maximizes biomass energy use but also enhances carbon sinks. Additionally, planned forest thinning to increase domestic timber production could expand carbon sinks and biomass resources. Investing in biotechnology and bio-based processing is also recommended to improve carbon utilization, enabling the production of bio-based chemicals and energy products (such as biofuels/aviation fuel) and fostering the development of a bioeconomy.

6. Innovative Development of Other Renewable Energy Options: Expanding the contribution of renewable sources, such as wind and bioenergy, requires innovation. However, as the share of intermittent renewable energy increases, energy storage must be enhanced beyond traditional pumped-storage hydropower and dispatchable

power from private plant operators. Developing gigawatt-scale storage infrastructure, particularly grid-scale battery storage systems, is essential to support a high share of wind and solar power.

7. Keeping a Close Eye on Emerging High-Potential Technologies: Attention should be given to the development of promising technologies, including future nuclear fusion and technologies that convert carbon dioxide (CO₂) into reusable chemicals, particularly bio-based and green chemical processes, to reduce reliance on petrochemical feedstocks.

8. Promoting Electrification and Fuel Substitution in the Industrial Sector: The industrial sector should drive the electrification of manufacturing processes and the substitution of traditional fuels with low- and zero-carbon technologies. In the transportation sector, efforts must intensify to promote the electrification, leveraging electric vehicles, which are more efficient than fuel-based vehicles. Until full electrification of all modes of transportation, bioethanol can be imported and blended into gasoline as a transitional fuel to support an equitable social transition. However, the carbon footprint of bioethanol production must fall within acceptable limits. The residential and commercial sectors should adopt energy-efficient equipment and green building materials, alongside enhanced incentive policies. The required new technologies should prioritize domestic R&D rather than relying solely on imports.

9. Designing Economic and Financial Incentives: Taiwan should align with international standards in the design of policy tools, such as carbon taxes, and establish mechanisms for the efficient allocation and utilization of carbon tax revenues to support net-zero technology development. A circular economy should be embedded as a core principle in the overall economic transformation, reducing total resource and energy demand. Additionally, Taiwan's electricity pricing formula should be re-evaluated to better reflect the actual cost of power generation.

10. Social Initiatives for Net-Zero Transformation: A comprehensive governance framework should foster public-private collaboration, and sustainability concepts should be embedded in education to strengthen societal alignment with sustainable values. Mechanisms for civic engagement and public communication should ensure that societal needs and stakeholder voices are included in the decision-making process, facilitating the development and implementation of carbon reduction policies. Furthermore, a thorough assessment of groups and sectors potentially impacted by the transition should be conducted, establishing a fair transition mechanism and corresponding resource allocation.

11. Scientific Research and Management Framework: Taiwan should adopt the mission-driven approach exemplified by international programs, such as the U.S. Department of Energy's ARPA-E, leveraging specialized technology management talent to drive goal-oriented innovative technology R&D. A systematic research platform would enhance project management efficiency. Additionally, to attract and retain talent, relevant agencies should implement incentive programs to ensure the long-term cultivation of key net-zero technology experts.

12. Vision for Overall Development: We aim to leverage our technological advantages to surpass current technology boundaries, creating net-zero opportunities that contribute to the global net-zero emissions goal and reversing resource overuse. We will position "circular sustainability" as a template for industrial transformation and stimulate the net-zero economy through innovative economic and financial tools, establishing a new circular economy model. This vision involves mobilizing society and fostering dialogue and mutual understanding across diverse communities to build a fair and just social foundation. Through robust public communication mechanisms, we seek to cultivate a harmonious society that embraces sustainable values, enabling citizens to adopt behaviors aligned with a net-zero lifestyle and ultimately achieving the national goal of a new prosperous and sustainable Taiwan.

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Chapter 1 The Rationale for Achieving Net-Zero Emissions by 2050

Sections

1.1 Introduction

**1.2 Analysis of the Current Status of Greenhouse Gas Emissions in
Our Country**

1.3 Guide to the Chapters of This Policy Recommendation Report

1.1 Introduction

Global climate scientists have warned that, in order to avoid many irreversible and catastrophic climate impacts, humanity must limit global warming to within 1.5°C above pre-industrial levels. This requires the world to achieve the goal of net-zero emissions by 2050 (Appendix 1A). The rise in greenhouse gas concentrations in the atmosphere stems from a fossil fuel-based energy economy over the past two centuries. With less than thirty years remaining to achieve net-zero emissions by 2050, many changes cannot be made overnight but will require a long-term, fundamental transformation. Therefore, we must take immediate action so that this challenging goal may be achieved by 2050. As a result, in recent years, governments, industries, non-governmental organizations, and academic researchers around the world have begun to promote a net-zero transition and undertake proactive carbon reduction actions (Appendix 1B).

Not being a member of the United Nations, Taiwan is not bound by international climate conventions. Although our past voluntary efforts have gradually stabilized our greenhouse gas emissions, actual reductions in emissions remain limited. As the international community begins to use carbon emissions as a benchmark for various economic activities, and global industry leaders start to pressure suppliers to reduce carbon emissions, this will inevitably impact the economic development of Taiwan, which is export-oriented and heavily reliant on energy-intensive manufacturing industries. In addition to facing global economic pressures, we also have a responsibility to leave a livable environment for future generations. Therefore, we must address this issue immediately. In March 2022, our government announced the "Taiwan 2050 Net-Zero Emissions Pathway¹," outlining the framework and direction for our country's net-zero transition. This includes four major transition strategies: "Energy Transition," "Industry Transition," "Lifestyle Transition," and "Social Transition," supported by two governance pillars: "Technological Research and Development" and "Climate Legislation," along with twelve key strategic initiatives. Based on this framework, various government departments have begun formulating action plans, with strategies for subsequent communication with the public.

However, while the current net-zero transition framework included strategic

¹ National Development Council (2022). *Taiwan's 2050 net-zero emissions pathway*.
https://www.ndc.gov.tw/Content_List.aspx?n=FD76ECBAE77D9811

directions and actions, the scientific basis and policy options for these actions still required further analysis and discussion to facilitate science-based dialogue and communication within society. To address this, Academia Sinica established the "Sustainable Transition and Carbon Reduction Pathway Policy Advisory Platform," inviting experts from various fields to participate in the discussion. Using quantitative data, this forum analyzed the challenges and opportunities for carbon reduction in Taiwan and explored potential carbon reduction options, ultimately resulting in this policy recommendation report (Box 1.1.1).

Box 1.1.1 Deliberation Process of Academia Sinica's "Taiwan Net-Zero Technology R&D Policy Recommendation Report"

From the end of 2020, the working group for this policy recommendation report collected data extensively and convened 18 domestic experts. In April 2021, the "Sustainable Transition and Carbon Reduction Pathway Policy Advisory Platform" was officially launched. During this period, 16 thematic meetings were held on specific topics, with over 300 expert participants discussing various approaches to carbon reduction. Additionally, the working group held seven committee meetings of the "Sustainable Transition and Carbon Reduction Pathway Policy Advisory Platform," during which members engaged in in-depth discussions on the challenges and potential of various carbon reduction options, offering many valuable cross-disciplinary suggestions. These were analyzed and integrated by the working group in the compilation of this policy recommendation report. The draft was then reviewed by academicians of Academia Sinica, the Policy Recommendation Committee of Academia Sinica, and external experts. After further revisions, the working group finalized the policy recommendation report. During the two-year deliberation process, committee members and participating experts also frequently attended governmental meetings on net-zero emissions policy. Many ideas in this report were raised during these discussions, and numerous government departments have referenced and incorporated them into their policy planning.

Achieving the goal of net-zero emissions requires integration from all sectors and across multiple dimensions. In addition to the recent efforts by various government departments, many scholars and experts in society have already published works and discussions on topics such as the governance, legal, social, and economic aspects of climate change and net-zero emissions in our country. Many scholars have also proposed that the overall demand side of our nation should be examined and appropriately adjusted and controlled. However, considering the role of Academia Sinica and aiming to provide more focused recommendations, this policy recommendation report centers on "technological research and development" as the core perspective, exploring how technology can assist in our country's carbon reduction efforts. Relying solely on existing technologies will not be enough to achieve the 2050 net-zero emissions goal. In addition to enhancing the use of current technologies, we must also focus on innovative technological research and development, while combining tools and methods from the fields of economics, society, and research management to accelerate the deployment of net-zero technologies. This would ensure that new technologies are developed in time, enabling Taiwan's net-zero transition to be completed as scheduled.

In addressing the broad-ranging issue of net-zero emissions, this report starts from the perspective of "emission sources," diagnosing and analyzing the sources and magnitudes of our greenhouse gas emissions, as well as identifying key challenges. The goal is to identify potential technology options for reducing carbon and rationally evaluate them using quantitative data. This involves considering the actual carbon reduction benefits of each option, as well as the speed and scale of their research, development, and deployment. These factors serve as the basis for prioritizing carbon reduction technologies. The carbon reduction and net-zero technology options proposed in this policy recommendation can also serve as a reference for future technological pathways in our country.

1.2 Analysis of the Current Status of Greenhouse Gas Emissions in Taiwan

To achieve the goal of net-zero emissions by 2050, it is crucial to first understand the trends, sectors, and sources of greenhouse gas emissions in Taiwan, as well as the underlying energy, social, and economic factors. These will facilitate the diagnosis and analysis of the reasons behind carbon emissions, the key challenges that make carbon reduction difficult, potential carbon reduction options, and the priority of solutions. According to the statistical data from the Environmental Protection Administration's 2021 National Greenhouse Gas Inventory Report, Taiwan's total greenhouse gas emissions increased from 137 million metric tons of carbon dioxide equivalent (Mt CO₂eq) in 1990 to 287 Mt CO₂eq in 2019. This doubling of emissions occurred primarily between 1990 and 2007 (Figure 1.2.1), a period of rapid economic growth for our country, indicating a strong correlation between carbon emissions and early economic development. However, after the sharp decline in emissions caused by the global financial crisis of 2008-2009, our greenhouse gas emissions have remained relatively stable over the past decade (for related indicators and data on Taiwan's greenhouse gas emissions, please refer to Appendix 1C).

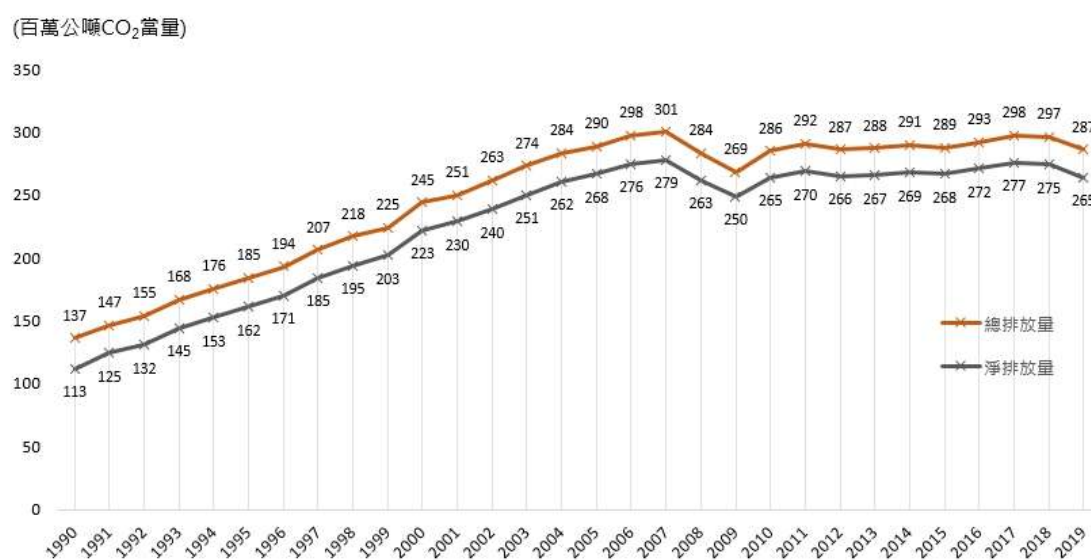


Figure 1.2.1 Greenhouse Gas Emissions in Taiwan (1990 to 2019)

Although Taiwan has continued to promote energy conservation and carbon reduction, this has only led to a stabilization of greenhouse gas emissions without clear signs of a significant reduction. This highlights that cutting carbon and effecting an

energy transition in Taiwan will be truly challenging tasks. An analysis using data from the International Energy Agency (IEA)² reveals that the main reasons include the fact that 98% of our energy supply relies on imports, unlike many other countries that have abundant resources for domestic energy production (e.g., the United States produces its own oil and natural gas; Iceland produces its own geothermal and hydropower). As an island nation, the possibility of cross-border power grids is less feasible due to cost and national security considerations. Moreover, 93% of our energy comes from high-carbon-emission fossil fuels, unlike many countries with more diversified energy sources (e.g., France and Sweden have high proportions of nuclear energy; Sweden uses a high percentage of bioenergy, and Iceland relies heavily on geothermal and hydropower). Completely replacing such a high proportion of fossil fuels is no easy task.

On the energy consumption side, our industrial sector accounts for a high percentage of energy usage (33%), while in countries like the United States and Australia, the transportation sector consumes around 40%, and in countries like the UK and France, other sectors (residential and commercial) have a higher consumption ratio. This shows that Taiwan's country's economic structure, with its energy-intensive and high-carbon-emitting industries, is a key factor, making it necessary to consider carbon reduction along with energy use and economic growth. Additionally, a high percentage of our petroleum is used to produce petroleum products for export (such as petrochemicals), accounting for about 14% of the total energy supply. Furthermore, a large portion is used to produce non-energy consumption products (such as light oil, coke, and asphalt), which accounts for approximately 33% of total energy consumption. This indicates that the petrochemical industry has played a critical role in Taiwan's past economic growth, making industrial transformation a major challenge with wide-ranging impacts.

These factors present significant challenges for our country in achieving the 2050 net-zero emissions goal. The following sections will analyze the sources, emission levels, and key points for carbon reduction in the major greenhouse gas-emitting sectors in our country.

2 IEA (2020). Sankey diagram. <https://www.iea.org/sankey/>

1.2.1 Providing Zero-Carbon Electricity Is a Major Challenge for Reducing Carbon in Taiwan

According to the greenhouse gas emission data from the National Greenhouse Gas Inventory Report, it is evident that emissions from the energy usage, primarily from fuel combustion, constitute the largest portion—up to 91% of total emissions. The remaining 9% of emissions include direct emissions from industrial processes, agricultural emissions, and waste emissions (Figure 1.2.2)³. According to data from the Bureau of Energy, Ministry of Economic Affairs, our total electricity generation in 2019 was approximately 274.1 billion kWh, with a carbon intensity of 0.509 kg CO₂eq/kWh. From this, we can determine that the carbon emissions from the power sector that year were 139.6 million metric tons of CO₂eq, accounting for 48.6% of the total emissions. This electricity was consumed by the industrial, residential, service, transportation, agricultural, and energy sectors.

As seen from the above, energy usage is the largest source of greenhouse gas emissions in our country (91%), primarily due to the use of various fossil fuels (such as oil, coal, and natural gas) for heat generation or power production, which leads to emissions during combustion. Figure 1.2.2 shows that the largest single source of emissions is electricity, mainly from thermal power generation (48.6%), followed by emissions from transportation, mainly fossil fuel-powered vehicles (12.6%)⁴; manufacturing/construction, including heat generation from boilers (11.4%); cogeneration plants' heat generation from boilers (8%); combustion activities in solid fuel production processes, such as coke (3.7%); residential, agricultural, forestry, fishery, and service sectors' heat generation from boilers/heaters (3.3%); and refinery activities, namely combustion during petroleum product refining (3.1%).

In the future, as the transportation sector and various industries move toward electrification, the share of emissions from power generation in total emissions will increase significantly. Therefore, providing zero-carbon electricity will be a major

³ IEA (2020). Sankey diagram. <https://www.iea.org/sankey/>

⁴ Taiwan's Greenhouse Gas Inventory is primarily established based on the guidelines set by the Intergovernmental Panel on Climate Change (IPCC) in 2006. It is mainly divided into the following categories: energy, industrial processes and product use, agriculture, land use, land-use change and forestry (LULUCF), and waste. The quantification methods are mostly based on the type of fuel, followed by calculations using activity data (the amount of fuel used) and emission factors (the greenhouse gas emissions per unit of fuel) to estimate the total emissions.

target for Taiwan's carbon reduction efforts (see Chapter 2 for details).

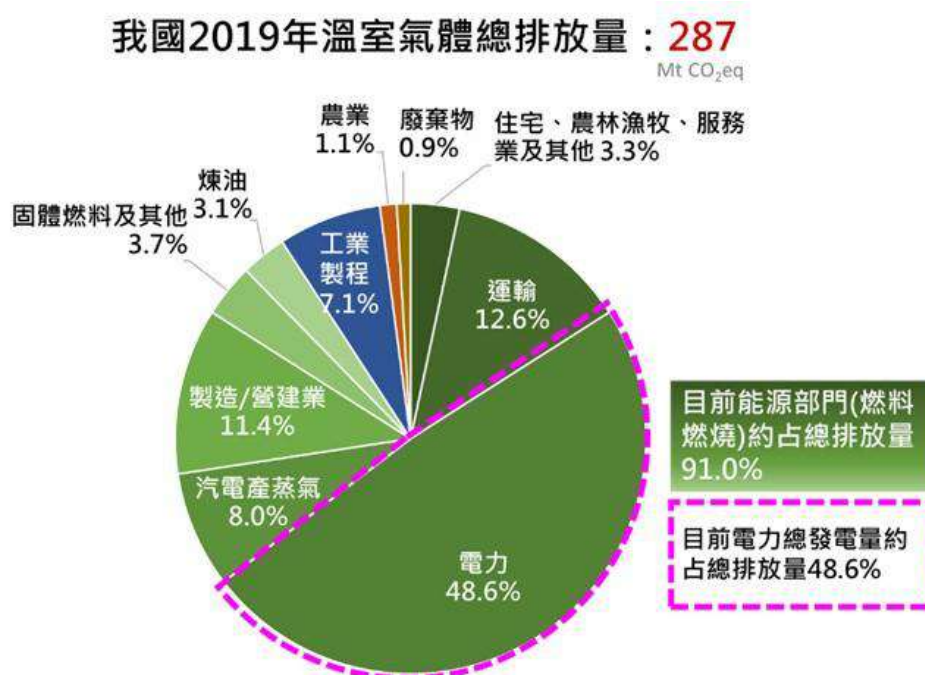


Figure 1.2.2 Taiwan's Greenhouse Gas Emissions in 2019 (Note: All energy uses, including direct combustion, account for approximately 91% of total emissions (indicated by the green segments); electricity accounts for 48.6% of total emissions (outlined by the pink dotted line).)

1.2.2 The Industrial Sector Drives the Economy, Hence Investment in Innovative Technologies and Operations Is Necessary

Greenhouse gas emissions in the industrial sector are diverse, including indirect emissions from electricity use (27%)⁵, fuel combustion from various boilers (11.4%), and emissions from industrial processes (7.1%), which together account for 45.5% of our total emissions (Figure 1.2.3). The industrial sector covers a wide range of industries with numerous companies of various sizes. In 2019, the industrial sector contributed about 35.5% of Taiwan's GDP. Although this proportion is lower than that of the service sector, the industrial sector (including manufacturing) forms the backbone of Taiwan's economic development. Many high-carbon-emission enterprises were also key drivers of Taiwan's early economic takeoff. As a result, carbon reduction in this sector will have a significant impact on Taiwan's economy, potentially affecting labor

⁵ According to the Bureau of Energy, Ministry of Economic Affairs (2022) *Energy Statistics Monthly Report*, the industrial sector accounted for approximately 55.6% of total electricity consumption in 2019, while electricity generation accounted for 48.6% of total emissions. Therefore, electricity use in the industrial sector contributed to about 27.0% of total emissions. <https://www.e-sist.org.tw/publication/monthly>

opportunities, making industrial sector decarbonization a focal point of attention.

The key opportunities for carbon reduction in the industrial sector include using zero-carbon electricity, adjusting electricity demand, using alternative fuels for boilers (such as electricity, biomass energy, and hydrogen), developing and implementing innovative technologies, and transforming industrial or business models. For Taiwanese companies, future operations and revenues could be impacted by demands for net-zero compliance from downstream manufacturers and supply chains. Therefore, companies must actively invest in the research and development of innovative technologies, implement them, and seek operational transformation and new business opportunities (see Chapter 4 for details).

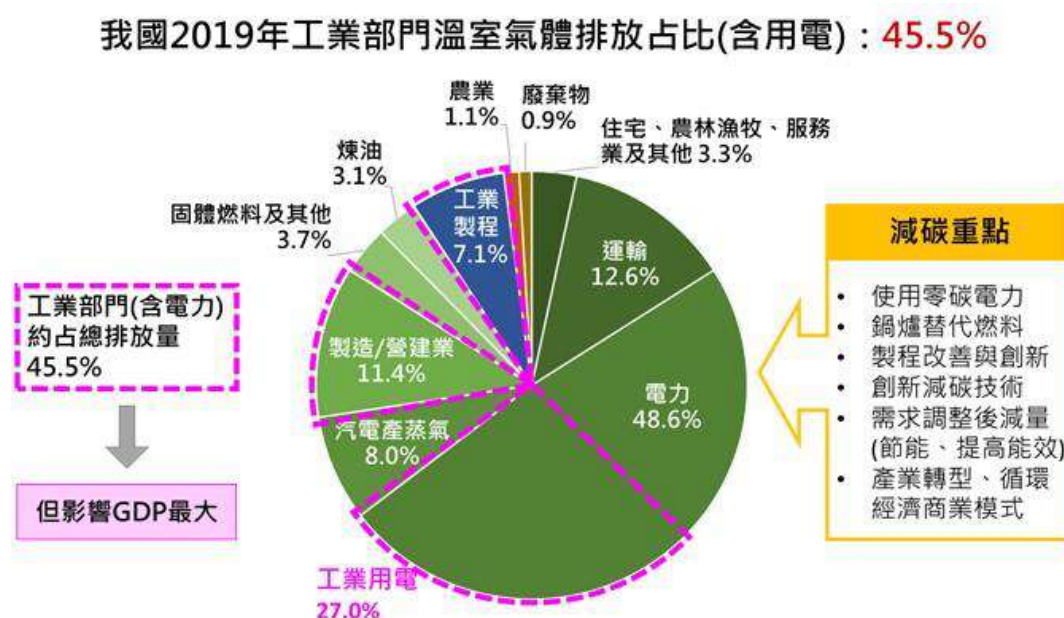


Figure 1.2.3 Sources of Greenhouse Gas Emissions and Key Carbon Reduction Focus Areas in the Industrial Sector of Taiwan in 2019 (Note: Emission sources are outlined with pink lines, and carbon reduction focus areas are indicated with yellow text boxes.)

1.2.3 The Transportation Sector Affects a Large Segment of the Population and Decarbonization Must Consider Social Factors

The transportation sector accounts for 12.9% of total emissions, which includes 12.6% from the fuel combustion of various motor vehicles and a small portion from electricity used in rail transport (0.3%)⁶. Although the share of emissions from this sector is not high, it affects the largest number of people (Figure 1.2.4). By the end of 2019, the number of registered motor vehicles in Taiwan had reached 22.1 million, including 8.1 million cars and 14.0 million motorcycles. On average, there were 93.7 motor vehicles and 34.4 cars per 100 people, and the number of licensed drivers reached 28.9 million⁷. Although some individuals may own multiple vehicles, these figures indicate that efforts to reduce carbon emissions in the transportation sector will impact the daily lives and even the livelihoods of a vast majority of citizens (see Chapter 5 for details).

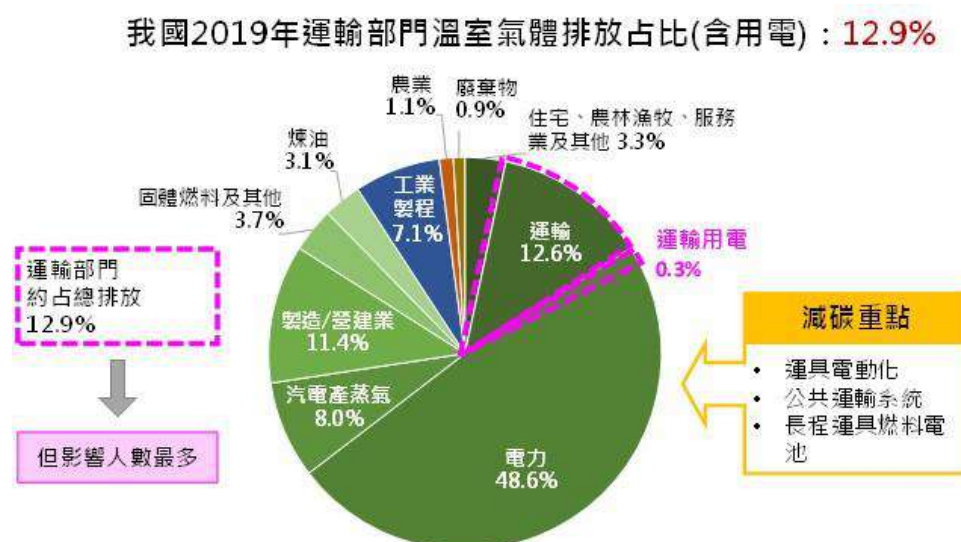


Figure 1.2.4 Greenhouse Gas Emission Sources and Key Carbon Reduction Opportunities in the Transportation Sector in 2019 (Note: Emission sources are outlined in dotted pink lines and key carbon reduction areas are highlighted in yellow text boxes.)

6 According to the Bureau of Energy, Ministry of Economic Affairs (2022) *Energy Statistics Monthly Report*, the transportation sector accounted for approximately 0.6% of total electricity consumption in 2019, while electricity generation accounted for 48.6% of total emissions. Therefore, the electricity used by the transportation sector contributed to approximately 0.3% of total emissions. <https://www.esist.org.tw/publication/monthly>

7 Ministry of Transportation and Communications (2022). Ministry of Transportation Statistics Query Website, number of registered motor vehicles and licensed drivers. <https://stat.motc.gov.tw/mocdb/stmain.jsp?sys=100&funid=a3301>

The key opportunities for carbon reduction in the transportation sector include switching to alternative fuels for motor vehicles, such as batteries or hydrogen fuel cells, and changing transportation behaviors and increasing the use of public transportation systems. Since carbon reduction in the transportation sector will affect a large number of people, and motorcycles are often essential for the daily lives and livelihoods of working class citizens, it is crucial to consider fairness during the transition to ensure effective implementation (see Chapter 5 for details).

1.2.4 Remaining Sectors: Lifestyle, Business Operations, and Carbon Sequestration in Agriculture and Forestry

The residential sector accounted for 10.3% of total emissions, primarily from household electricity consumption (8.7%)⁸ and stoves, including gas stoves (1.6%) (Figure 1.2.5). Since this involves every household and individual, the points of intervention and potential impact are not simple. Efforts can only begin with the electricity sector providing zero-carbon power or through the design of buildings and construction materials to reduce energy demand within buildings (such as for air conditioning). Like the transportation sector, given the large number of people affected, it is necessary to consider the differences between impacted groups and plan supportive measures to facilitate implementation (see Chapter 5 for details).

The commercial/service sector accounts for 9.8% of total emissions, primarily from electricity consumption in the service industry (8.6%)⁹ and fuel combustion from boilers and appliances, such as gas stoves (1.2%) (Figure 1.2.6). In 2019, the service sector contributed approximately 62.9% to the national GDP, indicating that it is a high-value industry with relatively low carbon emissions. This highlights the importance of the service sector within our current industrial structure. Given the large number of people involved in the service industry, beyond the provision of zero-carbon electricity, adjustments in operational models may be necessary in ways that can be accepted by

⁸ According to the Bureau of Energy, Ministry of Economic Affairs (2022) *Energy Statistics Monthly Report*, the residential sector accounted for approximately 17.8% of total electricity consumption in 2019, while power generation contributed about 48.6% of total emissions. Therefore, electricity usage in the residential sector accounted for approximately 8.7% of total emissions. <https://www.esist.org.tw/publication/monthly>

⁹ According to the Bureau of Energy, Ministry of Economic Affairs (2022) *Energy Statistics Monthly Report*, the service sector accounted for approximately 17.6% of total electricity consumption in 2019, while power generation contributed about 48.6% of total emissions. Therefore, electricity usage in the service sector accounted for approximately 8.6% of total emissions. <https://www.esist.org.tw/publication/monthly>

the public. For example, adjusting energy usage patterns in large or chain-operated commercial establishments. Therefore, social factors must be taken into account to facilitate the implementation of these measures (see Chapter 5 for details).

我國2019年住宅部門溫室氣體排放占比(含用電)：10.3%

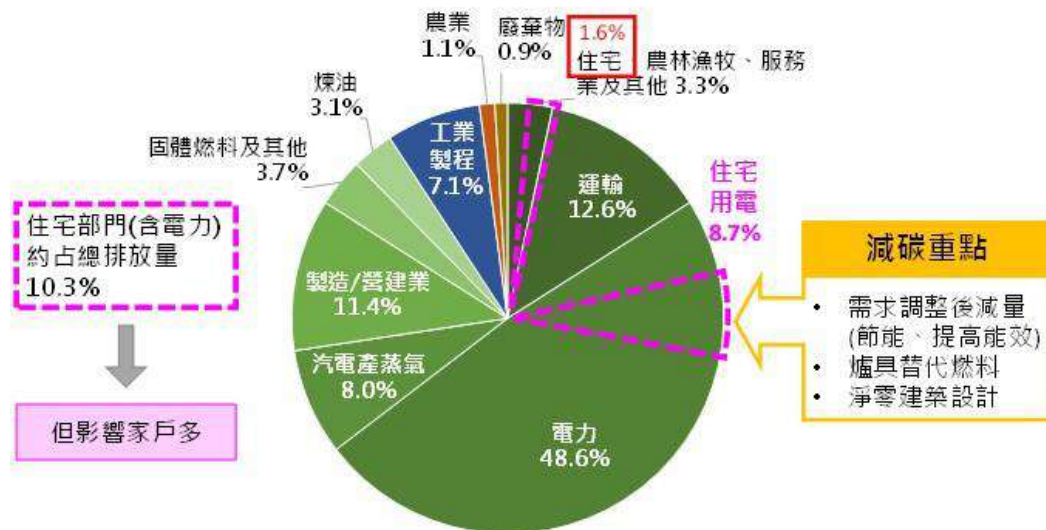


Figure 1.2.5 Greenhouse Gas Emission Sources and Key Carbon Reduction Opportunities in Residential Sector in 2019 (Note: Emission sources are outlined in dotted pink lines and key carbon reduction areas are highlighted in yellow text boxes.)

我國2019年商業/服務業部門溫室氣體排放占比(含用電)：9.8%

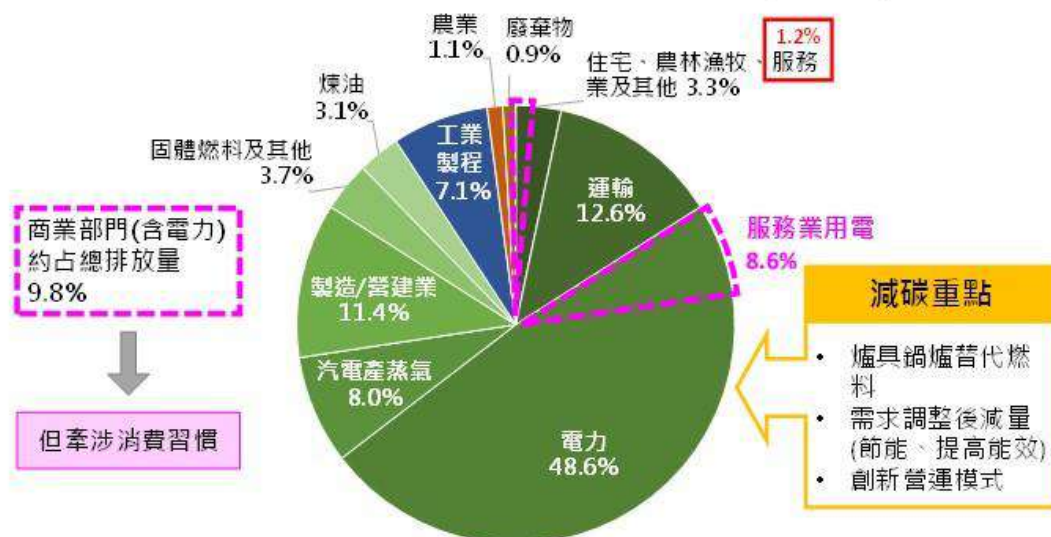


Figure 1.2.6 Greenhouse Gas Emission Sources and Key Carbon Reduction Areas in the Commercial/Service Sector of Our Country in 2019 (Note: Emission sources are outlined in pink dotted lines, and key carbon reduction areas are highlighted in yellow text boxes.)

The agricultural sector (including agriculture, forestry, fisheries, and livestock) accounted for 2.1% of total emissions, mainly from direct emissions from agricultural and livestock operations (1.1%), electricity consumption in agriculture (0.5%)¹⁰, and fuel combustion in agricultural, forestry, fishery, and livestock operations (0.5%). The waste sector accounted for 1% of total emissions, primarily from emissions during waste processing (Figure 1.2.7). The amount of carbon removal—mainly from forest carbon sequestration in the forestry sector—was equivalent to about 7.5% of total carbon emissions. Although the agricultural and waste sectors contribute a relatively small portion of total emissions, they are highly relevant to the issue of net-zero emissions. In addition to the need for carbon reduction in agriculture, forestry, and waste management industries, revitalizing agricultural and forestry biomass can significantly contribute to increasing natural carbon sinks and biomass energy supply. However, this will require comprehensive, system-wide planning to achieve noticeable results (see Chapter 5 for details).

我國2019年農業及廢棄物部門溫室氣體排放占比(含用電)：3.1%

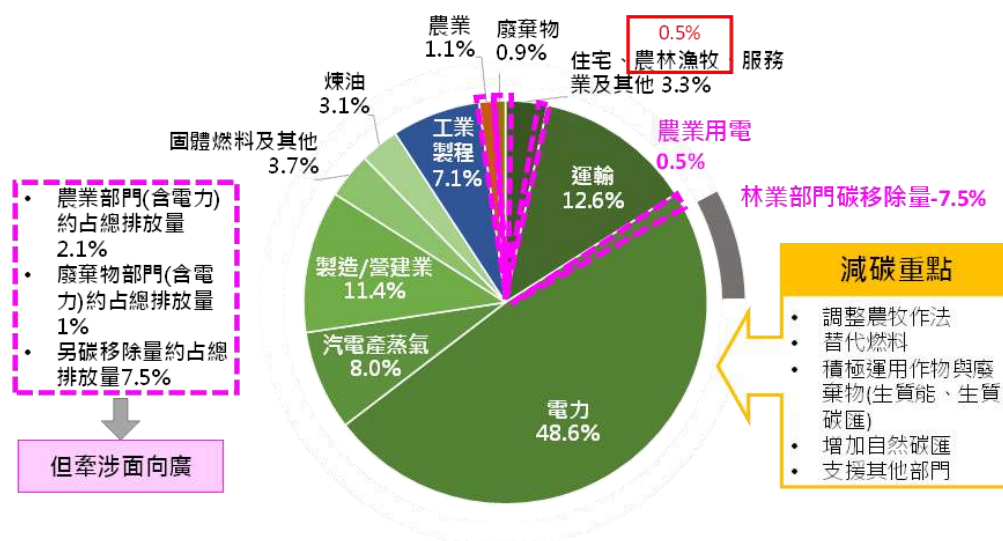


Figure 1.2.7 Greenhouse Gas Emission Sources, Absorption Sources, and Key Carbon Reduction Areas in the Agricultural and Waste Sectors in 2019 (Note: Emission sources are outlined in dotted pink lines, and key carbon reduction areas are highlighted in yellow text boxes.)

¹⁰ According to the Bureau of Energy, Ministry of Economic Affairs (2022) *Energy Statistics Monthly Report*, the agricultural sector accounted for approximately 1.1% of total electricity consumption in 2019, while power generation contributed about 48.6% of total emissions. Therefore, electricity usage in the agricultural sector accounted for approximately 0.5% of total emissions. <https://www.esist.org.tw/publication/monthly>

1.2.5 Technology Research and Development as the Key to Net Zero

Although the general goals for carbon reduction in the above sectors are clear, achieving them in a timely manner under conditions acceptable to both industry and society remains a serious challenge. Advanced countries aiming 2050 net-zero emissions recognize that this goal cannot be achieved solely with existing technologies. It requires setting new technological directions and investing in research and development (R&D) to overcome critical bottlenecks, with the hope that new technologies will be gradually implemented before 2050 to help achieve the net-zero emission target.

If Taiwan does not actively invest in R&D or invests in the wrong direction, we will not only face difficulties but also miss excellent opportunities to develop new technologies and tap into new markets. Therefore, this policy recommendation considers technology R&D to be key to reaching the net-zero emission target. Although net-zero technology R&D is based on science, there must also be efforts to overcome bottlenecks in critical engineering technologies. The main points of the R&D strategy are as follows:

1. Setting achievable goals for engineering technologies based on scientific principles.
2. Technology capabilities are quantitatively conceptualized, but not constrained by current engineering technologies.
3. Focusing on major carbon-emitting areas.
4. Emphasizing speed and scale of deployment.

When selecting technological R&D directions, in addition to considering Taiwan's unique conditions (including resources and environment), overall metrics such as emission volumes, carbon reduction potential, and power generation capacity must be analyzed. Clear benefit indicators should be used to determine the direction of innovative technology development. Since the scale of carbon reduction technologies often far exceeds what typical researchers are familiar with, careful selection of topics is essential, with adjustments made as development progresses. Moreover, this type of R&D differs from academic research conducted in typical institutions and from product-oriented research in industry. It often involves interdisciplinary team collaboration, requiring participants to possess comprehensive system integration knowledge to deeply explore and resolve the practical challenges in carbon reduction

technologies.

Figure 1.2.8 outlines the areas where the technological R&D sector can support carbon reduction. However, designing an effective scientific research management framework to promote net-zero technology development is also a crucial task.

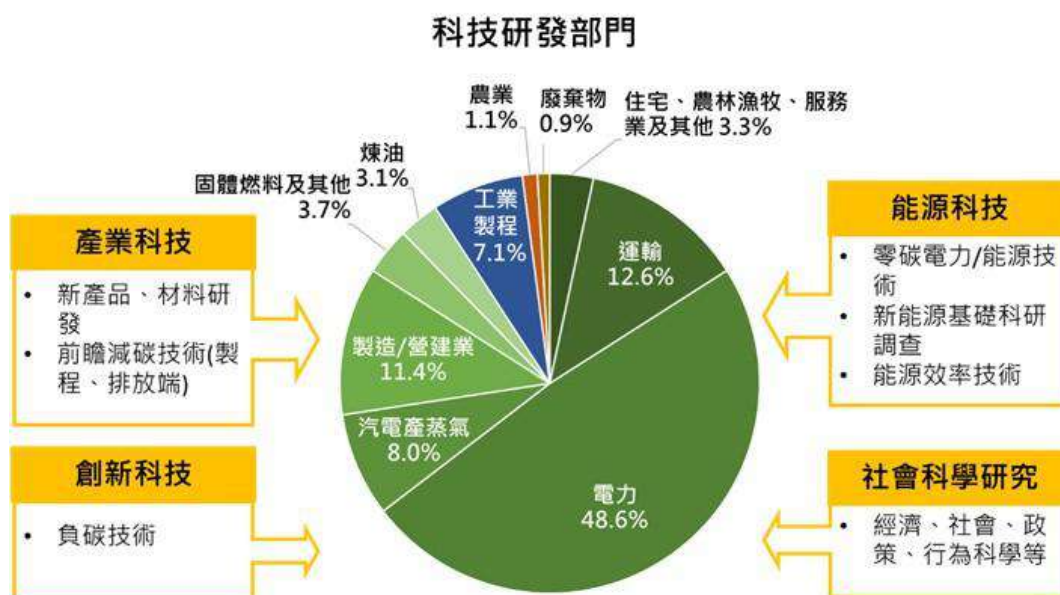


Figure 1.2.8 Key Role of the Research and Development in Carbon Reduction

1.2.6 Support from the Economic, Financial, Social, Educational, and International Cooperation and Trade Sectors

In addition to technological advancements, achieving 2050 net-zero emissions target requires other supporting and accelerating measures. Therefore, the economic, financial, social, educational, and international cooperation and trade sectors must also provide strong support (see Figure 1.2.9).

The economic and financial sectors can offer supportive economic tools, such as green finance programs, to drive industrial transformation and accelerate technological development (see Chapter 7 for details). The social and educational sectors can assist in communication and engagement during the transformation process to increase social acceptance (see Chapter 7 for details).

Lastly, although the expansion of domestic energy sources (such as wind, solar, geothermal, and marine energy) will increase Taiwan's energy self-sufficiency under the net-zero scenario, imports of new energy may still be required. Thus, early planning for international cooperation and trade strategies is essential.

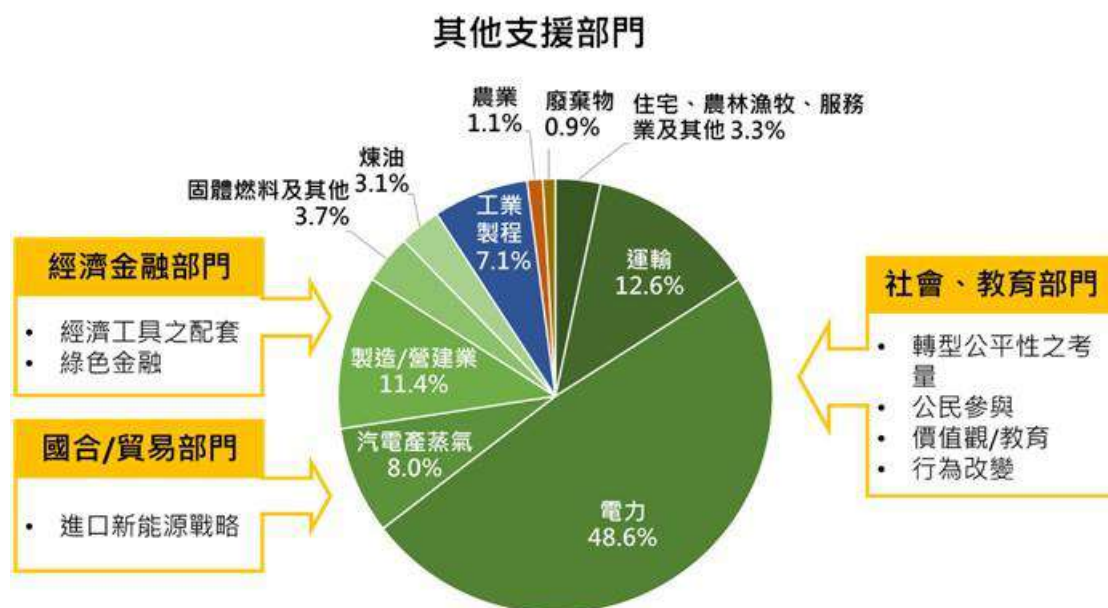


Figure 1.2.9 Key Role of Other Sectors in Supporting Carbon Reduction

1.3 Structure of this Policy Recommendation

This policy recommendation begins with Chapter 1 above outlining the reasons why Taiwan should align with the global trend toward net-zero emissions by 2050. It briefly analyzed Taiwan's major emission sources and examined key carbon reduction priorities based on emission levels from different sectors, helping to understand Taiwan's decarbonization priorities.

Since emissions from the power sector account for about half of total emissions, **Chapter 2** analyzes the strengths and weaknesses of ten zero-carbon power technologies and systems, assessing their potential contributions to overall carbon reduction by 2050, and offering specific R&D recommendations for each technology.

Chapter 3 focuses on carbon-negative technologies, discussing how short-term solutions like natural carbon sinks and traditional carbon-negative technologies can help reduce emissions, while long-term solutions aim to develop net-negative emission technologies by 2050. **Chapter 4** examines decarbonization options in the manufacturing sector, analyzing potential emission sources in Taiwan's four key industrial sectors, and proposing suitable technological solutions for each.

In **Chapter 5**, the report explores the current carbon emission status in the sectors that affect broad portions of society, such as transportation, residential and commercial buildings, agriculture, and waste management. It also assesses potential future carbon reduction technologies for each sector. **Chapter 6** highlights emerging technologies that are still in their infancy but are worth long-term attention, as they could become viable carbon reduction options by 2050 with continued breakthrough developments.

Chapter 7 provides a broad analysis of the economic and social enablers of carbon reduction and offers several insights on how these tools and approaches can accelerate the development and implementation of emerging net-zero technologies. Finally, **Chapter 8** summarizes key technological options from the previous chapters and proposes an integrated research and development management framework.

Chapter 2 Promoting Zero Carbon Electricity

Sections

2.1 Introduction	2.7 Biomass Energy
2.2 Photovoltaic Solar Power	2.8 Hydropower
2.3 Wind Energy	2.9 Ocean Energy
2.4 Geothermal Energy	2.10 Smart Grids
2.5 Hydrogen Energy	2.11 Energy Storage
2.6 Methane Pyrolysis	2.12 Conclusion

2.1 Introduction

According to the overview of Taiwan's greenhouse gas emissions described in Section 1.2 of this proposal, the energy sector accounted for approximately 91% of the national total emissions in 2019, with electricity generation making up 48.6% of total emissions. This indicates that the energy sector, particularly the electric power sector, is crucial for Taiwan's carbon reduction efforts. Moreover, with the development of technology and global carbon reduction trends, most of the energy currently supplied by fossil fuel combustion (thermal energy) will transition to electricity supply. The International Energy Agency (IEA) estimates that by 2050, electricity will account for about half of the world's total energy consumption. Due to Taiwan's high level of industrial and commercial development and relatively low heat energy demand during winter, the proportion of electricity consumption is expected to be even higher (refer to Appendix 2A for international energy trends; refer to Appendix 2B for the challenges in carbon reduction for Taiwan's energy sector). This also suggests that future electricity demand will continue to grow. The strategy of large-scale electrification not only makes energy usage more convenient for users but also concentrates carbon emissions at fixed sources, making them easier to manage. However, this approach both simplifies the carbon reduction issue—where the carbon reduction option for many sectors may be "electrification" or "electromobility"—and significantly increases the pressure and urgency on the power sector. Therefore, the challenge of how to generate sufficient zero-carbon electricity will be the most critical issue in the path to net-zero emissions.

Whether the electricity supply will be sufficient depends on future electricity demand. Currently, Taiwan's electricity is used for industrial, residential, commercial, and other purposes. Future changes in electricity demand may involve several factors, such as industrial transformation reducing industrial electricity use, factory expansions increasing industrial electricity demand, population decline reducing residential electricity demand, more advanced and convenient services increasing commercial electricity demand, and electrification causing other energy sources to be converted to electricity. These factors depend on Taiwan's future socioeconomic development scenarios, making it difficult to accurately quantify the potential increases or decreases in electricity demand. Additionally, some scholars have suggested that Taiwan should review and adjust overall demand, but this factor is even more challenging to quantify. Therefore, we primarily estimate electricity demand based on the electrification strategy,

without considering other socioeconomic factors that may impact electricity demand.

In 2019, Taiwan's electricity generation was 274.1 billion kWh, with a power sector carbon intensity of 0.509 kg CO₂eq/kWh. This results in a total carbon emission of 139.6 M ton CO₂eq from the power sector, accounting for 48.6% of the total emissions. In addition to electricity generation, the carbon emissions from other energy uses (direct combustion) accounted for 42.4% of total energy-related emissions. If zero-carbon electricity could replace this portion, Taiwan's carbon emissions would be significantly reduced. Therefore, assuming total energy demand remains unchanged, electrifying just 50% of the direct combustion portion would require Taiwan to increase its electricity generation to 393.7 billion kWh. If 90% of the direct combustion portion is electrified, electricity generation would need to increase to 489.3 billion kWh. This indicates that, under the scenario of maintaining the current level of energy demand (neither increasing nor decreasing), simply switching to "electrification" in fuel conversion could potentially increase Taiwan's electricity demand by 43.6% to 78.5%. When considering other socioeconomic factors that may increase electricity demand, Taiwan's future electricity demand could potentially double.

To calculate the changes in electricity demand more accurately due to electrification in each sector, we can analyze energy supply and consumption. According to data from the Energy Bureau of the Ministry of Economic Affairs, Taiwan's total energy supply in 2019 reached 148.4 million KLOE (Kiloliter of Oil Equivalent), and total energy consumption reached 84.91 million KLOE, with the difference representing energy losses (Figure 2.1.1). Fossil fuels (oil, coal, and natural gas) accounted for 91% of the total energy supply. Besides being used to produce chemicals, plastics, fibers, and asphalt, the rest of the fossil fuels were ultimately burned, generating carbon dioxide (CO₂).

For individual fossil fuels, petroleum products were the largest contributor, with a total supply of 69.55 million KLOE. Of this, more than 30% was used for non-energy consumption (24.12 million KLOE), such as lubricants, asphalt, and solvent oils that are not used for combustion. Additionally, 21.78 million KLOE was exported, 13.4 million KLOE was used by the transportation sector, and a small amount was used by the industrial sector. Coal was mainly used for electricity generation, with some directly provided to the industrial sector as energy. Natural gas was primarily used for electricity generation, with a small portion used by the industrial and residential sectors.

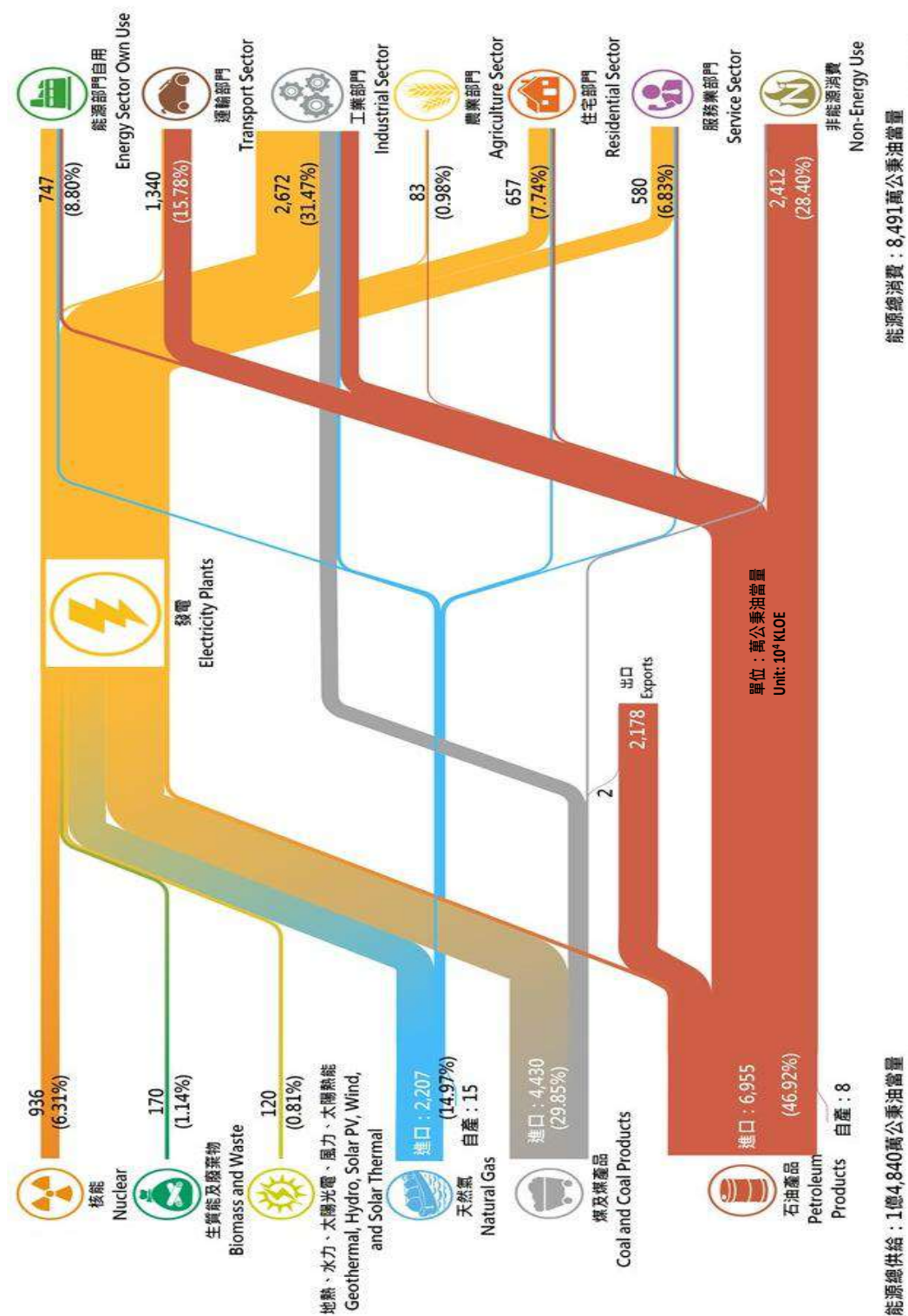


Figure 2.1.1 Taiwan's Total Energy Supply and Consumption in 2019

Currently, Taiwan's electricity generation mainly relies on coal and natural gas for fuel. Taking into account both traditional and newer technology power plants, the carbon emission factor for coal-fired power plants in Taiwan ranges from 0.78 to 0.92 kg CO₂/kWh, while for natural gas power plants, it ranges from 0.38 to 0.42 kg CO₂/kWh. Therefore, although natural gas is not a "completely carbon-free" energy option, compared to coal and oil, it is a significantly lower carbon-emitting fuel. Thus, Taiwan can follow the international trend by using natural gas to replace coal in the short term to reduce carbon emissions. However, in the long term, it will still be necessary to utilize hydrogen power generation and carbon capture, utilization, and storage (CCUS) technologies as negative carbon solutions (see Box 2.1.1).

Box 2.1.1 Why Can Natural Gas Power Generation Serve as a Transitional Option, Even though It Is Also a Fossil Fuel?

The combustion of fossil fuels emits carbon dioxide (CO₂), but the amount of CO₂ produced depends on the carbon content of the fuel itself. The energy (heat content) generated from combustion is determined by the carbon and hydrogen content of the fuel. Compared to other fuels, natural gas (mainly methane, CH₄) has a higher energy content. As a result, to achieve the same heat content, burning natural gas produces less CO₂ than other fossil fuels.

When comparing the amount of CO₂ produced per million BTU (British thermal unit) of fuel burned (as shown in Table 2.1.1), natural gas emits the least CO₂. Although the actual carbon emissions will depend on the efficiency of different power plant technologies, the carbon emissions from natural gas are approximately half those of coal. If we consider the carbon emission factor of electricity generation (the CO₂ equivalent produced per unit of electricity generated), the emissions from natural gas are 45.4% of those from coal (as shown in Table 2.1.2).

These data suggest that, setting aside the carbon emissions from fossil fuel extraction and transportation, natural gas is not a completely carbon-free energy option. However, compared to coal and oil, natural gas produces significantly lower carbon emissions. Therefore, replacing coal with natural gas in the short term could reduce carbon emissions from coal-fired power generation by 40% to 60%. Natural gas is considered a transitional option until new technologies can be implemented after 2030. As recommended in this report, the development of decarbonized hydrogen technology (detailed in Section 2.6) could further reduce or even eliminate

the carbon emissions from natural gas.

Table 2.1.1 Comparison of Carbon Dioxide Emissions from the Combustion of Different Fuels
(kg CO₂ emitted per million Btu)

Coal (anthracite)	103.7
Coal (bituminous)	93.3
Diesel fuel and heating oil	73.2
Gasoline (without ethanol)	71.3
Propane	63.0
Natural gas	53.1

Source: U.S. Energy Information Administration; unit conversions made Academia Sinica.

Table 2.1.2 Greenhouse Gas Emission Factors for Taiwan Power Company's Thermal Power Units (kg CO₂eq/kWh)
(2016 - 2018)

Taiwan Power Company Fuel Oil	0.770
Taiwan Power Company Traditional Gas-Fired / New Combined Cycle Gas Units	0.417/ 0.383
Taiwan Power Company Traditional Coal-Fired / New Ultra-Supercritical Coal Units	0.918/ 0.775

Source: Taiwan Power Company, Cheng Jui-Ho and Cheng Hsiang-Yun (2019), Liu Tseh-Huai (2020)

Thermal energy demand from Taiwan's residential and commercial sectors is not as significant as that of higher-latitude countries, and most energy consumption in these sectors is already in the form of electricity. Therefore, electrification efforts will primarily focus on the transportation and industrial sectors. Currently, countries worldwide are accelerating their electrification of the transportation sector, including by adopting electric vehicles. Many advanced nations have already announced sunset timelines for the sale of new gasoline vehicles. The decarbonization of the transportation sector will significantly reduce the demand for transportation fuel, with only aviation, long-distance freight, and other hard-to-electrify transport needs remaining.

On the other hand, not all energy consumption in the industrial sector can be electrified. Light industrial processes might be able to develop electrification

technologies. However, heavy industries like steelmaking, oil refining, and cement production, which require high-temperature heat, cannot be easily replaced by current electrification technologies. These industries will need to rely on zero-carbon hydrogen energy, biomass energy, or carbon capture, utilization, and storage (CCUS). Therefore, the development and application of these technologies are crucial for achieving stable energy supply and net-zero emissions in these industries.

To estimate the impact of electrification in the transportation sector, if the energy used was directly converted into electricity, the transportation sector would consume 13.4 million KLOE (Kiloliter of Oil Equivalent). If 60% of the sector is electrified, 8.04 million KLOE will need to be converted into electricity, which, considering the efficiency of electric vehicles, would require approximately 16.82 billion kWh of electricity. Another method estimates the electricity demand for fully electric vehicles based on the total number of vehicles and mileage, which would increase electricity demand by about 40.11 million kWh per day, or 14.64 billion kWh per year.

To estimate the electrification of the industrial sector, if the energy used today was directly converted into electricity, the industrial sector would consume approximately 26.82 million KLOE, of which 5.56 million KLOE comes from coal and coal products, 1.63 million KLOE from petroleum products, and 3.18 million KLOE from natural gas. If 60% of the sector is electrified, 6.22 million KLOE will need to be converted into electricity, requiring approximately 65.1 billion kWh of electricity. In 2019, Taiwan's electricity generation was 274.1 billion kWh. If direct energy conversion is used, the total electricity demand for 60% electrification of the transportation and industrial sectors would be approximately 81.92 billion kWh, which would require an increase of about 30% in electricity generation, reaching 356 billion kWh.

Conversely, if electrification does not take place, efforts must be significantly accelerated in the industrial sector to develop and deploy zero-carbon hydrogen energy, biomass energy, and carbon capture technologies. The transportation sector will also need to explore the development of non-fossil fuel, low-carbon transportation methods and related infrastructure (such as hydrogen-powered vehicles and hydrogen refueling stations). This presents a considerable challenge and requires a drastically different path for infrastructure investments.

From this analysis, it is evident that to achieve the goal of net-zero emissions by 2050, all technological options should be considered. Based on the current maturity of technology, electrifying as much as possible, along with developing zero-carbon

electricity supply, remains the primary pathway to achieve net-zero emissions. This should be complemented by the deployment of hydrogen energy, biomass energy, and carbon capture technologies.

Still, the goal of zero-carbon electricity has its limitations. As a result, Taiwan must also develop strategies to reduce electricity demand, such as energy-saving behaviors across different sectors, improving energy efficiency, economic transformation, and fostering social communication. These strategies are crucial to balance the supply and demand of electricity.

In this chapter, we will detail the potential zero-carbon electricity options and power generation capacity that Taiwan could develop.

2.2 Photovoltaic Solar Power

Summary

The primary objective for Taiwan to achieve its 2050 net-zero emissions target is to ensure the supply of carbon-free electricity. Given Taiwan's subtropical location and abundant annual sunlight hours, solar power is a viable option for the country's carbon-free electricity supply. This policy recommendation outlines several key suggestions:

1. Due to its limited land area and high population density, Taiwan faces keen competition for land usage. To increase solar photovoltaic (PV) capacity, it is essential to boost public interests for solar PV systems and achieve a general consensus on changes in land use patterns. Therefore, it is recommended that the government educate the public about the benefits and necessity of solar PV. Additionally, various incentive measures should be provided to accelerate deployment, such as simplifying administrative procedures or offering subsidies for agrivoltaic installations.
2. To alleviate the land pressure associated with solar PV deployment, the government should invest in the development of high-efficiency solar module technologies, such as Perovskite solar cells. By increasing the capacity and power generation per unit area of land, technological advancements can potentially mitigate the social conflicts arising from land-use changes.
3. To address supply instability due to the intermittent nature of solar PV, the power system must have robust infrastructure and management mechanisms. The government should expedite the establishment of grid-scale (GW-level) energy storage facilities, coupled with smart grid regulation. During normal operations, these measures can manage the "duck curve" characteristic of solar power supply by flexibly adjusting loads and implementing peak shaving and valley filling. In emergencies, they can provide ancillary services to stabilize grid voltage. Additionally, integrating climate forecasting systems with solar power generation systems can offer more accurate solar power generation forecasts, enabling timely power scheduling by power plants.
4. It is estimated that by 2050, Taiwan's solar PV capacity could reach 31.95-42.6 GW for ground-mounted systems and 12.21-15.72 GW for rooftop systems, totaling 44.16-58.32 GW. This would result in an annual power generation of approximately 46.421-61.316 billion kWh, with an average of 53.869 billion kWh.

To further increase solar PV capacity, more aggressive measures would be required to expand installation areas. However, this could lead to heightened social friction and impose significant pressure on grid stability.

2.2.1 Introduction

To achieve Taiwan's goal of net-zero emissions by 2050, the primary task is to supply carbon-free electricity. Solar power has become one of the rapidly developing options for carbon-free electricity worldwide due to its features including:

- providing sustainable and abundant energy,
- relatively environmentally friendly energy conversion process, and
- wide applicability.

However, solar power also has inherent challenges, such as:

- low energy density, and thus requires vast land,
- being an intermittent and unstable energy source, and
- lower efficiency and higher costs given current technology.

These challenges will need to be overcome to achieve scale expansion and stable electricity.

According to the International Energy Agency (IEA) projections for electricity supply proportions by energy type under the net-zero emissions scenario by 2050¹¹, global PV (excluding concentrated solar power) installed capacity is expected to reach 14,458 GW, accounting for approximately 43.3% of the global total installed electricity capacity. The projected electricity generation is 23,469 TWh, making up about 33.0% of the global total. This indicates that PV will continue to grow over the next 30 years and play a significant role in carbon-free electricity supply. The main reasons are the relative maturity of PV technology, its commercialization, and the continuous reduction in costs, allowing for large-scale deployment in the short term. However, the IEA's latest tracking report on PV development highlights that although global annual PV installed capacity has reached a new high, the rate of increase is still below expectations, indicating that both the public and private sectors need to put in more effort to achieve the 2050 target¹².

Thus, expanding PV installed capacity is a strategy many countries will adopt to move towards their net-zero emission goals. The top ten countries by cumulative

¹¹ As referenced in note 12.

¹² IEA (2021). Solar PV, IEA. Paris <https://www.iea.org/reports/solar-pv>

installed capacity are China, the United States, Japan, Germany, India, Italy, Australia, the United Kingdom, South Korea, and France. In addition to favorable sunlight conditions, these countries generally have larger land areas. For instance, the world's largest PV park, Bhadla Solar Park in India, has an installed capacity of 2.25 GW and covers approximately 5,670 hectares, equivalent to 218 Da-an Forest Parks (a park in central Taipei). For countries with relatively smaller land areas, achieving such scale is nearly impossible. Therefore, many new PV technologies are emerging, such as developing structures or materials that improve conversion efficiency. For example, a research team from the National University of Singapore has developed Perovskite materials, successfully increasing conversion efficiency to 23.6%¹³.

Another technological trend is system integration, which maximizes the multifunctional use of limited space. For example, Building Integrated Photovoltaics (BIPV) replace traditional building materials with photovoltaic modules, making them a part of the structure. This is commonly applied to rooftops, curtain walls, and windows. Floating photovoltaic modules utilize large surface areas of lakes, reservoirs, and the calm waters of harbors and inland seas.

Situated in the subtropical region, Taiwan has a total radiation per unit area that is lower than many tropical or desert countries¹⁴. However, the southern and central regions receive abundant annual sunlight, offering potential for solar energy development. Additionally, Taiwan's advanced high-tech and precision machinery industries, which are internationally competitive, favor the research and development of photovoltaic technologies and industry growth. Nevertheless, Taiwan faces competition for land use due to its small and densely populated territory. Thus, while solar photovoltaics present a viable carbon-free electricity option for reducing greenhouse gas emissions, the extent of its development in Taiwan hinges on several questions: How much solar photovoltaic capacity can Taiwan develop given its limited land resources? What is the potential for or limit of installed capacity? What are the carbon reduction benefits? These issues depend on how effectively Taiwan can utilize its land resources and develop high-efficiency photovoltaic panels to achieve the goal of developing "technology for land."

¹³ Wei Chen, et al. (2022). Monolithic perovskite/organic tandem solar cells with 23.6% efficiency enabled by reduced voltage losses and optimized interconnecting layer. *Nature Energy*; DOI: 10.1038/s41560-021-00966-8

¹⁴ ESMAP (2020). *Global photovoltaic power potential by country*. Washington, DC: World Bank.

2.2.2 Analysis of Current Issues in Solar Photovoltaic Development in Taiwan

In 2017, the Taiwanese government proposed an energy structure for 2025 where renewable energy would account for 20% of total energy use, natural gas for 50%, and coal for 30%. Among all renewable energy sources, solar photovoltaics (PV) were expected to have the highest share, with a target installed capacity of 20 GW by 2025. To support this policy goal, the Executive Yuan amended relevant regulations (such as the Electricity Act and the Renewable Energy Development Act) and actively promoted various action plans (such as the Solar PV Two-Year Plan, Green Energy Rooftop National Participation Plan, and the 2020 Solar PV 6.5 GW Target Achievement Plan). These efforts aimed to expand solar PV capacity by improving legislation, simplifying administrative procedures, establishing demonstration projects, creating a Green Energy Development Fund, and promoting agrivoltaics.

Through these policy initiatives, Taiwan's solar PV installed capacity has gradually scaled up. Figure 2.2.1 illustrates the installed capacity of solar PV in Taiwan from 2018 onwards (both target and actual values), with an anticipated goal of 20 GW by 2025. Originally, the plan included a rooftop PV capacity of 3 GW and a ground-mounted PV capacity of 17 GW. However, due to challenges in promoting ground-mounted PV systems, the Executive Yuan has revised the 2025 solar PV target twice. The current plan now adjusts the rooftop PV capacity to 8 GW and the ground-mounted PV capacity to 12 GW. Despite these efforts, by the end of 2021, Taiwan's actual installed solar PV capacity only reached 7.7 GW, falling short of the 2021 target. To achieve the 2025 goal, it is crucial to understand and address the current issues that hinder progress.

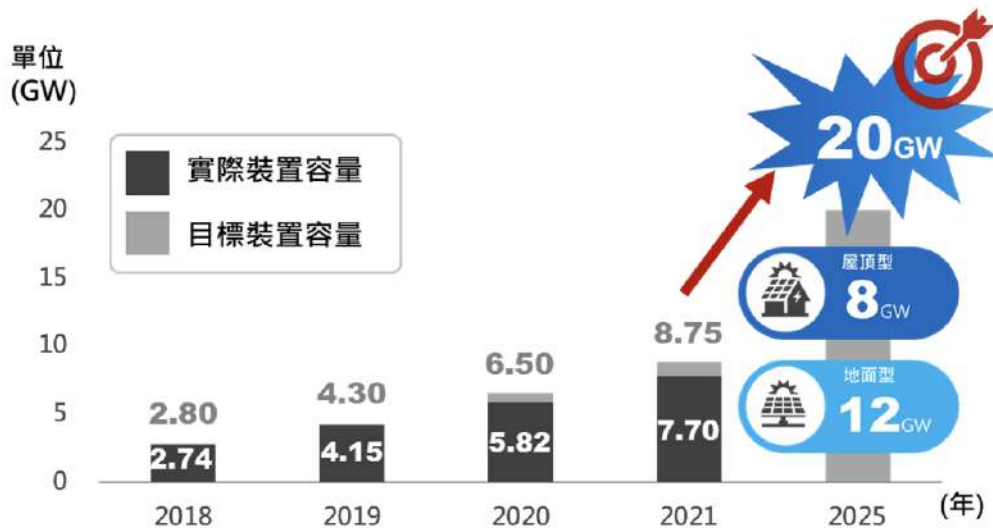


Figure 2.2.1 Installed Capacity of Solar Photovoltaics in Taiwan (Target vs. Actual Values)

Ground-mounted solar photovoltaics (PV) systems are relatively larger in scale compared to rooftop PV systems, making them more commercially valuable. Initially, ground-mounted PV was the primary focus of Taiwan's solar PV development. However, in recent years, ground-mounted PV systems have faced significant opposition due to land use issues. These objections from the society have created substantial obstacles in promoting ground-mounted PV installations. The practical issues encountered in promoting ground-mounted solar PV systems may be summarized and analyzed as follows:

- 1. Difficulty in Acquiring Large Tracts of Land:** Solar photovoltaics (PV) require extensive land due to their low energy density, posing a significant challenge for densely populated and geographically constrained Taiwan. The existing land use patterns are well-established (e.g., agricultural land designated for farming), land ownership is fragmented, and the availability of idle land is limited. To repurpose land for PV use would necessitate competition with existing land use projects, given that once a PV system is installed, it commits the land for at least 20 years. This necessitates a change in land use type, which has led to numerous disputes arising from a lack of consensus among stakeholders with different interests. Particularly contentious is the potential for the economic benefits from selling electricity to far outweigh those from the original land use. For example, installing PV systems on outdoor farmland has faced significant opposition from the agricultural sector (while landowners may be willing to convert to PV use, agricultural protection groups and authorities advocate for the

preservation of farmland). Similarly, using cultivated forest land for PV installations has drawn protests from environmental groups, fish pond PV installations have faced opposition from the fisheries sector due to concerns about impacts on aquatic yields, and there have been protests over changes in land use and landscape¹⁵.

2. Complex Regulations and Administrative Procedures: The application and approval processes for PV installations involve multiple ministries, various levels of government (central and local), and different regions (urban and rural), each with their own regulations and administrative procedures. These complexities make it difficult for the general public to understand and navigate, thereby affecting the deployment of PV systems.

3. Cost Concerns for PV Developers: Currently, the purchase of electricity only begins after the PV systems start generating and selling electricity. The high upfront investment costs, coupled with recent inflation and increased raw material costs, have affected the willingness to install these systems. Large-scale projects, in particular, need to go through price bidding, which further impacts such willingness.

4. Other Issues: Some PV projects located in more remote areas face issues with insufficient feeder lines. Additionally, environmental groups have raised concerns about pollution associated with the solar PV manufacturing process and the challenges of recycling PV materials.

¹⁵ Some of the issues discussed are excerpted from the research project "Research on Industry Transformation and Carbon Pricing Strategies towards Taiwan's 2050 Low-Carbon Emission Targets" (2022-2024), conducted by Research Fellow Ching-Cheng Chang and Assistant Research Fellow Tsung-Han Yang at the Institute of Economics, Academia Sinica, as part of the institute's Sustainable Science Research Program.

2.2.3 Assessment of the Potential and Limits of the Domestic Solar Photovoltaic Development

The solar photovoltaic (PV) systems require a significant amount of land resources. Table 2.2.1 presents the land use types potentially included for both the rooftop and ground-mounted (including water-based) solar PV installation¹⁶.

Table 2.2.1 Source Types of Land Use for PV Systems

Type	Land Source
Rooftop	Rooftops of the buildings owned by the central government, rooftops of factories in the industrial zones, agricultural facilities, and other rooftops (of local government, commercial, and residential buildings)
Ground-mounted (water-based included)	Salt industry land, Class 1 Groundwater Conservation Area, landfill sites and contaminated lands, and water areas (reservoirs, detention basins, ponds, common orient clam farms, and fish ponds), and other lands (idle industrial lands, idle military installations under the Ministry of National Defense, national lands under the National Property Administration, Ministry of Finance, and other idle lands)

1. Rooftop PV Systems

The areas of respective lands for the rooftop systems are retrieved from the open data of the government¹⁷, as shown in Table 2.2.1. After estimation, it is found that the total roof area of the buildings is 109.46 thousand hectares. The initial assumption is that emergency escape facilities, water towers, parapets, heat dissipation devices, ventilation facilities, lighting, and other necessary facilities account for approximately 50% of the rooftop area. As a result, the installable area for rooftop PV facilities approximates 50%, and that on the agricultural facilities is also limited to 50% due to the pertaining land use regulations, totaling about 54.73 thousand hectares. In addition, considering that the average service life of reinforced concrete buildings is 50 years, and the warranty period of solar PV systems is 25 years, with the buildings within 20

¹⁶ The Two-Year Solar PV Promotion Plan, Executive Yuan (2017); Briefing on the Stable Power Supply Strategies for Industries, Ministry of Economic Affairs (2017).

¹⁷ Huang, K. L. et al. (2018). Since renewable energy requires a large amount of land area, is Taiwan suitable for developing renewable energy? Data from the Statistical Yearbooks (2005-2015) of Construction and Planning Agency, Ministry of the Interior; Industrial Zone Development and Management Yearbook (2016), Industrial Development Bureau, MOEA; Statistics of National Land Use Investigation (2013), National Surveying and Mapping Center, Ministry of the Interior.

years of age included in the scope of analysis and estimation, the installable rooftop area of buildings within 20 years of age is 8.14 thousand hectares, and that of buildings within 15 years of age is 5.59 thousand hectares (Table 2.2.2).

**Table 2.2.2 Estimated Installable Rooftop Area and Installable Capacity
for Rooftop Solar PV Systems**

Building Type	Installable Area (thousand hectares)	Installable Capacity (GW)
Rooftops of Government-owned buildings	1.99	1.99
Rooftops of Buildings in the Industrial Zones	14.77	14.77
Other Rooftops	35.26	35.26
Agricultural Facilities	2.71	2.71
Total	54.73	54.73
Rooftops of the Buildings within 20 Years of Age	8.14	8.14
Rooftops of the Buildings within 15 Years of Age	5.59	5.59
30% of the Rooftops of Newly Constructed Buildings in 2030-2050	+2.34	+2.34

Note: Installed capacity conversion formula: 1 GW/thousand hectares

In addition, based on the current technological level available, the conversion rate for commercial single crystalline silicon PV modules (approx. 20-22%) is adopted in the calculation, and the conversion formula for the installed capacity of rooftop PV system, 1 GW/1000 hectares (Appendix 2C), is used. The final estimated potential rooftop solar photovoltaic installed capacity on the planned lands in the national policy is 54.73 GW; the installed capacity for the rooftops of the buildings within 20 years of age is 8.14 GW; and the installed capacity for the rooftops of the buildings within 15 years of age is 5.59 GW. It suggests that the current government-set installed capacity target for rooftop PV systems (8 GW) has already fully leveraged the rooftops of the buildings of 20 years old or less. If we aim to increase the rooftop solar PV installed capacity in the future, the installable area of new building rooftops may need to be considered. Furthermore, incentive measures, or adjustment to the building laws and

regulations and other supporting measures, may be required as well.

The total floor area of buildings registered on the building usage licenses issued by the Republic of China in 2021 was approximately 2.8 thousand hectares¹⁸, with a ground floor area of about 0.77 thousand hectares. Assuming that the ground floor area represents the rooftop area of new building each year, the potentially installable area for solar PV systems is 0.39 thousand hectares. If the building-related laws and regulations are amended to encourage the installation of solar panels onto new buildings starting from 2030, and assuming that solar panels are installed to 30% of new buildings, there will be approximately 2.34 thousand hectares of new building installed with rooftop solar PV systems in the following 20 years (2030-2050), with the installed capacity increased by another 2.34 GW (Table 2.2.2).

2. Ground-mounted Solar PV Systems

The area of each land use type for the ground-mounted solar PV systems can be retrieved from the open data of the government¹⁹, as shown in Table 2.2.1. The proportion of solar PV installation area varies subject to the different laws and regulations pertaining to land use, with reservoirs, ports, and lakes at 5%, ponds at 50%, agricultural lands at 20-40%, others at 70%, and idle lands assumed to be 100%. After these installation area regulations taken into account, the total land area available can be estimated to be 106.5 thousand hectares (Table 2.2.3). In addition, the converted

¹⁸ Building usage licenses issued by land use types, monthly bulletin of interior statistics, Republic of China (2022).

¹⁹ Huang, K. L. et al. (2018). Since renewable energy requires a large amount of land area, is Taiwan suitable for developing renewable energy? Sources: the data on the salt industry land; scope of agricultural land within severe land subsidence areas unfit for agricultural operations where green energy facilities may be installed; the waste disposal data from the Environmental Protection Administration, Executive Yuan; Soil and Groundwater Pollution Remediation Website, Environmental Management Administration, Ministry of Environment—Domestic Contaminated Site Information; The Single Service Window for Solar PV—Land and Power Grid Information (Water Areas – Reservoirs; detention basins); Briefing on the Stable Power Supply Strategies for Industries, Ministry of Economic Affairs (Lunwei East District, Lunwei West District, and Taixi Industrial Park); 2015 Statistical Yearbook of Fisheries (common orient clam farms), Fishery Agency, Ministry of Agriculture; 2015 Statistical Yearbook of Agriculture (Long-term Fallow Land; Long-term Cultivated Land), Council of Agriculture, Executive Yuan; 2015 Statistical Yearbook of Agriculture (Fish Ponds; Fallow Fish Ponds), Fisheries Agency, Council of Agriculture, Executive Yuan; Statistical Data Query, Ministry of Transportation and Communications (Transportation and Communication Land: National Highways; Railways; High Speed Rail); Analysis on the Indicators for County/City Statistics, Water Resources Agency, MOEA—Reservoir Information; Water Resources Agency, MOEA—Planned Capacity for Detention Basins in the Minutes of the 16th Promotion Meeting of the Reservoir and Flood Detention Basin Water-based Solar PV System; Statistics of National Land Use Investigation (2013), National Surveying and Mapping Center, Ministry of the Interior (Ponds; Pools; Basins); List of Idle Facilities Managed by the Public Construction Commission, Executive Yuan.

installed capacity of ground-mounted solar PV systems is smaller than that of rooftop counterparts due to different land use restrictions. It is approximately 0.667 GW per a thousand hectares. As a result, if all the land use types are changed for the purpose of solar PV installation, a maximum of 71.04 GW may be achieved.

Further analysis and comparison of Taiwan, Germany, Japan, and the United Kingdom on the solar PV installation indicators (Table 2.2.4) reveal that in 2020, the difference in capacity density (MW/km^2) between Taiwan and the other countries was not significant, ranging from $0.15 \text{ MW}/\text{km}^2$ to $0.2 \text{ MW}/\text{km}^2$. However, regarding the estimated target values for 2025, the capacity density will increase significantly by about five times, reaching $0.56 \text{ MW}/\text{km}^2$. In the same period, Germany's capacity density will slightly increase to $0.2 \text{ MW}/\text{km}^2$, and Japan's will increase to $0.25 \text{ MW}/\text{km}^2$. It indicates that due to the limited land area of Taiwan, the capacity density of solar energy of Taiwan is significantly higher than that of the other countries.

When solar energy becomes a primary energy source for our country in the future, the extensive land use change and high capacity density may lead to tremendous social controversies and burdens on power supply stability. Hence, it is conservatively estimated in the Policy Recommendations that with 30-40% of the area available, there may be approximately 31.95-42.6 thousand hectares of area for installation, offering an installed capacity of 21.3-28.41 GW. Nevertheless, it still requires the government to engage in extensive and long-term active communication to address concerns from all parties in the society and to provide various incentives to achieve this goal. As for the potential burden on power supply stability, it necessitates installation of sufficient energy storage and an effective power grid system for support (see Sections 2.10 and 2.11 in this chapter for more details).

**Table 2.2.3 Estimated Land Area Available and Installable Capacity
for Ground-Mounted Solar PV Systems**

Land Use Type	Area Available (thousand hectares)	Installable Capacity (GW)
Salt Industry Land	0.8	0.53
Class 1 Groundwater Conservation Area (with Severe Land Subsidence)	1.51	1.01
Landfill Sites and Contaminated Land	0.39	0.26
Water Area (Reservoirs, Detention Basins, Ponds, Common Orient Clam Farms, and Fish Ponds)	20.78	13.86
Agricultural Lands Listed in the Treatment Plan for the Pits Left by Illegal Sand and Gravel Excavation on Land	0.008	0.01
Idle Industrial Land (Taixi Industrial Park, Lunwei East District, and Lunwei West District)	1.61	1.08
National Land under the National Property Administration, Ministry of Finance	7.46	4.98
Idle Military Installation under the Ministry of National Defense	0.13	0.09
Cultivated Land (Long-Term Cultivated Lands for Agriculture), Which Can Only Be Used to Grow Upland Rice, Coarse Grains, Fruit Trees, etc. Due to Difficulties of Soil to Retain Water or Sufficient Water	52.7	35.15
Long-Term Fallow Land; Uncultivated Land (Long-Term Idle Agricultural Land)	19.87	13.25
Transportation and Communication Land (the Lands Adjacent to Arteries Like the National Highways, Taiwan High Speed Rail, Taiwan Railway, etc.)	1.12	0.75
Idle Transportation and Communication Land (Airports; Ports)	0.13	0.09
Total	106.5	71.04
30% of the Area Available for Use	31.95	21.31
40% of the Area Available for Use	42.60	28.41

Note: Installed capacity conversion formula: 0.667 GW/thousand hectares

Table 2.2.4 Comparison of Countries on the Solar Energy Indicators

Indicator	Taiwan		Germany		Japan		United Kingdoms	
	2020	2025	2020	2025	2020	2025	2020	2023
Capacity density of solar energy installation (MW/km ²)	0.16	0.56	0.15	0.2	0.18	0.25	0.056	0.07
Total land area (km ²)	35,960		349,360		364,560		241,930	
Installed capacity of solar energy in 2020 (GW)	5.82		53.78		67.0		13.56	
Installed capacity of solar energy in 2025 (GW)	20		70		92		15.7 (in 2023)	

3. Solar energy conversion efficiency

If Taiwan aims to increase the capacity of solar photovoltaic devices, apart from increasing the area of rooftop and ground-mounted photovoltaic systems, another feasible strategy is to improve the conversion efficiency of solar photovoltaic devices. At present, the majority of solar cells are made up of monocrystalline silicon wafers using the passivated emitter and rear contact (PERC) structure. The conversion efficiency of PERC solar cells can reach 23%, and the efficiency of commercial PERC solar cells is about 20-22%. It is commonly believed that the conversion efficiency of PERC solar cells has nearly reached its maximum. However, through continuous optimization, the efficiency of PERC solar cells can be improved by about 0.5%.

At present, efforts to improve the conversion efficiency of silicon solar cells concentrate on the n-type tunnel oxide passivated contact (TOPCon) structure as well as heterojunction with intrinsic thin layer (HJT) structure. TOPCon is a solar cell technology based on the principle of selective carrier transport. The structure uses passivation material, a very thin tunneling oxide layer and a heavily doped multi-Si thin film. The current conversion efficiency can reach up to 24%. HJT adds a layer of non-doped amorphous silicon (i-a-Si:H) between p-type and n-type amorphous silicon layers and the n-type hydrogenated amorphous silicon (α -Si:H) and the n-type silicon substrate. The current cell conversion efficiency can reach up to 25%. Whether n-type TOPCon or HJT will become the next mainstream technology depends on the improvement of efficiency and the reduction of cost per kilowatt hour.

Although silicon solar cells can improve cell conversion efficiency by optimizing production processes and changing structures, silicon solar cells will eventually reach the maximum theoretical efficiency, known as the Shockley-Queisser limit (33.7%). In addition, current records show that the maximum efficiency is only 26.1%, and it is difficult to improve the solar cell conversion efficiency to over 30%. If the aim is for the conversion efficiency to reach over 30%, then it would be necessary to change the structure (such as multi-junction cells or stacked cells), or use different materials (such as Perovskite) (See Box 2.2.1 and Appendix 2D).

Box 2.2.1 Solar Photovoltaic Technology

Generally speaking, solar photovoltaic devices can be categorized according to type of material, which includes single-junction silicon-based photovoltaic devices and multi-junction photovoltaic devices based on III–V semiconductor materials, as well as Perovskite-silicon multi-junction stacked photovoltaic devices. There are also amorphous silicon photovoltaic devices and thin-film photovoltaic devices. Please see (Appendix 2D) for details.

Table 2.2.5 Comparison of Three Types of Solar Cells

Type	I	II	III
	Crystalline silicon	Thin film technology and multi-junction cell	Use of non-silicon materials
Categorization and conversion efficiency	• Polycrystalline silicon 23.3% • Monocrystalline silicon 26.1%-27.6% • Silicon heterojunction solar cells 26.7%	• Thin film 29.1% • Multi-junction 39.2%	• Organic solar energy 17.5% • Quantum dot 16.6% • Perovskite 25.5%
Advantages	The production volume has achieved economy of scale with both cost and technical advantages.	• Thin film technology uses direct bandgap semiconductors with excellent light absorption properties. • Multi-junction (stacked) solar cells have the best spectral response at various	Perovskite has good light absorption rate and its power conversion efficiency (PCE) has increased rapidly.

		wavelengths in sunlight.	
Challenges	With mature production processes, the room to improve conversion efficiency is limited.	• GaAs in thin film technology have little tolerance for impurities during the production process. • Multi-junction solar cells require expensive materials and production processes. It is necessary to lower the costs of production equipment and substrates.	• There are doubts about the stability and weather resistance of Perovskite • Existing high-performance Perovskite solar cells contain significant amount of lead which can lead to environmental hazards

If Taiwan develops multi-junction/stacked solar cells or Perovskite solar cells in with conversion efficiency 50% higher than crystalline silicon cells, we will be able to increase device capacity and electricity generated by 50% with the same area of installation. This is a vital strategy, as Taiwan has limited land resources. If we can reach this goal by 2050, the capacity of rooftop solar photovoltaic systems can grow from 8.14-10.48 GW to 12.21-15.72 GW (the estimate includes rooftops of 20-year-old buildings and 30% of the roofs on newly constructed buildings). The capacity of ground-mounted solar photovoltaic systems can grow from 21.3-28.41 GW to 31.95-42.6 GW (with 30-40% land occupation; see Figures 2.2.2 and 2.2.3). In total, the target capacity combining rooftop and ground-mounted PV systems is 44.16-58.32 GW.

Different natural lighting conditions in different parts of Taiwan lead to varying solar photovoltaic capacity factors across Taiwan, ranging between 9% to 15%.²⁰ Hence, the estimation uses the average value of 12%. The target capacity of solar photovoltaic devices is 44.16 to 58.32 GW, and it is expected to generate 46.421 to 61.316 billion kilowatt-hours with an average of 53.859 billion kilowatt-hours.

²⁰ Taiwan Power Company (2021). Overview of purchased electricity: Solar photovoltaic capacity factors of renewable energy by county and city.

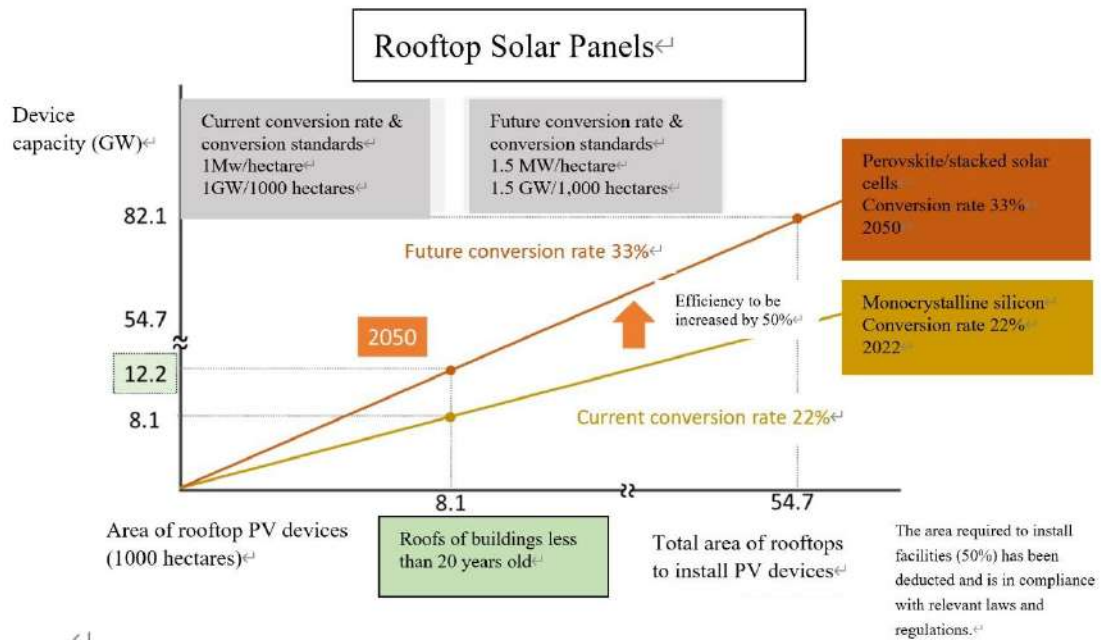


Figure 2.2.2 A Conceptual Diagram Showing the Estimated Capacity of a Rooftop PV System (Using the Rooftop of a 20-Year-Old Building)

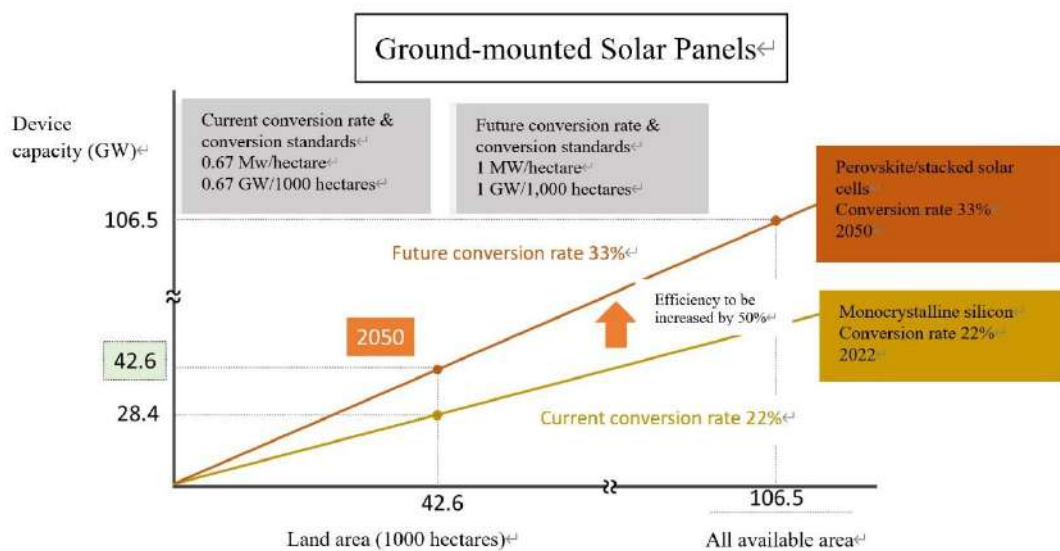


Figure 2.2.3 A Conceptual Diagram Showing the Estimated Capacity of a Ground-Mounted PV System (with 40% of Land Occupation)

2.2.4 Policy Recommendations

Among all existing options for carbon-free electricity, solar energy is the renewable energy with the most mature technology and relatively low cost. By investing in device capacity and supporting power systems, we can see a boost in the supply of renewable energy in the short term. However, support from society, technological innovation as well as policy support are all necessary to help solve current practical challenges, accelerate the installation of PV systems, and achieve the long-term goals of carbon reduction. Our recommendations:

1. Gain social support for land use for solar photovoltaic systems in order to increase the capacity and generated energy of solar photovoltaic systems

The low energy efficiency of PV systems means that a large amount of ground surface is required to install solar panels. To increase the power generated by PV systems, the usual approach is to expand the installation area. However, with very limited land in Taiwan (especially on the plains in western Taiwan suitable to develop solar energy), expanding the installation area will crowd out other land uses, such as agriculture. This is why with all the government incentives to encourage people to develop solar energy—for instance, Taiwan Power Company uses Feed-In Tariff (FiT) for renewable energy, subsidies for solar energy generated for self-consumption, and agrivoltaic farms that merge solar farms with traditional working farms—there is still opposition and controversy whenever there are suggestions to set up large-scale solar farms. This indicates that Taiwanese society has not yet reached a consensus regarding the land use for solar. It is thus vital to gain support from the society. Only then can the government work to increase the capacity or power generated by PV systems, and the installation of PV systems can be accelerated with the provision of various incentives. Our recommendations are to:

- (1) Strengthen inter-ministerial coordination to draft a long-term national spatial plan for net-zero emissions (including land for photovoltaic systems, land for energy crops, land for infrastructure for energy storage and grid). Relevant regulatory constraints and administrative rules would need to be changed. For instance, for inarable land (crop land that lacks water and can only be cultivated with upland rice, grains, and fruits; abandoned fields that have been deserted for a long time and not planting crops) there needs to be a land-use change, compensation for the land, a way to deal with the incremental tax for land value,

etc.

(2) Improve communication with the general public for them to understand the advantages and necessity of the development of solar energy, and resolve doubts for the general public to reach a consensus on issues like the necessity to reach the goal of net-zero emissions, comparison of various energy options, and scientific and empirical studies on the impact of solar energy, such as the impact of PV system on soil, the agricultural goals of long-term land use, the impact of PV systems on aquaculture, and the environmental impact of PV systems.).

(3) Review and adjust the current system to purchase, trade and manage green energy. At present, with relatively low electricity prices, Taiwan uses a Feed-In Tariff (FiT) to purchase renewable energy to increase incentives. Although such an approach can help promote green energy, in the long run, the renewable-energy industry will rely too much on the FiT so it is recommended to use a renewable portfolio standard (RPS) to reasonably control the budget, lower procurement costs, and improve economic benefits to promote healthy competition in the renewable energy market (Box 2.2.2).

(4) Use incentives and supporting measures to increase the general public's willingness to install PV systems. Such incentives can promote agrivoltaics (AgroPV), photovoltaic-aquaculture (Box 2.2.3) and rooftop solar panels for private buildings. Supporting measures include simplifying the procedures to apply for permission to install solar panels; subsidies for installation (to reduce the initial installation costs); cultivating professional teams to help ordinary citizens or communities to install solar panels; and government rewards for green energy investment. All these measures will help the general public increase their willingness to install solar panels. The cost of installing solar panels is still high. The levelized cost of (residential) solar energy is about 147-221 USD/MWh, and the levelized cost of (commercial) solar energy is about 67-180 USD/MWh. However, if the government implements carbon pricing in the future, the levelized cost of energy of traditional fossil fuels will increase. Taking a combined cycle gas turbine (CCGT) plant as an example, if the price of carbon is set at 40 USD/tCO₂eq, the levelized cost of energy will increase to 93-218 USD/MWh. As such, green

energy will be able to compete with traditional fossil fuels²¹.

Box 2.2.2 Comparison between FiT System and RPS System for Green Energy

Table 2.2.6 Comparison Between FiT System and RPS System for Green Energy

System	FiT system (Feed in Tariff)	RPS system (Renewable Portfolio Standard)
Description	According to the different attributes of renewable energy such as type, scale, quality, location, etc., the government formulates the power purchase rates and applicable periods for various types of renewable energy.	The government requires the electricity industry or energy users to meet the renewable energy power generation ratio obligations through legislative regulations and other means. Industry can purchase renewable energy (including renewable energy credits) market to meet its obligations.
Countries adopting this system	113 countries (2019), including Germany, France, Finland, Taiwan.	34 countries (2019), including South Korea, Norway, Sweden.
Advantages	• Guaranteed return on investment for businesses of renewable energy and achieving the expected outcomes in the early stages of market formation • Developing a cost-effective procurement mechanism • Encouraging investment in renewable energy and simplicity	• The price is determined by market supply and demand, so it is flexible, and the government does not need to set the price. • The quota can be achieved with the lowest cost • Accelerates development of low-cost renewable energy • Easier to predict the scale of power supply

Sources: REN21(2021); Renewable Energy Information Network (2021); Chung-Hua Institution for Economic Research (2013); Taiwan TIMES Model (2015)

²¹ Lazard (2021). Lazard's levelized cost of energy analysis — Version 15.0, levelized cost of energy comparison—sensitivity to carbon pricing, P5, <https://www.lazard.com/media/451905/lazards-levelized-cost-of-energy-version-150-vf.pdf>

Box 2.2.3 Agrivoltaic Farm that Merges Solar Farm with the Traditional Working Farm - Photovoltaic-Aquaculture²²

If a ground-mounted solar photovoltaic system involves a change of land use, the barriers, time, and cost will be higher. Hence, PV businesses tend to apply for “agrivoltaic farms,” including PV-aquaculture, agrivoltaics, and photovoltaic panels for livestock. Photovoltaic aquaculture is one type of “agrivoltaic farm” and a production model that combines aquaculture with PV systems to maintain aquaculture. Such an approach will not damage farmland; at the same time, it can help to ensure food security, protect water resources, and generate power; hence, it has been considered to be an important solution. At present, the government has allocated 14,480 hectares of land for photovoltaic aquaculture, mainly for ponds and fish farms in Taoyuan and southern Taiwan. However, in addition to the difference in solar radiation between northern and southern Taiwan, there are also differences in property rights. For instance, fish ponds in Taoyuan are usually not owned by the operators, so there are conflicts of interest. On the other hand, most fish ponds in southern Taiwan are operated by aquaculture operators with property rights. At present, there are three business models of photovoltaic aquaculture: self-installation, contracting, and community renewable energy project. Each model has its own strengths and weaknesses regarding the initial cost, the maintenance cost, and total returns. Comprehensive evaluation of the economic and social aspects can be useful when we need to communicate with stakeholders to increase their willingness to install solar panels and to resolve disputes (See Chapter 7 for details).

²² *Ibid.*, 44.

2. Allocating additional funds towards the research and development of high conversion-efficiency solar-energy module technologies to enhance the capacity and power generation per unit of land area from photoelectric devices

Unlike countries with vast land resources, Taiwan can't afford to pursue the traditional approach of using large land area for photovoltaic devices. Instead, Taiwan should focus on investing in high conversion-efficiency solar-energy module technologies, which encompass innovative technologies and advancements in the manufacturing process. This strategic shift aims to reduce the land demand of the photovoltaic industry by leveraging technology to compensate for land scarcity.

Moreover, with the anticipated global increase in the installation of solar energy devices and the competitive pricing pressures from China, Taiwan must proactively develop new materials and production equipment to establish a competitive edge. Failure to do so could result in challenges for Taiwan's solar cell industry. Our recommendations to address this issue are as follows:

(1) Establish a set of efficacy targets for high conversion-efficiency solar-energy modules. The global target for solar photovoltaic installations is expected to reach 14,458 GW by 2050, indicating a significant need for large-scale commercialization of this technology. In addition to research projects focused on increasing conversion efficiency, it is hence crucial to include technologies with commercial value that enable mass production at a low cost. For instance, by utilizing III-V family multi-junction photovoltaic elements, a conversion efficiency of 39.2% in daylight and 47.1% under conditions with a brightness 143 times that of sunlight can be reached. Despite its high efficiency, the cost of such materials is prohibitively expensive, leading to limited application, primarily in specialized fields like military and aerospace technologies. This reduces its feasibility for broader adoption. Further, considering that the current operational lifespan of photovoltaic facilities is around 20 years, it is suggested to set future technology goal of improving the conversion efficiency by 50% compared to current silicon-based solar photovoltaic devices and developing a technology or business model with commercial value which can enter mass production by 2040. This approach would enable the new technology to enter the market in around 2040, replacing existing technologies.

(2) Setting a research and development agenda to address the gaps in the new solar photovoltaic technologies is vital. Take the Perovskite solar cell as an example. It

boasts a high conversion rate of 36% and requires low power consumption for production, making large-scale production feasible. Additionally, the Perovskite solar cell has various advantages such as low cost, straightforward manufacturing process, lightweight nature, and the recent resolution of lead content in its products, which creates a conducive environment for the extensive commercialization of the Perovskite technology. The potential for mass production is promising. Moreover, the Perovskite solar cell exhibits an adjustable energy gap, high-absorption coefficient, and ease of processing, making it a prime candidate for integration with silicon-based solar cells to create a low-cost and high-efficiency laminated solar cell. Currently, the silicon-based Perovskite laminated solar cell has achieved a lab conversion efficiency of 29.5%, which is highly appealing to the industry. However, the primary research and development challenge lies in increasing the number of stacked absorbing layers to enhance cell efficiency within the limitations of the spectral absorption range. Unresolved issues include:

- Reducing transparent electrode resistance (metal mesh electrode optimization).
- Designing Perovskite materials with different energy gaps to absorb light of various bands and optimize each layer.
- Developing proper deposition methods to address the greatly uneven surfaces of silicon chips, ensuring that each layer is deposited evenly.
- Optimizing the optical designs of each layer to minimize light loss.
- Seeking a suitable electric charge recombination layer with high conductivity and high transmittance.
- Reducing voltage loss in wide energy-gap Perovskite solar cells.
- Improving the durability of Perovskite to weather conditions.
- Enhancing environmental friendliness.

(3) Regarding the integration of our nation's research and development and commercial capabilities, it is recommended that our academic community continues to focus on key technological gaps in high-efficiency solar cells, and the industry provides testing equipment and evaluates solar cell lifespan. Other research facilities and organizations are also encouraged to contribute to developing new processing equipment for manufacturing advanced cell materials.

Box 2.2.4 Research and Development Progress at Academia Sinica

Academia Sinica has long been investing in the research and development of Perovskite thin-film nucleation technology. Concurrently, efforts are being made to address the flaws related to grain boundaries and passivated Perovskite thin films by incorporating additives. This aims to enhance the conversion efficiency and improve the resistance of Perovskite solar cells to environmental conditions. Our objective is to develop laminated silicon Perovskite solar cells with efficiencies exceeding 30%. Moving forward, the domestic industry will primarily focus on investing in and producing 188mm x 210mm cells.

We have been conducting experiments to explore different coating technologies for producing large-area Perovskite thin films. Once we identify the optimal coating technology and complete the optimization of coating conditions, we aim to seamlessly transfer Perovskite solar energy technologies to the Taiwanese solar energy industry.

3. Build additional infrastructure to complement Taiwan's electric system and develop a management and dispatch mechanism to offset changes in sunlight

Even during daytime, the intermittence of sunlight leads to instability in power generation, influenced by the Earth's rotation and weather conditions such as clouds and high heat. Abrupt reductions in sunlight exposure directly impact power generation stability. Our recommendations to address this issue are as follows:

- (1) It is necessary to promptly build grid-level energy storage facilities and integrate them with a smart grid modulation strategy. During regular periods, flexible ramping should be implemented to offset the "duck curve" and facilitate peak load shifting for solar energy. In emergencies, these facilities can provide essential support services to stabilize grid voltage. (For more detailed information, please refer to sections 2.10 and 2.11 in this chapter.)
- (2) By improving weather forecasting capabilities with more precise time and spatial units, and by integrating the weather forecast system with solar energy generation, we can enhance the prediction of solar energy output. This would allow power plants to schedule dispatches promptly. In essence, we maximize solar power utilization during abundant sunlight and supplement with other energy sources during periods of reduced sunlight exposure.

4. Other recommendation: Drive the industry with new technologies to develop our country's solar photovoltaic industry

In addition to the policy suggestions mentioned above, it is crucial that we prioritize the development of our photovoltaic industry. This entails taking control of the research and development of new technologies, as well as focusing on mass production, equipment installation, and system maintenance. However, the solar photovoltaic industry in Taiwan faces significant challenges due to the entry of numerous international firms and trade barriers, gradually making investment from Taiwanese firms more conservative.

China has significantly supported its upstream and midstream solar energy sectors in recent years with substantial subsidies and large-scale production advantages. Chinese policies have enabled lower, or even disruptive, prices that compete at unreasonably low levels. As a result, many of our firms find themselves at a disadvantage or have even been forced to shut down. This competitive environment has caused many European and American pioneers in solar energy to exit the market due to high costs. Consequently, Europe has become protective of its domestic solar energy industry, while the US has imposed high tariffs on Chinese imports to combat dumping practices, inadvertently impacting our own solar energy firms.

Fortunately, our solar cell technologies continue to be recognized internationally for their higher conversion efficiency compared to those from China. By continuing to advance related technologies and meet future governmental requirements for high-efficiency module technologies—by developing a roadmap towards achieving photovoltaic conversion efficiencies exceeding 30%—we can distinguish ourselves from competitors in the global market.

5. Additional recommendation: Mitigating the environmental impact from solar panel production to disposal through proper technologies and coordinated measures

While solar energy is promoted as a clean power source, a type of solid waste known as "Diatom" is generated during the manufacturing process. Diatom consists of silicon carbide particles, silicon scraps, metal, and cutting oil. Currently, this waste is mostly disposed of through landfills or dumping, which has a significant environmental impact. This issue has contributed to the opposition to solar energy by various groups. Therefore, as we commit to developing the solar energy industry, it is essential to invest in waste disposal technologies in advance.

For example, the Diatom Recycling Sorting Technology, developed by the

research team at National Cheng Kung University, can convert this waste into ferrosilicon, which serves as an auxiliary fuel in the iron and steel industry. This innovation helps partially mitigate the waste generated by the widespread deployment of solar devices²³.

In addition, most of Taiwan's installed solar panels have a guaranteed generating efficiency of 25 years, meaning they have not yet entered their recycling periods. However, this is an inevitable issue in the foreseeable future, necessitating planning for the disposal of a large number of retired solar energy modules. European countries and Japan developed solar energy earlier and are now approaching their solar panel recycling periods. Consequently, many facilities and firms in these regions have already invested in disposal solutions. For instance, the current recycling rate of solar panels for the PV Cycle is as high as 97%.

In Taiwan, the Bureau of Energy, Ministry of Economic Affairs, and Environmental Protection Administration, Executive Yuan, have collaborated to propose that firms set aside funds for future recycling needs. They have assisted two lawful disposal facilities in managing retired solar panels and obtained Japan's and Germany's consent to accept and dispose of Taiwan's retired devices. As a result, Taiwan's solar panel recycling amount is currently under control.

Nevertheless, once Taiwan enters the recycling period for photovoltaic modules, the large quantity and varied sizes of solar panels will make recycling more challenging. It is therefore recommended to establish a coalition solely responsible for recycling. Further, building an automated solar panel recycling system to handle panels of diverse specifications will be imperative.

²³ National Cheng Kung University (2016). NCKU Presents "Solar Cell Waste - Oil Sludge Resource Recycling Technology" at the Press Conference, Turning Waste into Gold. <https://web.ncku.edu.tw/p/404-1000-156134.php?Lang=zh-tw>

2.3 Wind Energy

Summary

Thanks to its geographical location, which is prone to influence of monsoons, Taiwan enjoys relatively abundant wind resources. Coupled with the mountainous terrain, the western Taiwan and the Taiwan Strait offer relatively decent wind conditions. As we strive towards our goal of net-zero emissions, wind power, alongside solar power, is undoubtedly an indispensable source of carbon-free power option for Taiwan. To accelerate the increase of our installed capacity of wind power, recommendations are made as follows:

1. Although the installation costs of onshore wind power are lower than those of the offshore counterpart, the restricted land availability due to the limited land and dense population in Taiwan, coupled with community opposition to noise pollution, relatively confines the development of onshore wind power. To increase the installed capacity of onshore wind power, it is crucial to secure the support from residents in the communities nearby. Therefore, it is advised that the government, in addition to the consideration of wind speed, should incorporate population factors into the site selection assessment for onshore wind turbines. Furthermore, it is essential to strengthen social communication or to provide various incentives and supporting measures to increase community support, such as subsidy for the installation of soundproof windows.
2. In the future, offshore wind power will be the primary focus of wind energy development. Although the government has designated suitable sea areas for wind farms, the existing restrictions may be re-assessed due to advancements in wind power technology (e.g., larger turbines and deep-water wind turbine foundation installation techniques). Hence, it is recommended that the government re-examines and reviews the wind farm areas in the Taiwan Strait to seek optimal configurations of wind farms and wind turbines for power generation (unit installed capacity, number of turbines, sea area, etc.), such as deep-water areas for wind farms and communication with fishermen at local fisheries.
3. At present, the installation capacity of offshore wind power is limited by the engineering throughput of port bases and the capabilities of maritime engineering. To accelerate the deployment of wind power, it is necessary to simultaneously construct relevant infrastructure. To increase the installation capacity to 1.5 GW

or more per year, it is necessary to expand the area at port bases for component production, storage, assembly, and maintenance. Therefore, it is recommended that the government conducts comprehensive planning and design for the land use requirements of our ports and harbors.

4. While the wind turbines are predominantly sourced from international suppliers, given Taiwan's significant development potential and business opportunities for wind power in the future, apart from introducing foreign technologies (high power generation efficiency and large-scale wind turbines) and replacing aging turbines that reach their service life, we can further invest in developing technologies in alignment with our national conditions, so as to achieve the goal of technological autonomy from construction to long-term operation and maintenance in the areas such as floating wind turbine technology, marine engineering technology, management of the wind power systems in the Taiwan Strait (including accurate wind energy and power generation forecasting information), and noise reduction in blade design.

5. It is estimated that wind power capacities in Taiwan could reach the following targets by 2050: 1.2-3.8 GW for onshore wind power and 43.2-53.2 GW for offshore wind power, generating electricity totaled approximately 154.32-195.71 billion kWh with an average of 175.015 billion kWh. A further increase of wind power capacity will necessitate stronger measures to enhance port and harbor capacities, just so we may overcome the temporal and spatial constraints of offshore wind turbine installation with the hope of achieving targets within the timeframe by the target year.

2.3.1 Preface

Apart from solar energy in the previous section, wind energy is another key renewable energy that is currently “accelerating the electricity decarbonization”. Wind energy has the characteristics of “sustainable and abundant energy resources” and “relatively eco-friendly energy conversion into electricity”, and it is also one of the fastest-growing carbon-free power options around the world²⁴. However, wind energy also presents the disadvantages of “low energy density that requires a large area of land (for both onshore and offshore)”, “intermittency and instability as an energy source”,

²⁴ Our world in data based on BP Statistical Review of World Energy & Ember. IEA (2020). *Renewables 2020: Analysis and forecast to 2025*.

“noise generated in operation”, “regionality that requires suitable wind fields”, and “high initial costs in infrastructure and installation²⁵”. As such, the development of wind power, like solar power, needs to overcome the challenges in “scalability” and “power stability”.

The geographical location of Taiwan making it prone to influence of monsoons, resulting in relatively abundant wind resources. Coupled with the influence of mountainous terrain, excellent wind fields were born in western Taiwan and the Taiwan Strait. The top 10% of the windiest areas in Taiwan have an average wind speed of 8 m/s or more throughout the year, and the average wind power density exceeds 700 W/m². The average wind speed in the Taiwan Strait reaches a minimum of 10 m/s, and the average wind power density exceeds 1,500 W/m². In addition, 16 of the 20 best offshore wind farms in the world are located in the Taiwan Strait, which gives the Taiwan Strait a relatively favorable wind field environment, making it very suitable for the development of offshore wind power²⁶. As for onshore wind power, since Taiwan is densely populated, it is difficult to avoid the proximity of onshore wind farms to residential areas, along with frequent opposition from local communities, the development of onshore wind power is relatively limited.

Although Taiwan’s wind conditions are perfect for wind energy development, and wind energy is also a carbon-free energy option that Taiwan can develop to effectively reduce Taiwan’s greenhouse gas emissions, if huge land and sea areas are used to develop wind energy (wind farms and base sites), it will present the problem of competition for land from different uses. Therefore, with its limited land resources, how much wind energy can Taiwan develop, what is the potential or limit of the installation, and what is the carbon reduction benefit it offers? These are the key issues to be analyzed urgently. Only with answers to these questions can we engage in path planning and related deployment analysis that follow.

²⁵ Industrial Technology Research Institute (2011). Assessment handbook for the wind energy in Taiwan.

²⁶ *Global Wind Atlas*. <https://globalwindatlas.info/area/Taiwan>

2.3.2 Analysis of the Current Issues with the Wind Energy Development in Taiwan

Green energy technology has been included as one of the “5+2” Innovative Industries Plan since 2016. Solar and wind energy projects have been actively promoted with the aim to achieve the goal of renewable energy accounting for 20% of power mix by 2025. Specifically, wind power is the second largest renewable energy category after solar power. Under the policy goal, the Ministry of Economic Affairs adopted the “Four-year Wind Power Promotion Plan (2017-2020)” in 2017, actively optimizing the installation environment, including establishing demonstration wind farms, completing offshore wind power infrastructure, attracting domestic and foreign investments, streamlining administrative procedures, upgrading local industries, etc. These promotion measures are expected to drive the development of wind power technology and industry domestically in the long run. It is projected to complete an installed capacity of 6.9 GW for wind power by 2025 (1.2 GW onshore and 5.7 GW offshore), with an estimated power generated yearly at 23.5 billion kWh (2.8 billion kWh onshore and 20.7 billion kWh offshore)²⁷.

As of the end of 2020, 361 onshore wind turbines have been installed across 31 wind farms in Taiwan, with a total installed capacity of 726 MW. In the offshore wind sector, 22 turbines have been installed in demonstration wind farms, with a total capacity of 128 MW. The combined installed capacity of both reached 0.85 GW²⁸, which was less than half of the target capacity, leaving a considerable gap from the 2025 goal, nevertheless (Figure 2.3.1). Furthermore, due to the length, weight, and width of offshore wind turbine components, the installation necessitates ports and harbors with a vast hinterland for the purposes of storage, assembly, and underwater foundation connection. Consequently, the installation capacity of offshore wind power is limited by the engineering throughput of port bases. Presently, the ports in Taiwan can manage an annual installation capacity of approximately 1 GW. The government plans to release an additional 1.5 GW of offshore wind power installation capacity from 2026 onwards to accelerate the development of offshore wind power in Taiwan.

²⁷ Bureau of Energy, Ministry of Economic Affairs. Four-year wind power promotion plan (2017-2020).

²⁸ Green Energy Industry Promotion Center (2022). Monthly report of energy.

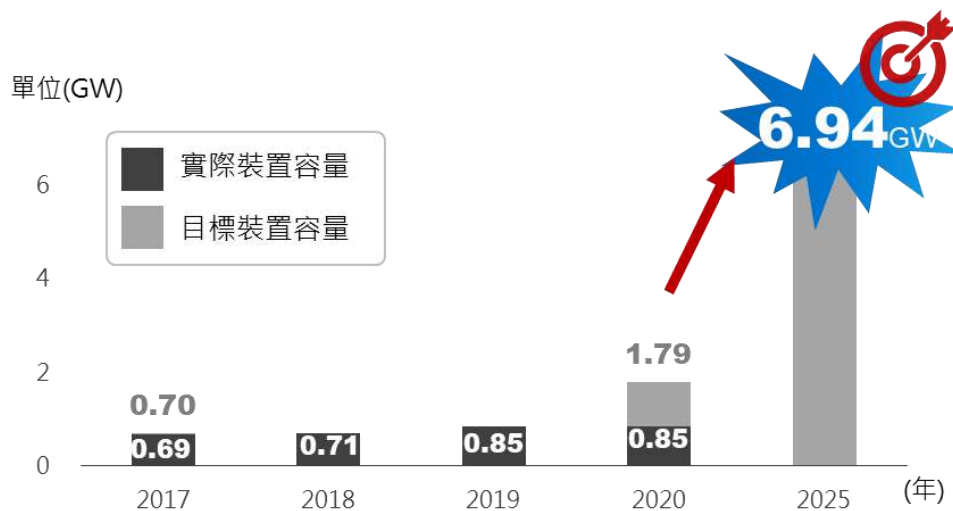


Figure 2.3.1 The Installed Capacity of Wind Power Systems in Taiwan over the Years (Target vs. Actual)

As such, it can be seen that despite the great efforts the government has made in promoting wind power installation, there is still a clear gap in achieving the target in reality. A comprehensive analysis regarding the issues with the promotion in practice is as follows:

1. **Endless waves of social opposition:** While wind power is considered a clean and renewable energy source, its installation still affects certain people, leading to opposition in the society of Taiwan, including protests from nearby communities against the low-frequency noise from onshore wind turbines, protests from fishing groups over the impacts of offshore wind power systems on fisheries and fishing rights, oppositions from environmental groups over the potential impact of offshore wind power systems on marine ecosystems (e.g., birds or dolphins), and protests against landscape changes. These social oppositions have hindered the promotion of wind power, and the installation progresses have not met expectations as a result²⁹.
2. **Dependency on foreign companies for wind power technology introduction:** Due to the insufficient offshore wind power technology domestically, the marine engineering especially depends on international companies, as well as foreign suppliers and workers. With a capacity of 8-10 MW per wind turbine as the assumption, to achieve the target installed capacity of 5.7

²⁹ National Academy of Marine Research (2020). Ecological conservation and environmental monitoring and research regarding offshore wind farms: The potential impact of benthic environment's changes on marine ecology.

GW for offshore wind power by 2025, we would need more than 600 wind turbines. Owing to COVID-19 in recent years, restrictions on the import of equipment and the movement of workers have affected the progresses of relevant projects³⁰. Although the government requires developers to procure certain components locally, and that the localization policy has achieved partial success, the specifications and certification requirements for the components needed in offshore wind power systems are high. Therefore, it takes a learning curve and time for the domestic supply chain and industry, making it difficult for local suppliers to compete internationally. Consequently, it has affected the development progress as well, rendering a failure of the overall strategy to achieve synergy.

3. Short supply of related infrastructure: The majority of wind power in Taiwan is generated from January to March and from October to December, accounting for approximately 70% of the annual total. Nonetheless, the electricity demand reaches its peak in summer (April to June), during which the wind power generated is relatively low. Similar to solar power, such intermittency prevents a stable power supply, requiring connection to the grid through ultra-high voltage cables for a sustainable provision. Yet, the offshore wind farms in Taiwan are located in the southwestern waters. If the submarine cables land in agricultural counties such as Changhua, Yunlin, or Chiayi, the existing low-voltage agricultural power grids will be inadequate. It will be necessary to redeploy the transmission and distribution power grids, substations, and other infrastructure³¹. In addition, the throughput capacity of ports will also affect the speed of deployment. Although the existing port base's space has not been fully utilized, the space issue will inevitably affect the project schedule and progress in the future³².

Hence, it means that if we are to achieve, or even surpass, the current targets set for the installed capacity of wind power in the future, it is necessary for us to overcome the issues of varied social opinions and the need to elevate wind power capacity.

³⁰ CTCI Foundation (2021). Comprehensively building the offshore wind power industry's competitiveness of Taiwan.

³¹ Industrial Development Bureau, Ministry of Economic Affairs (2018). Offshore Wind Power Industry Policy.

³² Ministry of Transportation and Communications (2017). The Offshore Wind Power Industrial Zone of the Taichung Port.

2.3.3 Assessment of the Potential and Limitations of Wind Energy Development in Taiwan

To ensure that each wind turbine can utilize wind energy to the fullest, there must be a reasonable distance between turbines. Generally speaking, the larger the installed capacity of the turbine, the longer the turbine blades and the longer the turbine diameter, and the longer the distance required between the turbine bases, and the larger the land area occupied. In other words, if the same land or sea area is installed with large single-unit wind turbines (such as wind turbines of 15-20 MW), the number of wind turbines will be less than that of small single-unit wind turbines (such as wind turbines of 5-8 MW), so the total power generated by a wind farm equals to the single-unit wind turbine capacity multiplied by the number of wind turbines. Therefore, factors such as “wind farm area,” “single-unit wind turbine capacity,” and “number of wind turbines” are mostly taken into a comprehensive consideration for the potential and limitations of wind power, before estimation of the optimal installed capacity.

1. Onshore Wind Power

Although the western Taiwan offers good wind fields, now that the western Taiwan is mostly packed with densely populated cities and towns, only the sparsely populated coasts are suitable for installation. Based on aerial photos of various cities/counties, and in consideration of the basic criterion for wind farm development (an average wind speed of 4 m/s or higher), the land area available is approximately 1,941 km². Since small single-unit wind turbines are more suitable for onshore wind power system, if we employ a capacity of 2 MW per wind turbine for estimation, and calculate with an capacity density of 2 wind turbines per square kilometer (4 MW/km²), the potential of onshore wind power is estimated to be 7.7 GW. If we adopt a capacity of 3.6 MW per wind turbine for estimation, and calculate with a capacity density of 2 wind turbines per square kilometer (7.2 MW/km²), the potential of onshore wind power is estimated to be 14 GW. If the spacing between wind turbines is adjusted within a reasonable range—increasing the capacity density per unit area—the potential is expected to increase further³³.

However, in practice, due to Taiwan’s high population density over a limited land area, even when wind turbines are installed in sparsely populated coastal areas, it is

³³ Pei-Ling Wen et al. (2014). Cost-benefit analysis of Taiwan’s onshore wind power development.

difficult to avoid their proximity to communities. The low-frequency noise generated during turbine operation will impact residents' lives and health. In addition, in the early stages of wind turbine planning and design, public participation was relatively limited, leading to frequent protests against wind turbines in the past, such as those in the coastal areas of Yuanli Township, Miaoli County, and the Changbin Industrial Park. This has presented challenges to the onshore wind power promotion, hindering its development³⁴. If the installed capacity of onshore wind power is to increase from the current 726 MW to the target of 1.2 GW by 2025, or even reach the estimated potential of 7.7 GW, the government will need to further optimize supporting measures for social communication in order to have a chance of attaining the set target.

Due to the challenges in onshore wind power promotion, the Policy Proposal estimates the future onshore power capacity to be 1.2-3.8 GW. As wind conditions vary across regions, the capacity factor of onshore wind power also varies throughout Taiwan, ranging from 26 to 30% in the past five years³⁵. Therefore, the average value (28%) is employed as the capacity factor for estimation. It is projected that onshore power can reach approximately 2.9-9.3 billion kWh.

2. Offshore Wind Power

The offshore wind farms in the western waters of Taiwan are excellent, with considerable potential for offshore wind power development. First, the western waters within 12 nautical miles from the border lines, and the water depth within 5-100 m, were taken as the area for initial assessment³⁶. Then, areas that meet the wind power criterion (an average wind speed at 10 m above sea level of 8 m/s or more) were selected. Finally, the sea areas with various considerations, such as maritime safety, submarine cables, oil and gas pipelines, exclusive fishing rights, artillery firing areas, areas of steep terrain, etc., were excluded. In the end, the wind energy distribution and potential areas for development in the Taiwan Strait were estimated. There are 36 potential offshore wind power sites with a total area of approximately 3,000 km².

³⁴ Atomic Energy Council, Executive Yuan (2013). Techno-economic analysis and 3E efficiency evaluation of Taiwan's wind power.

³⁵ Taiwan Power Company (2021). Operations of wind power generation of the company in the last 5 years.

³⁶ Shiue-Der Lu et al. (2015). A research on the potential energy of offshore wind power and preferable offshore blocks in Taiwan.

At present, all the offshore wind turbines installed in the western waters of Taiwan are of fixed foundations, with water depths within 50 meters. Turbines of 8 MW account for the majority. Therefore, if turbines of 8 MW are used, and the capacity density is calculated at 15.5 MW/km², the total development potential is estimated to be 47 GW. If turbines of 10 MW are used, and the capacity density is calculated at 24.7 MW/km², the total development potential is estimated to be 74 GW. However, if large wind turbines of future technology with an installed capacity of 20 MW are used, due to the increased diameter of turbines, the number of turbines per unit area will decrease, and the capacity density can only be calculated at 17.8 MW/km², the total development potential is estimated to be a mere 53.4 GW. Although the use of large wind turbines does not increase the total installed capacity, it can reduce the number of wind turbines used, which offers the advantage of reduced installation costs (Figure 2.3.2).

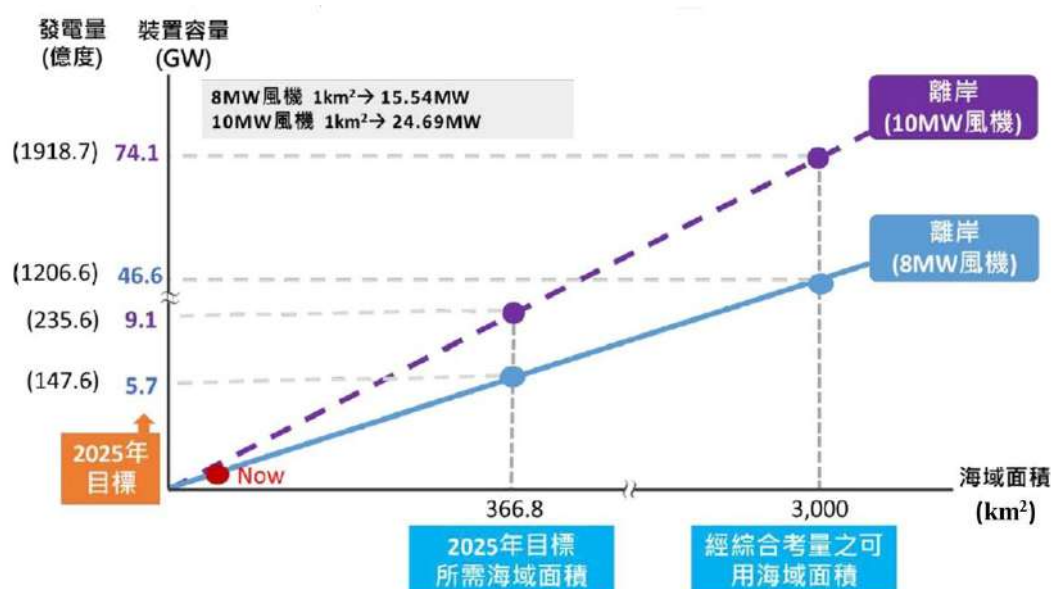


Figure 2.3.2 Estimated Installed Capacity of Offshore Wind Power Systems

Although the potential of offshore wind power is assessed to reach an extremely high installed capacity, as mentioned earlier, the development potential and deployment speed of offshore wind power are limited by the capacity of relevant infrastructure. The engineering planning of offshore wind farm development and construction includes berthing ports and onshore work stations. Berthing ports mainly provide construction docks for loading, transportation and berthing of work vessels during offshore construction. Onshore work stations serve as sites for manufacturing, processing, assembly, and storage of underwater foundations, towers, and various wind turbine components. At present, the Taichung Port serves as the base for offshore wind turbine

production, storage, assembly, and transportation for various wind farm developers in Taiwan, covering an area of approximately 60.5 hectares (including wharfs #2, #5A, #5B, etc.). According to the statistics of the Taichung Port, to build offshore wind farms of 0.5 GW per year, approximately 30 hectares of port land are required for component storage and assembly³⁷. Based on the “Draft Regulations Governing the Development and Supplier Selection for the Offshore Wind Sector” promulgated by the government for the period from 2026 to 2035, it is planned to release 1.5 GW of offshore wind power installation capacity and grid connection capacity per year starting from 2026³⁸. Therefore, the Taichung Port needs to expand its plan to 90 hectares of port for relevant construction. If the offshore wind turbines will increase from 8 MW to over 14 MW per unit in the future, it will be necessary to further scale up the design and load capacity of the port to accommodate larger wind turbine components and larger construction vessels.

Therefore, according to the preliminary estimation, there can be an additional 37.5 GW of installed capacity for the installed capacity target of offshore wind power in Taiwan in the 25-year period from 2026 to 2050. Combined with the 5.7 GW to be achieved by 2025, the estimated offshore wind power capacity by 2050 can reach 43.2 GW. Now that the capacity factor of offshore wind power will be larger than that of onshore wind power, but the capacity factor varies greatly from one sea area to another, a relatively conservative value (40%) is adopted for the preliminary estimation. It is projected that the estimated annual power generated can reach 151.373 billion kWh.

3. Future Wind Power Technologies

Offshore wind turbine technology is developing rapidly. Specifically, single-unit turbines of large installed capacity, such as those exceeding 14 MW, are the wind power technology that develop the fastest. As suitable locations for wind farms of offshore wind turbines with fixed foundations are becoming saturated, the deployment of offshore wind turbines will gradually shift towards deeper waters (of 50 meters or deeper in depth) (Box 2.3.1). Floating offshore wind power systems will become a key focus for the next stage of wind power technology development. Floating platforms will be adopted in place of the existing traditional fixed foundations for floating offshore

³⁷ Institute of Transportation, Ministry of Transportation and Communications (2021). Submarine engineering technology research and development program for offshore wind power.

³⁸ Bureau of Energy, Ministry of Economic Affairs (2021). Plan of the development and supplier selection mechanisms for offshore wind power zones.

wind turbines. At present, the platform technologies fit for offshore wind turbines include tension-leg platforms (TLPs), spar buoys, and semi-submersibles³⁹. These technologies come with capabilities to withstand wind, waves, and currents. In particular, semi-submersible offshore wind turbines are currently the most suitable technology for development in Taiwan. Their advantage lies in the fact that both the floating platform and the wind turbine can be assembled onshore, and only need to be towed offshore by ships for placement, which can reduce the construction time affected by sea conditions. The offshore wind power potential in Taiwan's deep-water areas is estimated to be as high as 90 GW⁴⁰. The demonstration project for floating offshore wind farms has been planned, with the target to complete the installation and grid connection of floating offshore wind turbines with a total installed capacity of 100 MW by 2026. It is expected that the deployment and commercial operation of floating offshore wind farms can be carried out in 2030⁴¹. With the target set at an installation capacity of 0.5 GW per year, the installed capacity will reach 10 GW by 2050, with an estimated 35.04 billion kWh of power generated per year (calculated with the capacity factor at 40%).

Box 2.3.1 Hywind Tampen Floating Offshore Wind Farm

The Norwegian energy company Equinor is to install an 88-MW floating wind farm, aiming to supply the power needed for offshore oil installations. A total of 11 8-MW wind turbines shall be installed at the depths ranging from 260 to 300 meters. It is by far the largest floating offshore wind farm in the world, projected to be completed by 2022.

As the costs of wind power technology decrease, and the scale of wind farm development expands, year by year, the overall power supply and demand will become unbalanced often due to the poor dispatchability of wind farms. In the future, through the integration of weather/climate forecasting systems and wind power systems, more accurate wind power forecasting information will be available, enabling power plants to schedule and dispatch power in a timely manner and plan the long-term power

³⁹ IRENA (2020). *Fostering a blue economy: Offshore renewable energy*.

⁴⁰ Green Energy & Environment Research Laboratories, Industrial Technology Research Institute (2011). *Assessment handbook for the wind energy in Taiwan*.

⁴¹ Bureau of Energy, Ministry of Economic Affairs (2021). *Briefing of the demonstration plan for floating offshore wind farms*.

generation strategies⁴². If the balance of power regulation and management cannot be achieved in time, wind curtailment will occur. Therefore, the concept of “Power to X,” which is the concept of converting electricity into other energy for storage or fuel for use, has recently gained an increasing attention⁴³. The most emphasized model at present is the combination of offshore wind power and water electrolysis to produce hydrogen, which can alleviate the problem of seasonal or temporal surplus power in supply (see Chapter 2.5 Hydrogen Energy). In addition, as the distance between offshore wind farms and the shore increases, the costs of grid construction will also rise. Part of the grid investment costs may be diverted to building hydrogen conversion- and transportation-related facilities. The Danish developer Ørsted completed the H2RES demonstration project in 2021, making it the world’s first project of offshore wind power project with hydrogen production officially put into operation⁴⁴.

It is estimated that by 2025, the number of offshore wind turbines installed in Taiwan will soar to over 600. By 2035, there will be approximately 1,000 offshore wind turbines in our waters⁴⁵. The overall maintenance period for offshore wind turbines is as long as 20 years. In addition to regular basic maintenance, timely inspections will be necessary after strong typhoons and earthquakes. Therefore, it is essential to establish local maintenance operators and component supply chains, which can significantly reduce the maintenance costs. The development trend of offshore wind farm maintenance technology will shift from the traditional single-point control to overall management. By utilizing big data analytics, advanced monitoring systems, and sensors, the health status of equipment and components can be diagnosed in advance for maintenance or replacement. Furthermore, the optimal maintenance schedule and repair strategies can be determined after assessment to predict the overall wind farm conditions⁴⁶. In addition, unmanned equipment will be a development focus for wind turbine and underwater structure maintenance, including drone inspections, automatic

⁴² Taiwan Power Company (2018). Current landscape of the forecasting and studies of Taipower’s power generation with renewable energy.

⁴³ Manuel Götz et al. (2016). Renewable power to gas: A technological and economic review. *Renewable Energy* 85, 1371-1390.

⁴⁴ 4C OFFSHORE (2021). Uniper and Ørsted forge offshore wind and hydrogen alliance.

⁴⁵ National Academy of Marine Research (2020). The current status and trends of offshore wind farm operation and maintenance.

⁴⁶ Ministry of Economic Affairs (2017). Technology development program for efficiency enhancement of offshore wind farm operation and maintenance.

climbing robots, and underwater unmanned vehicles⁴⁷. With the help of innovative technologies and equipment, the diagnosis time will be shortened, and the risks associated with human maintenance activities in practice will be reduced.

2.3.4 Policy Recommendations

In order to maintain the energy autonomy, reduce environmental pollution, and decrease GHG emissions, Taiwan needs to develop carbon-free and “local” renewable energy sources. In particular, wind power has become a crucial option for carbon reduction thanks to the excellent wind fields available in Taiwan. Based on the aforementioned analysis of issues, potentials, and limitations regarding the promotion of wind power in Taiwan, it is clear that wind power is the most technologically mature renewable energy among all the carbon-free power options available at present. As long as investments are made in the construction of installation capacity and supporting infrastructure, the supply of renewable energy can be raised in the short term. Nevertheless, social support, as well as comprehensive policy planning encompassing wind power technologies, industries, and port spaces, are necessary to resolve the present issues in practice, accelerate deployment, and reach the long-term carbon reduction targets. The Policy Proposal puts forward recommendations as follows:

1. A Full Provision of Various Supporting Measures for Offshore Wind Power Development to Boost the Installed Capacity and Power Generated by Offshore Wind Power Systems

Thanks to our high potential for offshore wind power development, offshore wind power will be the primary focus of wind energy development. Although the government has taken numerous proactive actions to promote wind power development, the issues identified in the analysis afore have made the development progresses falling behind schedule. Hence, if we are to increase the installed capacity of offshore wind power, it is imperative to provide comprehensive supports and supporting measures to accelerate the installation and deployment. The Policy Proposal puts forward implementation recommendations as follows:

- (1) Once an offshore wind power system is installed, it is necessary to align the underwater pin piles and cable layouts with the relevant construction. Developers will also need to invest a large amount of funds. In light of the impact of future

⁴⁷ Market Intelligence & Consulting Institute (2020). Underwater unmanned vehicle industry observation – offshore wind power application as a case study.

wind power technology development (e.g., large-scale wind turbines, deep-water wind turbine foundation installation technology, etc.), the existing restrictions on the designated wind farm areas should be reviewed, moving from shallow waters to deeper waters with a greater potential, seeking the optimal wind farm and turbine configurations for power generation (unit installed capacity, number of turbines, sea area, etc.), and implementing supporting measures for the fine-tuned wind farms and development conditions, such as deep-water areas for wind farms and communication with fishermen at local fisheries.

(2) Actively carry out comprehensive planning and design for the land use demand at ports in western Taiwan, including the hinterland development of the port bases (like the hinterland of the Taichung Port at present and even those of other ports) as well as the construction of feeder lines (power transmission/distribution networks, substations, and other NIMBY facilities), thereby elevating the installation capacity to 1.5 GW or higher per year to speed up the deployment.

(3) Keep tabs on and introduce the up-to-date international wind power technologies, and invest in the research and development of relevant technologies fit for the conditions in Taiwan, so as to achieve the goal of technological autonomy from construction to long-term operation and maintenance, such as floating wind turbine technology, marine engineering technology, management of the wind power systems in the Taiwan Strait (including accurate wind energy and power generation forecasting information), and noise reduction in blade design.

(4) Timely adjust the localization policies for offshore wind power development at present in Taiwan. In addition to supporting the development of our domestic wind power industry chain and encouraging investment from domestic companies, it is even more necessary to take installation progress into consideration. On one hand, it will make the local procurement policy more flexible (e.g., items for maintenance). On the other, it will enable diversified developments of the wind power sector and localized maritime engineering technologies, thus strengthening the international competitiveness of the suppliers from Taiwan. As such, the relevant vessels, talents, and technologies may be cultivated in depth and retained in Taiwan, before a further expansion to the Asia-Pacific and international markets.

2. Strengthening Social Communication and Relevant Public Participation Mechanisms to Secure Social Support

Since onshore wind power projects tend to impact communities nearby, while offshore wind farms are prone to disrupt fishing activities, wind power development at present often faces social opposition. It is recommended that the government engages in an effective social communication to ensure a steady progress in the face of various challenges. The Policy Proposal puts forward implementation recommendations as follows:

- (1) Enhance public participation mechanisms and social communication, especially in the early stages of onshore wind farm planning and design, and take the initiative to communicate with nearby communities and fishing groups during the planning and construction of offshore wind farms.
- (2) Provide various incentives and supporting measures to increase the support from residents near onshore wind farms and affected fishermen, such as subsidies for installation of soundproof windows and compensation for catch impacts.
- (3) Conduct ecological monitoring and survey for the waters of offshore wind farms to probe into the possible impacts on the ecosystems and fisheries.

2.4 Geothermal Energy

Summary

Geothermal energy is one of the few self-produced renewable energies in Taiwan, and it can be used as base load power. With a sufficient supply of power, geothermal energy can help improve the stability of the power grid. Hence, geothermal energy is a zero-carbon option that has to be taken into account as Taiwan works to reach the goal of net-zero emissions by 2050. Taiwan's reserves of shallow geothermal energy eclipse 0.986 GW, and deep geothermal potential is about 31.8 GW. The keys to successfully using geothermal energy are “precise mapping” and “drilling and heat extraction”, and both technologies have made great progress in recent years. It is important to increase investment in R&D and deployment to find suitable sites to harness geothermal energy. Strategically speaking, with years of experience in harnessing shallow geothermal energy to generate power around the world, the technology is mature. Taiwan should accelerate its development. On the other hand, the technology to use deep geothermal energy is expected to be more mature by 2030, so Taiwan should actively develop deep geothermal energy so that deep geothermal energy can become a main source of energy in Taiwan. Moreover, the geological data accumulated during the early phase of developing shallow geothermal energy can be used to help deep geothermal energy in the future. Our recommendations are as follows:

1. Encouraging the development of precise mapping as well as drilling and heat extraction technology to harness shallow and deep geothermal energy in Taiwan with an in-depth understanding of potential geothermal distribution across Taiwan. Paying close attention to the latest developments in deep drilling and heat extraction technology around the world to ensure that Taiwan can use the latest technology in a timely manner.
2. Drafting a special act for geothermal energy with a clear indication of the competent authorities to provide more incentives, simplify the review process for initial exploration activities, protect exploration rights and interests, and foster industrial development.
3. In the short term, the goal is to increase geothermal electricity capacity with shallow geothermal power plants. The ultimate goal in the long run is to increase electricity capacity by adding deep geothermal power plants. It is estimated that the installed electricity capacity from Taiwan's geothermal energy will reach 8.13-

12.88 GW by 2050. Power generated will reach 46.829-74.189 billion kWh, and the average power generation will be 60.509 billion kWh.

2.4.1 Preface

Future economic development and comprehensive electrification mean that Taiwan's electricity demand will grow significantly by 2050. Power generated from geothermal energy is relatively stable and can be used as base load power. Proper utilization of geothermal energy can help stabilize the supply of renewable energy and minimize the potential impact of blackouts. Taiwan may have more than 30 GW of potential deep geothermal energy. If deep geothermal energy can contribute more to Taiwan's power generation, it will definitely help Taiwan reach its goal of net-zero emissions by 2050. Geothermal systems can be divided into two categories: traditional hydrothermal systems and enhanced geothermal systems (EGSs). The depth of traditional geothermal wells usually does not exceed 3,000 meters; hence, such wells are considered shallow geothermal energy. EGS wells, on the other hand, are usually deeper than 3,000 meters, so EGS is known as deep geothermal energy. At present, the development of EGS is restrained by technology and cost issues. Despite the fact that shallow geothermal technology is fairly advanced, Taiwan's shallow geothermal potential is less than 1 GW, which means that it can only offer limited help for Taiwan to reach its net-zero emissions goal by 2050. However, we have about 30 years between now and 2050. In the foreseeable future, EGS has the potential to achieve economies of scale and help Taiwan achieve its goal of net-zero emissions by 2050.

As for why Taiwan should choose to develop its geothermal energy industry, in addition to the fact that Taiwan has abundant geothermal resources, geothermal energy can also be a critical baseload power for Taiwan. Statistics from Taiwan Power Company showed that the capacity factors of solar energy from various parts of Taiwan in 2020 were between 9 and 15%. In other words, solar energy was not able to generate electricity for more than 85% of the year⁴⁸. The capacity factor of onshore wind energy in 2020 was about 26 to 30%. The capacity factor of offshore wind energy was higher,

⁴⁸ Taiwan Power Company (2021). Solar photovoltaic capacity factor for all counties and cities in Taiwan in 2020. <https://www.taipower.com.tw/tc/page.aspx?mid=207&cid=165&cchk=a83cd635-a792-4660-9f02-f71d5d925911#b04>

but the numbers change greatly from month to month⁴⁹. In comparison, geothermal energy will not be affected by the weather, and its average capacity factor globally is higher than 80%. Some independent power plants even boast a capacity factor of over 90%.⁵⁰ While wind and solar power have a fluctuation cycle and are not suitable to be used as baseload power, thermal energy can be used as base load power. In the near future, as part of the trend to reach net-zero emissions and as the share of wind and solar power gradually increases, geothermal energy can help provide Taiwan with stable electricity.

2.4.2 Current International Development

At present, there are less than 10 EGS power plants in commercial operation around the world, including Insheim Power Plant (4.8 MW)⁵¹ and Landau Power Plant (3.8 MW)⁵² in Germany, Desert Peak Power Plant (1.7 MW)⁵³ in Nevada, US, and Soultz Power Plant (1.5 MW)⁵⁴ in France. The development of EGS is mainly restrained by technology and cost issues. Hence, the European Engine Power Plants Association (EUGINE) has put together 35 teams from and outside the EU who will work together to reduce the cost of exploration and drilling of EGS by 20%, respectively, and increase the thermoelectric conversion efficiency by 20%⁵⁵. The Frontier Observatory for Research in Geothermal Energy (FORGE), supported by the US Department of Energy (DOE), is a program dedicated to the technological development of EGS. The program has put together resources from industry, government, academia, and research institutions and provides grants to support research (47-70% of the project costs). The goal is to reduce the cost of EGS to US\$0.06/kWh (approximately NT\$1.8/kWh; at present, the levelized cost of electricity of geothermal power falls

⁴⁹ Taiwan Power Company (2021). Overview of the development of renewable energy: Wind power generation. <https://www.taipower.com.tw/tc/page.aspx?mid=204&cid=1581&cchk=82fb957e-2fe8-49b6-90a9-b750387de936>

⁵⁰ International Renewable Energy Agency (IRENA) (2017). *Geothermal power – Technology brief*. <https://www.irena.org/publications/2017/Aug/Geothermal-power-Technology-brief>

⁵¹ BESTEC (2012). The Insheim Geothermal Project. <https://www.bestec-for-nature.com/index.php/en/projects-en/insheim-en>

⁵² BESTEC (2007). The Landau geothermal power plant. <https://www.bestec-for-nature.com/index.php/en/projects-en/landau-en>

⁵³ POWER (2013). U.S. EGS project adds 1.7 MW grid-connected output. <https://www.powermag.com/u-s-egs-project-adds-1-7-mw-grid-connected-output/>

⁵⁴ Lu, S. M. (2018). A global review of enhanced geothermal system (EGS). *Renewable and Sustainable Energy Reviews*, 81, 2902-2921. <https://doi.org/10.1016/j.rser.2017.06.097>

⁵⁵ Li Boheng, Lao Zhixi, Liu Liwei, Xie Ruiqing, Guo Tairong, Wang Junyao (June 2014). Analysis and discussion on the development of enhanced geothermal system.

between NT\$1.68 and NT\$2.79/kWh). The ultimate goal is for the installed capacity to reach 100 GW in the US by 2050.

Saskatchewan in Canada is the sixth largest oil producer in North America. Over the years, Saskatchewan has accumulated a lot of local geological information. Today, this geological information has been used to develop geothermal energy. Natural Resources Canada invested \$1 million Canadian dollars in preliminary research in 2014 and added \$525,000 Canadian dollars for test drilling. The development of geothermal energy was carried out by DEEP Earth Energy Production Corp., with a total budget of \$51.3 million Canadian dollars. In January 2019, the Canadian government further invested \$25.6 million Canadian dollars (approximately NT\$587 million) to build a power plant with an installed electricity capacity of 5 MW⁵⁶. According to the design of DEEP, for the installed electricity capacity to reach 20 MW, they will need only four cool water injection wells and six hot water production wells that are 3.5 kilometers deep⁵⁷. The hydraulic fracturing range required for this design is small and is unlikely to induce earthquakes that can be felt (like the suspected incident related to EGS in Pohang, South Korea, in 2017⁵⁸). It is also more suitable to Taiwan's geographical environment.

The top 10 countries with the highest installed geothermal electric capacity in 2020 are the United States (3.714 GW), Indonesia (2.133 GW), the Philippines (1.918 GW), Turkey (1.688 GW), New Zealand (1.005 GW), and Mexico (0.963 GW), Italy (0.944 GW) and Kenya (0.861 GW)⁵⁹. From 2008 to 2018, Turkey, with the highest capacity addition, increased its installed electricity capacity by 1.317 GW. In other words, the capacity saw a 44-fold increase in 10 years. The second to fifth place in capacity gains from 2008 to 2018 were Indonesia (0.956 GW), the United States (0.599 GW), Kenya

⁵⁶ DEEP (2019). Prime Minister announces support for Canada's first geothermal power facility. <https://deepcorp.ca/prime-minister-announces-support-for-canadas-first-geothermal-power-facility/>

⁵⁷ DEEP (2021). Saskatchewan is ready for final geothermal power feasibility engineering – 53 day large volume production and injection test successful – first in Canada. <https://deepcorp.ca/saskatchewan-is-ready-for-final-geothermal-power-feasibility-engineering-53-day-large-volume-production-and-injection-test-successful-first-in-canada/>

⁵⁸ Mark Zastrow (2019). South Korea accepts geothermal plant probably caused destructive quake. <https://www.nature.com/articles/d41586-019-00959-4>

⁵⁹ Richter, A. (2021). ThinkGeoEnergy's top 10 geothermal countries 2020 – installed power generation capacity (MWe). <https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2020-installed-power-generation-capacity-mwe/>

(0.509 GW), and New Zealand (0.421 GW)⁶⁰.

The reasons why Taiwan was not able to develop its geothermal energy include lack of experience and high drilling costs. Perhaps Taiwan can learn from the experience of Kenya, a country with an installed electricity capacity of 861 MW. Kenya's per capita GDP is less than US\$2,000, which is about 6.3% of Taiwan's per capita GDP. However, more than 75% of geothermal power plants in Kenya are built by the local Kenya Electricity Generating Company.⁶¹ Turkey, with the highest capacity addition from 2008 to 2018, is another good example. Turkey's Feed-in Tariff—a scheme that ensures that the government purchases green electricity with fixed electricity prices—per kilowatt hour is 10.5 cents (roughly the same as the electricity rate of Taiwan Power Company). Although the contract for the Feed-in Tariff lasts only ten years, it is enough to cultivate domestic key infrastructure to support Turkey's development of geothermal energy⁶².

2.4.3 Analysis of the Current Problems of Developing Geothermal Energy in Taiwan

The installed electric capacity of geothermal energy in Taiwan in 2020 was about 0.3 MW, and the generated energy was about 2 million kWh. For Taiwan, an island located in the Ring of Fire, these figures were low, and there is certainly considerable room for future growth. Taiwan was slower in developing its geothermal energy, and the main reason was a failure experienced early on. From 1981 to 1993, Qingshui Geothermal Power Plant failed after being in operation for over 10 years. The result was the government was hesitant to invest in geothermal power generation technology in the following 20 years. One failure can result in an immature technology being shelved and falling into what was known as the “Valley of Death”. The potential of geothermal power was ignored and international developments were not followed. This is a lesson that Taiwan has to take into consideration for the research and development

⁶⁰ Richter, A. (2021). Global geothermal power generation capacity reaches 14,600 MW at year end 2018. <https://www.thinkgeoenergy.com/global-geothermal-power-generation-capacity-reaches-14600-mw-at-year-end-2018/>

⁶¹ Macharia, M. W., Gachari, M. K., Kuria, D. N., Mariita, N. O. (2017). Low cost geothermal energy indicators and exploration methods in Kenya. *Journal of Geography and Regional Planning*. 10 (9), 254-265. <https://academicjournals.org/journal/JGRP/article-abstract/4C7023B65573>

⁶² Risk Society and Policy Research Center, College of Social Sciences, National Taiwan University (February 23, 2019). Referendum to promote green: Essential knowledge for developing geothermal energy. <https://rsprc.ntu.edu.tw/zh-tw/m01-3/en-trans/1112-green-nuclear-vote-necessary-knowledge.html>

of Net Zero technologies in the future. It was not until recently that the government began to introduce demonstration incentives and deregulation measures that we saw a gradual increase in the number of applications after 2018. Most of these small, shallow geothermal power plants are located in eastern Taiwan. By 2023, it is expected that the electricity capacity of geothermal power plants that can be made commercially available will be increased to 35 MW (see Appendix 2E). Taiwan's challenges to develop geothermal energy include:

- 1. Taiwan's development of precise mapping is lagging behind, so there is a need to collect the latest high-resolution geological data:** Taiwan's current assessment of areas with potential geothermal resources is based on geothermal data previously collected for the Energy National Science and Technology Program. However, since mapping and exploration technologies have matured, Taiwan should obtain high-resolution geothermal data by using precise mapping technology. At the same time, by cooperating with international partners, Taiwan can locate areas with potential deep geothermal resources, which will reduce the cost and risk of drilling.
- 2. Taiwan's development of heat extraction technology to utilize deep geothermal energy is lagging behind:** There are examples of EGS power plants that utilize deep geothermal energy around the world, and the relevant technology is developing rapidly, including horizontal drilling. In comparison, Taiwan's geothermal power generation technology still needs to be brought up to date for deployment.
- 3. With higher risk involved in initial drilling, businesses are not motivated to invest:** About 40% of geothermal well drilling around the world failed to find geothermal energy suitable for commercial operation⁶³. When the investment risks are too high for businesses, government grants and incentives are needed to provide assistance.

⁶³ Bill Gates (2021). *How to avoid a climate disaster*. <https://www.penguinrandomhouse.com/books/633968/how-to-avoid-a-climate-disaster-by-bill-gates/>

4. Regulatory restrictions involving multiple government agencies and complicated administrative procedures⁶⁴: Despite the fact that Taiwan has passed the “Regulations on Demonstration and Encouragement of Geothermal Power Generation,” the incentives granted cannot exceed 50% of the total cost for geothermal energy exploration, and the maximum amount of incentives granted cannot exceed NT\$100 million. The “Standards for Determining Specific Items and Scope of Environmental Impact Assessments for Development Activities” announced in 2018 exempt projects to develop geothermal energy with up to 10MW of electricity capacity from environmental impact assessment. However, the installed electric capacity of a geothermal power plant is not directly linked to the scope of development, so this affects businesses' willingness to invest in projects with commercial scale and higher capacity. As for other laws and policies, Article 18 of the Electricity Act states that “The Electricity Transmission and Distribution Enterprise shall not reject any request put forward by the Electricity Generating Enterprise or Self-Use Power Generation Equipment for connection to its power grid. The Renewable-Energy-Based Electricity Generating Enterprise shall be given priority to connect to the grid...” but in practice, businesses need to overcome the challenge of coordinating and cooperating with Taiwan Power Company. After the Fukushima nuclear disaster (2011) after the Great East Japan Earthquake, Japan began to promote the development of geothermal energy for power generation⁶⁵. Table 2.4.1 compares laws and policies on geothermal power generation in Taiwan and Japan.

⁶⁴ Kwangyin Liu (2021). "Exclusive Insight" Why companies by Bill Gates and Bezos favor Taiwan, a small island challenged with dense population? *Commonwealth Magazine*. <https://www.cw.com.tw/article/5114679>

⁶⁵ Shengrong Song (2015). Current status, prospects and challenges of geothermal developments in Taiwan. *Journal of Petroleum*, 61-82.

Table 2.4.1 Comparison of Laws, Policies and Measures to Promote Geothermal Power Generation in Taiwan and Japan

Country	Japan	Taiwan
Policies and Measures		
Investment in EGS R&D	Active	Less obvious
Subsidize 50% of geothermal exploration drilling costs	○	○*
Subsidize 100% of the cost for developers to hold public briefing to facilitate the construction of geothermal power plants	○	×
Feed-in Tariff	For power plants with capacities of over 15 MW, the rate per kilowatt hour is 27.3 yen; for power plants with capacities of less than 15 MW, the rate per kilowatt hour is 42 yen.	NT\$5.1956 per kilowatt hour**
Amended laws to allow exploration and construction of power plants in national parks	○	***

*Regulations on Demonstration and Encouragement of Geothermal Power Generation; announced on May 20, 2022

**2021 FiT rate for electricity generated with renewable energy sources

***Standards for Determining Specific Items and Scope of Environmental Impact Assessments for Development Activities; geothermal power plants with capacities under 10 MW are exempt from environmental impact assessment

2.4.4 Assessment of the Potential and Limitations for Taiwan to Develop Geothermal Energy

Early assessments estimated that Taiwan has a generation potential of about 159.6 GW, but only 20-22% can be exploited. It is estimated that the potential of shallow geothermal energy is about 0.986 GW (Table 2.4.2), but EGS potential can reach 31.8 GW (Table 2.4.3). In other words, if Taiwan aims to reach the net-zero emissions target by 2050, it will need to develop the EGS industry. At the same time when Taiwan is developing its EGS technology, with precise geothermal exploration underground in potential areas should be accelerated. The more precise the mapping, the lower the risk of drilling during the development phase. Moreover, the exploration data can be used for future assessments of deep geothermal energy for the establishment of EGS power plants. This will enable Taiwan to gradually increase the annual contribution of geothermal power to the grid by 2050. For example, the “Plan to Accelerate Comprehensive Exploration of Geothermal Resources and Information Provision” included in the government's “Forward-looking Infrastructure Development Program” has been approved with an annual budget of NT\$70 million in 2020 and 2021, respectively, to explore geothermal resources. We are seeing progress, but long-term and stable support will be needed to achieve the desired results.

Table 2.4.2 Assessment of Shallow Geothermal Potential in Taiwan⁶⁶

Area	Temperature range (°C)	Reserve volume (km ³)	Power generation potential (MW)
Datun Mountain	200-290	40.0	514
Qingshui	180-220	6.0	61
Tuchang	160-180	3.0	25
Lushan	150-210	4.5	41
Jhihben	140-200	3.0	25
Jinlun	140-180	6.0	48
Mizuho	140-180	2.0	16

⁶⁶ Environment and Development Foundation (2013). Final report of potential sites to develop geothermal energy in Taiwan.

Hongye	130-190	1.5	12
Paolai	110-160	2.0	14
Fuyuan	80-160	1.5	9
Wulu	150-210	2.0	18
Dongpu	120-180	2.0	16
Lele	120-140	1.5	9
Guguan	130-180	2.0	15
Maling	130-170	1.5	11
Knazyi	130-170	1.5	11
Nanao/Sihcyu	140-210	2.0	18
Nanao/Wugu	150-210	2.0	18
Choucian	135-185	2.0	16
Maobian	170-210	2.0	19
Wulai	150-200	1.5	13
Guanziling	120-190	1.5	11
Jhonglun	120-185	1.5	11
Jiaosi	100-160	1.5	9
Taolin	150-210	1.5	14
Bilu	130-190	1.5	12
Total			986

Table 2.4.3 Assessment of Deep Geothermal Potential in Taiwan⁶⁷

Area	Area (km ²)	Average temperature (°C)	Geothermal potential (10 ¹⁸ J)	Power generation potential (GW)
Datun Mountain	278	236	252	2.7
Qingshui, Tuchang	909	223	760	7.8
Lushan	279	210	209	2.0
Mizuho, Antong	467	195	297	2.6
Wulu, Hongye	571	196	366	3.3
Jhihben, Jinlun	701	214	545	5.4
Paolai	476	205	336	3.1
Guanziling	510	197	334	3.0
Hsinchu, Miaoli	343	192	209	1.8
Total	4,532	208	3,307	31.8

Using data from the past two years, it is estimated that at present, Taiwan's development of shallow geothermal energy can increase capacity by about 17 MW per year, and capacity may reach 51 MW by 2025. If the annual capacity can increase by 25 to 35 MW per year from 2026, the total capacity of shallow geothermal energy can be increased by 625-875 MW by 2050, and the total capacity may reach between 676 and 926 MW. As for deep geothermal energy, the target is to develop 500MW to 800MW annually starting from 2035, and it is estimated that the capacity can increase to 7.5-12 GW by 2050. Hence, the capacity of geothermal energy will reach approximately 8.13-12.88 GW by 2050. Using a capacity factor of 80% and approximately 300 operating days per year, the power generated can reach approximately 46.829 to 74.189 billion kilowatt-hours, with an average power of 60.509 billion kilowatt-hours.

⁶⁷ Bureau of Energy, Ministry of Economic Affairs (2014). *White paper on energy industry technology in 2014*.

2.4.5 Policy Recommendations

Solar or wind energy can be observed at ground level, so finding a suitable site to set up power-generating units seems relatively easy. In comparison, geothermal energy is underground, and there are technical barriers to drilling and exploration as well as a higher risk of failure. In 2020, the average capacity factor of Taiwan's solar energy was only 14.44%⁶⁸, and wind power was only 29.56%⁶⁹. In comparison, geothermal energy has an average capacity factor of higher than 80%. Hence, electricity generated from geothermal sources will not be affected by the weather and it has become a key option for stable power supply. For policies, our recommendations are:

1. Encouraging the development of high-precision prospecting and drilling technology to harness shallow and deep geothermal energy in Taiwan with an in-depth understanding of potential geothermal distribution across Taiwan. Keeping a close eye on the latest development of deep drilling and heat extraction technology around the world so that Taiwan can use the latest technology in a timely manner

Considering the risks involved in drilling, government promotion will be needed to establish the geothermal industry supply chain. At the same time, investment should be made to develop technologies that can improve the resolution of geological information (such as the telluric-magnetotelluric method and seismic velocity structure inversion) and establish a high-resolution underground geological database. The technology to generate electricity using shallow geothermal energy is quite mature. For example, the Geysers complex of geothermal power plants in California was built in 1960, and the capacity of the complex already has exceeded 0.8 GW⁷⁰. At the same time, technical problems like acid corrosion⁷¹ and scaling have been solved. Taiwan has the potential to use shallow geothermal energy to generate nearly 1 GW⁷² of electricity. Although the potential capacity is not as high as EGS with deep geothermal

⁶⁸ Taiwan Power Company (2022). Solar photovoltaic capacity factor for all counties and cities in Taiwan in 2021. <https://www.taipower.com.tw/tc/page.aspx?mid=207&cid=165&cchk=a83cd635-a792-4660-9f02-f71d5d925911#b04>

⁶⁹ Taiwan Power Company (2022). Wind power generation. <https://www.taipower.com.tw/tc/page.aspx?mid=204&cid=1581&cchk=82fb957e-2fe8-49b6-90a9-b750387de936>

⁷⁰ California Energy Commission (2021). California geothermal energy statistics and data. from https://ww2.energy.ca.gov/almanac/renewables_data/geothermal/index_cms.php

⁷¹ Peng Xiaojuan (2021). Case studies of international development of acid geothermal systems. <https://km.twenergy.org.tw/ReadFile/?p=KLBase&n=20210609172327.pdf>

⁷² *Ibid.*, 72.

energy, Taiwan can use shallow geothermal energy to promote the establishment of the industry and cultivate talent. In the future, with a better foundation of shallow geothermal energy, Taiwan can move towards EGS with more resources. Kenya's per capita GDP is only about 6% of that of Taiwan, but Kenya already has an installed electricity capacity of 0.861 GW with its geothermal energy⁷³. With Taiwan's advanced technological development, the risk of development would be relatively low, so Taiwan should work to increase the electricity capacity of shallow geothermal energy.

In terms of the technology for geothermal exploration, we can follow the example of the oil drilling industry. The oil industry also faces the risk of not being able to locate the oil reserves, but once economies of scale are reached, the price of crude oil can come down. The geothermal energy industry can follow a similar trajectory. With more geothermal power plants in the future, developers' costs will be reduced significantly. As the world moves towards the target of net-zero emissions and oil drilling faces more restrictions, oil companies can also transform themselves and apply their drilling technology to develop geothermal energy. Both traditional geothermal prospecting and horizontal drilling technology will be helpful for Taiwan in generating electricity with EGS.

⁷³ Alexander Richter (2021). Global geothermal power generation capacity stood at 15,608 MW at the year-end 2020. The current pandemic situation clearly slowed down development with limited growth reported. Turkey represents nearly all geothermal generation capacity added in 2020. <https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2020-installed-power-generation-capacity-mwe/>

2. To provide more incentives, it is recommended to establish a special act for geothermal energy and clearly specify the competent authorities who can then help simplify the review procedures of development activities, protect exploration rights, and accelerate industrial development

In terms of supporting regulatory measures, at present, Taiwan does not have a special act on geothermal energy and no competent authority that can serve as a single contact point to protect exploration rights, simplify the review process⁷⁴, and support the industry. As a result, domestic and foreign companies are not willing to invest in the exploration or development of geothermal energy. Only public entities have so far been assigned to develop geothermal energy. Recently, the investment from the “Forward-looking Infrastructure Development Program”, Measures for Geothermal Power Generation System Demonstration Incentives (abolished on December 31, 2020), Regulations on Demonstration and Encouragement of Geothermal Power Generation (announced on May 20, 2022), or deregulation for development in protected areas such as national parks⁷⁵ have all shown some preliminary results as we follow examples from the international community. However, as a country with abundant geothermal resources, Taiwan's development is indeed too slow when compared with the top 10 countries with the highest geothermal electricity capacity. The government should speed up the establishment of the special act for geothermal energy, actively assist businesses to engage in communication and coordination with local residents, create relevant local job opportunities, and encourage international professional drilling teams to come help Taiwan's geothermal industry develop as soon as possible.

⁷⁴ Jui-Chu Lin, Chung-Huei Kuan, Chen-Hsiung Shen, Dan-Dan Zhu (2019). A study on regulation adaptation for the exploration stage of Taiwan geothermal power development. https://km.twenergy.org.tw/Publication/thesis_down?id=220

⁷⁵ Laws and Regulations Database of the Republic of China (2020). Standards for determining specific items and scope of environmental impact assessments for development activities. <https://law.moj.gov.tw/LawClass/LawAll.aspx?pcode=O0090012>

3. The short-term goal is to increase the installed electricity capacity of shallow geothermal power plants, and the long-term goal is to increase the electricity capacity of deep geothermal power plants. It is estimated that in 2050, Taiwan's geothermal electricity capacity will reach 8.13-12.88 GW, and can generate 46.829-74.189 billion kWh of electricity.

At present, shallow geothermal technology is mature. The total installed geothermal capacity in many countries in the Pacific “Ring of Fire” has reached over 1 GW. Taiwan should engage in international cooperation and start to invest in exploration and development as soon as possible, so Taiwan's technological development will not lag behind. Specifically, a comprehensive precision geological survey should be conducted to obtain high-precision 3D geological information on Taiwan's geothermal potential areas. Such information will be useful to Taiwan in developing and applying shallow geothermal energy; at the same time, the information can be used to explore how heat is conducted underground with deep geothermal energy and prepare for the development of deep geothermal energy. If Taiwan can add 25-35 MW per year from shallow geothermal energy from 2025, and add 500-800 MW per year from deep geothermal energy from 2035, then by 2050, Taiwan's geothermal electricity capacity will reach 8.13-12.88 GW. Using a capacity factor of 80% and 300 operating days per year, the power generated can reach approximately 46.829 to 74.189 billion kilowatt-hours.

2.5 Summary

The production of hydrogen energy should adhere to the principle of not increasing carbon emissions. However, the cheapest hydrogen production method at present, natural gas steam reforming, also releases carbon dioxide (CO₂). Therefore, if hydrogen is produced from natural gas through natural gas steam reforming (blue hydrogen), it must be coupled with carbon capture, utilization, and storage (CCUS) technology. If hydrogen is produced directly from natural gas pyrolysis (turquoise hydrogen), although the technology is still under development, it presents a promising future (technical details are described in Section 2.6 Carbon-free Hydrogen Production). Producing hydrogen through water electrolysis using domestic green power (green hydrogen) requires consideration of the supply of domestic green power and the need for long-term energy storage. Only the green power that cannot be used immediately should be considered for storage through batteries, pumped storage hydropower, and hydrogen production via water electrolysis. Currently, we are still in the stage of expanding renewable energy, and the supply of green power is not sufficient to produce a large amount of green hydrogen yet. In the future, if there is a need for energy storage, the different viable options should be compared for propriety.

Hydrogen can be used by blending it with natural gas for combustion to generate power, with the potential for transitioning to pure hydrogen to replace natural gas in combustion in the future, or by utilizing fuel cells for power generation. Hydrogen fuel cells can also be used in vehicles such as long-haul trucks and buses. Nevertheless, their application in smaller vehicles encounters strong competition from electric vehicles and challenges in hydrogen refueling infrastructure. In addition, hydrogen has other applications in industrial processes such as steelmaking and hydrogenation. Considering various factors at play in our country, this Policy Proposal puts forward recommendations as follows:

1. Develop hydrogen-blended natural gas combustion power generation technology. In the past, the gas-fired power generation technology in Taiwan has mostly been package plant import. In the short term, the development of hydrogen-blended natural gas combustion power generation technology will still need to rely on the R&D experience of international giants. However, considering the increasing importance of hydrogen-blended or hydrogen-fired power generation technology in the coming decades, apart from introducing hydrogen-blended or

hydrogen-fired power generation equipment, we may try to develop small-scale hydrogen-blended or hydrogen-fired boilers and power generation equipment to enhance our capabilities and for industrial process application.

2. Import green hydrogen with reference to the collaboration model of Japan and Australia in place of certain portion of natural gas in power generation. (It is estimated to generate 57.5-108.4 billion kWh of power by 2050, with an installed capacity of 8.2-15.5 GW. See Appendix 2F for details)
3. Introduce and develop infrastructure and technologies related to hydrogen import, such as hydrogen receiving terminals and hydrogen storage materials.
4. Effectively utilize non-dispatchable (not immediately available in the short term) green power to produce green hydrogen domestically, optimize fuel cells, and develop related technologies for hydrogen applications in the steelmaking and petrochemical industries.

2.5.1 Preface

Hydrogen is an energy carrier⁷⁶, meaning that it can store energy derived from electricity, heat, or light. The end-use application of hydrogen requires conversion thereof into electricity, heat, or chemical energy.

If hydrogen is produced by electrolyzing water and used to generate electricity in the end, it can be considered a form of electrical energy storage. As such, its efficiency must compete with that of battery storage (see Section 2.11). The best efficiency for water electrolysis to produce hydrogen is 0.8⁷⁷, and the best efficiency for hydrogen power generation is 0.6. The overall energy conversion efficiency is thus less than 0.5, lower than the efficiency of lithium-ion battery (0.8-0.9). Nonetheless, hydrogen can be stored for a long period, while lithium-ion battery cannot. In terms of convenience and efficiency, batteries have an advantage in small vehicles and short-term energy storage.

However, hydrogen is more durable than the batteries currently available and has

⁷⁶ Hydrogen energy comes with the characteristics of zero pollution and zero carbon emissions. This is mainly because the product of “hydrogen” combustion is water, which is not only attributable to its zero carbon emissions, but also to the fact that the abundant water resources on Earth may in turn be utilized. Therefore, hydrogen energy is a recyclable clean energy source.

⁷⁷ The efficiency of hydrogen production via water electrolysis (lower heating value) is projected to be 64% based on the International Energy Agency (IEA) parameters, with an estimated value of 69% by 2030 and a long-term outlook of up to 74%. Please refer to IEA (2019). *IEA G20 hydrogen report: Assumptions*. https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf

a higher energy density by weight [with a lower heating value (LHV)⁷⁸ of 120 MJ/kg (compared to 0.97 MJ/kg of lithium battery⁷⁹, 44 MJ/kg of gasoline⁸⁰, 26.95 MJ/kg of ethanol, and 47.13 MJ/kg of natural gas⁸¹)], but it has a disadvantage in terms of volume. The advantage of high energy density is manifested in long-haul transportation, so hydrogen-powered trucks are still regarded as promising.

Compared to hydrogen energy (see Section 2.11), even though batteries have lower short-term costs and are easy to charge and discharge, their lifespan decreases over time, making them more expensive for long-term energy storage. Hydrogen energy, on the other hand, is suitable for large-scale, long-term storage scenarios⁸². However, hydrogen can penetrate the lattice of various metals, leading to hydrogen embrittlement. Therefore, special materials are required for hydrogen storage containers and pipelines. Also, their safety and stability must be carefully managed. Hydrogen storage requires high pressure as well, which further increases energy consumption costs. Due to the current green power deficit in Taiwan, the feasibility of long-term energy storage is not optimistic in the preliminary assessment. However, if there is a need for long-term (>1 week) energy storage, water electrolysis to produce hydrogen is a possible option. For short-term energy storage (1-3 days), batteries are currently more efficient and cost-effective.

Importing green hydrogen from countries with abundant green power, such as Australia, is perhaps a viable option. If hydrogen fuel is employed in place of fossil fuels for the power system, a significant proportion of baseload power can be maintained, preventing the growth of other non-baseload renewable energy sources from destabilizing the transmission grid.

⁷⁸ The lower heating value (also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C.

⁷⁹ The current maximum energy density designed for the commercially available lithium-ion batteries is 250-270 Wh/kg, equivalent to approx. 0.97 MJ/kg. Please refer to ASME (2021). Advancing battery technology for modern innovations. <https://www.asme.org/topics-resources/content/advancing-battery-technology-for-modern-innovations>

⁸⁰ Shadidi, B., Najafi, G., & Yusaf, T. (2021). A review of hydrogen as a fuel in internal combustion engines. *Energies*, 14(19), 6209. <http://dx.doi.org/10.3390/en14196209>

⁸¹ Retrieved from H₂ Tools. <https://h2tools.org/hyarc/calculator-tools/lower-and-higher-heating-values-fuels>

⁸² The study of the National Renewable Energy Laboratory (NREL) suggests that by 2050, storing hydrogen for two weeks is expected to be cost-effective. Also, hydrogen is the first viable option for seasonal storage (up to 1.5 USD/kWh in 2050) as well. See pv magazine (2020). NREL study backs hydrogen for long-duration storage. <https://pv-magazine-usa.com/2020/07/03/nrel-study-backs-hydrogen-for-long-duration-storage/>

If the end-use application of hydrogen is to generate heat for industries like the chemical, steelmaking, and cement industries, it is more efficient than batteries. If it is used as a chemical reducing agent for purposes like steelmaking, chemical reactions of hydrogenation, and extreme ultraviolet lithography (EUV) in the semiconductor industry, hydrogen presents its unique necessity. As for the direct production of hydrogen through photocatalytic water splitting, it is still in the early stage of research that requires further assessment on whether the green energy in Taiwan is sufficient to meet the demand (Box 2.5.1).

Box 2.5.1 How Green Is Hydrogen?

Hydrogen produced using green power is referred to as green hydrogen. With the hydrogen production technology currently available, 1 kilowatt-hour (kWh) of electricity can produce 0.02 kg of hydrogen. If such hydrogen is used for power generation through combustion (with 60% efficiency), it can generate 0.48 kWh of electricity. At present, the average carbon emissions per kWh of electricity generated in Taiwan is about 0.5 kg. Thus, 0.48 kWh of electricity is equivalent to 0.24 kg of carbon emissions. Therefore, using green hydrogen for power generation can save 0.24 kg of carbon emissions. However, if green power is used directly in lieu of coal-fired or gas-fired power generation, it can save 0.9 kg or 0.4 kg of CO₂, respectively. Hence, the most efficient way to utilize green power is a direct use thereof to replace coal-fired or gas-fired power generation.

Only when there is excess green power that cannot be used immediately, should it be stored long-term by means of hydrogen production. Nevertheless, batteries remain the most efficient method for short-term energy storage. The issues of hydrogen storage are still to be taken into consideration for long-term storage using hydrogen. Green hydrogen can be used not only for power generation but also in industrial processes such as steelmaking, chemical reactions of hydrogenation, and extreme ultraviolet lithography (EUV) in the semiconductor industry. In addition, hydrogen can be used for transportation that cannot be electrified, such as long-haul transportation. With current technology, natural gas steam reforming is the cheapest pathway to hydrogen production, but the process also produces carbon dioxide. As such, it is not green hydrogen, which thus needs to be coupled with CO₂ capture technology to be “green”.

2.5.2 Current Landscape of International Development

The higher cost of producing hydrogen from renewable energy has led to its importance in carbon reduction being overlooked. However, the IEA report for the G20 summit in Japan in 2019 indicated that with the rapid decline in renewable energy costs and the expansion of hydrogen production scale, the cost of producing hydrogen from renewable energy could decrease by 30% by 2030⁸³. The IEA report in 2021 also predicted that in the Net Zero Emissions by 2050 Scenario (NZE Scenario), hydrogen production will entirely rely on low-carbon technologies, with water electrolysis accounting for 60% of global hydrogen production and the remaining 40% coming from natural gas production combined with CO₂ capture, utilization, and storage technologies⁸⁴. Besides, the Hydrogen Council's report in 2020, *Path to Hydrogen Competitiveness - A Cost Perspective*, suggested that by expanding hydrogen production, sales, and manufacturing of equipment and components, the cost of hydrogen solutions could be reduced by 50% through extensive applications by 2030. It also projected that hydrogen would meet approximately 18% of the global final energy demand by 2050⁸⁵. In 2019, the International Renewable Energy Agency (IRENA) estimated the average levelized cost of electricity (LCoE) for wind and solar energy in different regions worldwide, predicting that the cost of producing hydrogen from renewable energy will be lower than that from fossil fuels by 2035⁸⁶. On the ground of these trends, we can see that the importance of hydrogen will gradually increase over the next 30 years. By proactively planning and replacing a portion of energy generated from traditional fossil fuels in Taiwan with imported hydrogen, it will contribute to Taiwan's carbon reduction goal of Net Zero by 2050.

Many countries have identified hydrogen as a key to replacing fossil fuels in their power transition to a net-zero society. For example, the European Union (EU) released the EU Hydrogen Strategy in July 2020⁸⁷, with plans to utilize green hydrogen in hard-

⁸³ IEA (2019). *The future of hydrogen*. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

⁸⁴ *Ibid.*, note 錯誤! 尚未定義書籤。

⁸⁵ Hydrogen Council (2020). *Path to hydrogen competitiveness: A cost perspective*. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

⁸⁶ Science, Technology & Innovation Policy Outlook (2020). EU's competitive advantage in hydrogen energy and global hydrogen technology development. <https://outlook.stpi.narl.org.tw/index/focus-theme/detail?id=4b11410075b8452d0175d9e818381f39>

⁸⁷ EU (2020). *EU hydrogen strategy*. https://ec.europa.eu/commission/presscorner/detail/en/FS_20_1296

to-decarbonize sectors like heavy industry after 2030, increasing the share of hydrogen in the overall energy mix from 3% to 14%. The U.S. Department of Energy (DOE) recently released the Hydrogen Program Plan 2020, offering supporting strategies for hydrogen research, development, and demonstration in the U.S. The plan focuses on technological R&D, demonstration, and deployment of hydrogen across the entire industrial chain to achieve scale. In addition, *Road Map to a US Hydrogen Economy in 2020*, published by McKinsey & Company at the commission of a consortium of over 20 companies, projected that hydrogen could account for 14% of total U.S. energy consumption by 2050 (under the ambitious scenario)⁸⁸. In Japan, after its official declaration of transitioning to a hydrogen economy in 2014, Japan actively prepared various hydrogen-related demonstrations for the Tokyo 2020 Olympic Games. Despite the pandemic impact in 2021, the Olympic Games were successfully held, and some of the planned hydrogen targets were achieved⁸⁹. In addition, following the release of the growth strategy for net-zero emissions in 2050 in 2021 (Green Growth Strategy Through Achieving Carbon Neutrality in 2050), a new 2-trillion-yen fund was established to encourage private investment in hydrogen facilities⁹⁰, with an aim of 3 million tons of hydrogen installed by 2030, and an expansion to 20 million tons in 2050⁹¹.

Take Japan as an example, to achieve its target of net-zero emissions by 2050, JXTG, the largest petroleum conglomerate in Japan, recently (2019) conducted a trial using the solar power facilities of the Queensland University of Technology (QUT) in Australia as the power source. Water was electrolyzed to produce hydrogen, which then underwent an electrochemical reaction with toluene to form liquid organic hydrogen

⁸⁸ Fuel Cell and Hydrogen Energy Association (2020). *Road map to a US hydrogen economy*. <https://www.fchea.org/us-hydrogen-study>

⁸⁹ Originally, hydrogen was planned to be used as the energy source for the Olympic Village, fuel for shuttle buses between venues, and the Olympic torch at the Tokyo Olympic Games. Nonetheless, despite the partial impacts on the number of fuel cell buses and the use of hydrogen in the Olympic Village due to the COVID-19 impact, the original hydrogen application targets were mostly achieved. The hydrogen produced with the renewable energy from Fukushima was used for the Olympic cauldron. Yet, propane was used in combination with hydrogen for the torch relay. Please refer to Chuang, D. (2021). Did the Tokyo 2020 Olympic Games, with an aim for environmental protection, realize a hydrogen society? <https://technews.tw/2021/08/05/hydrogen-2020tokyo-olympics/>

⁹⁰ Department of International Cooperation, Ministry of Economic Affairs (MOEA) (2021). Specific actions taken by Japan to achieve net-zero emissions by 2050. Economic Division, Taipei Economic and Cultural Representative Office in Japan. https://mnscdn.moea.gov.tw/MNS/ietc/bulletin/Bulletin.aspx?kind=54&html=1&menu_id=33779&bull_id=8838

⁹¹ Cabinet Secretariat et al. (2021). Green growth strategy through achieving carbon neutrality in 2050. <https://www.meti.go.jp/press/2021/06/20210618005/20210618005-3.pdf>

(methylcyclohexane, MCH) for storage. The MCH was successfully shipped to Japan, where it was converted back into hydrogen and toluene. The hydrogen was used locally in Japan, while the toluene could be shipped back to Australia for reuse in the electrochemical reaction cycle. The trial serves as R&D testing for Japan's long-term import of green hydrogen from Australia in large quantities in the future^{92,93} (Figure 2.5.1).

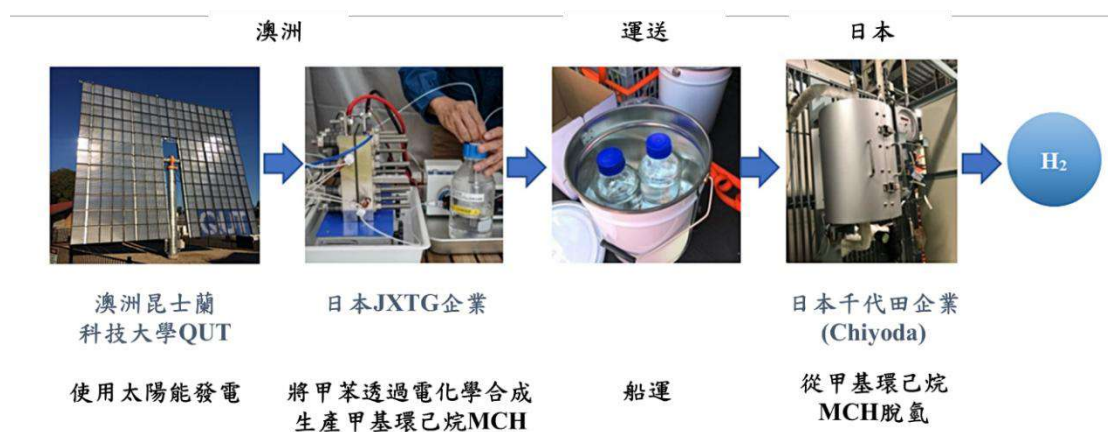


Figure 2.5.1 Japan and Australia's Collaborative Solar-Powered Hydrogen Production Project⁹⁴

Before that, Japan also had several other international collaborative projects in progress, including a joint liquid hydrogen project with Australia (the hydrogen supply chain project) to test Japan's ability to stably import liquid hydrogen from Australia for power generation. Hence, it involved producing hydrogen from water and lignite in Victoria, Australia, before liquification for transport. In addition, it also sought to store captured CO₂ beneath the seabed near Victoria through the "CarbonNet" project, aiming for commercial operation by 2030⁹⁵. In 2017, Japan's Kawasaki Heavy Industries, Ltd. and Norway's Nel Hydrogen partnered on a renewable energy-powered hydrogen production (power-to-gas) project. Hydropower was used to produce hydrogen, with the hope of eventually expanding to wind-powered hydrogen production and

⁹² pv magazine (2019). Queensland sends first green hydrogen shipment to Japan. <https://www.pv-magazine.com/2019/03/29/queensland-sends-first-green-hydrogen-shipment-to-japan/>

⁹³ QUT (2018). QUT leads new hydrogen pilot plant. <https://www.qut.edu.au/research/article?id=135488>

⁹⁴ Research Center for Advanced Science and Technology, The University of Tokyo (2019). Succeeded in the world's first technical verification to produce "CO₂-free hydrogen" at low cost -trial of hydrogen supply chain establishment and hydrogen based society. <https://www.rcast.u-tokyo.ac.jp/en/news/release/20190315.html>

⁹⁵ iKnow, Science and Technology Policy Research and Information Center, National Applied Research Laboratories (2020). The Japanese and Australian Governments collaborate on a hydrogen supply chain project with an investment of 350 million USD. <https://iknow.stpi.narl.org.tw/Post/Read.aspx?PostID=17195>

transporting the liquefied hydrogen to Japan⁹⁶. In terms of hydrogen transportation, Japan and Brunei are working on a demonstration project for hydrogen transport by means of MCH. Furthermore, Japan and Saudi Arabia were undertaking a joint demonstration project for ammonia-based hydrogen transport, so as to transport hydrogen produced in Saudi Arabia to Japan⁹⁷. The first shipment of ammonia (blue ammonia) to Japan under this project was completed in the fall of 2020.

2.5.3 Analysis of the Current Issues with the Hydrogen Energy Development in Taiwan

For a smooth transition to and deployment of carbon-free hydrogen energy in Taiwan, the top priority is to improve the planning of hydrogen energy supply chain and construction of the related infrastructure. This involves various elements, including the source, storage, transportation, and application of hydrogen, with challenges still to be addressed. In terms of technology, we still need to cultivate domestic hydrogen-blending/pure hydrogen combustion technology capabilities. The existing safe hydrogen storage and transportation technologies (including cross-border storage and transportation) are costly and energy-demanding, so it is necessary to strengthen the deployment of infrastructure and the development of storage and transportation technologies to make breakthroughs. On the policy front, although Taiwan has included hydrogen energy and fuel cell research and development planning in the National Energy Program (NEP) Phase I & II⁹⁸, enabling many domestic research institutions and developers to invest in fuel cell technology development, seemingly forming a prototype of an industrial value chain division. However, our country still lacks a long-term and comprehensive plan for various carbon reduction applications with hydrogen energy by 2050, such as power and industrial carbon reduction. Furthermore, complete legal and regulatory measures are required for hydrogen energy from production, storage, and transportation to application. Other issues include the need for a clearer definition of the application positioning of hydrogen energy to strengthen the willingness of industries in investment, and that the public still has concerns over the

⁹⁶ Nengyuanjie (2021). The strategies and implications from Japan's hydrogen energy development. <http://www.nengyuanjie.net/article/45067.html>

⁹⁷ Hellenic Shipping News Worldwide (2021). Blue ammonia's role in the energy transition of Saudi Arabia and Japan. <https://www.hellenicshippingnews.com/blue-ammonias-role-in-the-energy-transition-of-saudi-arabia-and-japan/>

⁹⁸ National Science Council, Executive Yuan (2013). Master Plan for the National Energy Program Phase II (Approved Version).

safety of hydrogen energy use and some toxic chemicals used as hydrogen storage carriers, requiring improvement to the regulations and standards for the handling of related chemicals. It is worth noting that the use of renewable energy to produce green hydrogen in Taiwan, with few exceptions, presents less benefit than a direct use of green power produced by renewable energy. It is more appropriate to store the green power that cannot be used immediately in the short term in batteries or pumped storage hydropower⁹⁹. In addition, due to the lack of green power domestically, it is still necessary to consider the option of green hydrogen import, such as the current Japan-Australia hydrogen collaboration model.

2.5.4 Assessment of the Potential and Limitations of Hydrogen Energy Development in Taiwan

The verification of hydrogen energy's application potential mainly necessitates the consideration of the possibility and feasibility of the complete integration of all elements in the entire hydrogen energy supply chain. Generally speaking, the hydrogen energy supply chain can roughly fall into stages like hydrogen sources, hydrogen storage, hydrogen transportation, and application (Figure 2.5.2). Different alternative options can be selected and combined for each stage to verify the feasibility of the final application. Especially from the perspective of infrastructure construction costs, it is best to use hydrogen as soon as it is produced, such as producing hydrogen directly next to a thermal power plant, which saves storage and transportation costs without going through hydrogen storage or transportation stages. One possible option is to produce hydrogen directly from carbon-free natural gas pyrolysis for direct power generation (see Section 2.6 Carbon-free Hydrogen Production).

⁹⁹ In addition to a pure energy storage, domestic scholars have also proposed a systematic integration of renewable energy and water resources, including pumped storage hydropower, solar energy, wind energy, desalination plants, and reservoirs, to achieve the synergetic benefits of resolving both the intermittency of renewable energy and the water scarcity under climate change. For reference, see Tsai, Y. C., Chan, Y. K., Ko, F. K. & Yang, J. T. (2018). Integrated operation of renewable energy sources and water resources. *Energy Conversion and Management*, 160, 439-454. 10.1016/j.enconman.2018.01.062

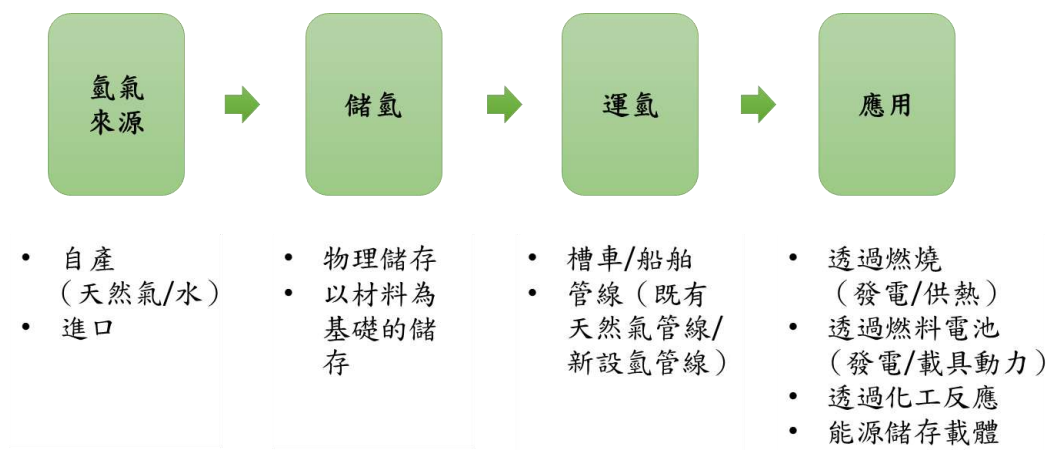


Figure 2.5.2 Stages and Alternative Options on the Hydrogen Energy Supply Chain

The analysis and assessment of the potential applications with hydrogen and the limitations in each stage of the hydrogen energy supply chain are as follows.

1. Applications of Hydrogen Energy and Carbon Reduction Potential

The applications of hydrogen energy can fall into six categories, as shown in Table 2.5.1. Categories (1) and (2) primarily involve the direct combustion of hydrogen or the combustion blended with natural gas for power generation or heating purposes (e.g., in end-user consumption). Categories (3) and (4) utilize hydrogen as fuel for fuel cells, serving as a decentralized power source (e.g., for industrial or disaster preparedness) or for heavy-duty vehicles of long-haul transportation (heavy-duty trucks or vessels). Category (5) involves the application of hydrogen through chemical reactions in industrial processes, such as in the petrochemical or ICT industries. Category (6) employs hydrogen as an energy storage carrier for long-duration discharge.

Among the aforementioned applications, (1) hydrogen combustion for power generation, (2) hydrogen combustion for heating, and (4) hydrogen as fuel for fuel cells to power vehicles are the three applications with the greatest carbon reduction potential for Taiwan, which have had basic viable technologies available. However, Taiwan has not conducted systematic research or development in categories (1) and (2).

Table 2.5.1 General Applications of Hydrogen

Category	Direct Application Pathway	End-use Application
(1)	Direct combustion	Power generation
(2)	Blended with natural gas for combustion	Heating
(3)	Fuel cells	Decentralized power source
(4)		Long-haul transportation (heavy-duty trucks & vessels ¹⁰⁰)
(5)	Chemical reactions	Industrial applications (e.g., the petrochemical and ICT industries)
(6)	Energy storage carrier	

In the applications of (1) and (2), since pure hydrogen produces only water and no CO₂ after combustion, using hydrogen for power generation or heating through combustion can contribute to carbon reduction. Most commercial gas turbine designs at present can handle fuels with a certain percentage of hydrogen. Therefore, before 2030, it is feasible to co-fire hydrogen with traditional fossil fuels (such as natural gas) (e.g., <10-60%), mainly because turbines burning pure hydrogen require special high-temperature resistant materials. However, major manufacturers currently have not yet commercialized large-scale turbines capable of burning pure hydrogen¹⁰¹. They are still mostly in the operational testing phase, so only co-firing is possible at present. The gas turbines burning pure hydrogen are expected to be commercialized around

¹⁰⁰ The New Energy and Industrial Technology Development Organization (NEDO) in Japan released a roadmap for fuel cell technology development in heavy-duty vehicles (HDVs) in March 2022. This roadmap lays out key specifications for 2030, particularly for coastal cargo ships and passenger ships that demand long operating hours. For reference, see NEDO (2022). NEDO fuel cell technology development roadmap - HDV fuel cell roadmap (manual). <https://www.nedo.go.jp/content/100944011.pdf>

¹⁰¹ Some manufacturers possess gas turbine models that can be retrofitted for 100% hydrogen combustion, such as GE's F-class combustion system. However, these systems still require further operational testing and have not yet reached the stage of large-scale commercial deployment. For example, GE received funding from the U.S. Department of Energy in May 2022 to accelerate the development and testing of retrofittable F-class combustion systems capable of operation on 100% hydrogen using a combination of micro mixer and axial fuel staging technologies. For reference, see GE (2022). GE, DOE accelerating the path towards 100% hydrogen combustion in gas turbines. <https://www.ge.com/news/press-releases/ge-doe-accelerating-the-path-towards-100-hydrogen-combustion-in-gas-turbines>

2030^{102,103,104,105}. Therefore, it is expected that after 2030, there will be a gradual transition to ultimately achieve power generation or heating applications with pure hydrogen as fuel (in consideration of the long life cycle of existing power plants, which can reach up to 40 years, it is difficult to replace them instantly). For details of the efficiency of gas and hydrogen-fired power generation, please refer to Appendix 2G.

If the power sector uses hydrogen combustion for electricity generation, or carbon-intensive industries such as petrochemicals and steelmaking switch to hydrogen combustion for heating, it can reduce the use of fossil fuels and thus lower carbon emissions. However, the domestic pure hydrogen combustion technologies still need to be improved to meet the overall demand in the future. In the application of (4), hydrogen can be used as fuel for fuel cells to power vehicles, especially for long-distance, heavy-duty vehicles. For smaller vehicles, hydrogen faces direct competition from electric vehicles, while the current cost of fuel cell installation is relatively higher. Establishing extensively high-pressure hydrogen refueling stations domestically is challenging. However, hydrogen's ability to store energy for a longer period is advantageous compared to lithium battery storage. Therefore, in long-haul transportation or logistics, such as large container trucks and vessels, use of hydrogen to replace traditional fossil fuels is a feasible way to reduce carbon emissions.

In the application of (3), hydrogen is mainly used as the fuel for fuel cells to generate power when needed (e.g., in industry). This function is similar to other battery technologies and may lead to technical competition, but it can be developed towards long-term energy storage and discharge to achieve functional differentiation. In

¹⁰² European manufacturers claimed that turbines will be able to operate on 100% hydrogen by 2030. For reference, see Fairley, P. (2020). Is Renewable Energy Easy with Hydrogen? *Scientific American*. <https://sa.ylib.com/MagArticle.aspx?id=4835>

¹⁰³ GE plans to realize power plants to run 100% on hydrogen by 2030. Please see Simon, F. (2021). GE eyes 100% hydrogen-fuelled power plants by 2030. <https://www.euractiv.com/section/energy/news/ge-eyes-100-hydrogen-fuelled-power-plants-by-2030/>

¹⁰⁴ *The 11th Science and Technology Foresight: Delphi Survey of Japan* estimated that the technology for a 1-GW large-scale gas turbine power generation system operating on 100% hydrogen fuel will be technically feasible around 2030. For reference see NISTEP (2020). The 11th science and technology foresight: Delphi survey. https://nistep.repo.nii.ac.jp/?action=pages_view_main&active_action=repository_view_main_item_detail&item_id=6692&item_no=1&page_id=13&block_id=21

¹⁰⁵ Currently, New Fortress Energy (NFE) and GE are collaborating with the Long Ridge Energy Terminal in the U.S. to develop a GE 7HA.02 combustion turbine capable of co-firing 15-20% hydrogen. The goal is to gradually transition the turbine to be capable of burning 100% hydrogen over the next decade. Please refer to the NS Energy (2021). Gas turbines in the US are being prepped for a hydrogen-fuelled future. <https://www.nsenergybusiness.com/features/gas-turbines-hydrogen-us/>

addition, solid oxide fuel cells (SOFCs) have the potential for heat integration, which can improve energy efficiency. In the application of (5), hydrogen is mainly used in the industries through chemical processes, including the production of general chemical raw materials (such as ethylene glycol), the production of high value-added pharmaceuticals or chemicals as byproducts of hydrogen production, or as a reducing agent in the ICT industry. At present, according to the assessment, the demands from the electronics and steelmaking industries are higher, and the petrochemical industry can recycle byproduct hydrogen, with carbon reduction merely part of the goals. In the application of (6), hydrogen energy, thanks to its storage characteristics similar to pumped storage hydropower, has a higher energy density and longer discharge duration compared to other energy carriers. Therefore, internationally, it is considered that in scenarios with a high share of renewable energy (50% or more), hydrogen energy can assist in renewable energy storage and achieve lower energy loss. In large-scale and long-term storage, its cost can also be lower than those of batteries. However, this application is mainly aimed at storing surplus renewable energy to provide peak shaving and valley filling functions for power, so it offers limited support in actual carbon reduction. Nevertheless, the hydrogen produced from surplus renewable energy can be used to directly meet the needs of other applications and replace part of the imported hydrogen.

2. Sources and Possible Innovative Models of Hydrogen

The sources of hydrogen can be mainly divided into four types: (1) water electrolysis; (2) natural gas steam reforming; (3) byproducts in industrial processes; and (4) hydrogen import. All of these are technologies or business models that are available before 2030. In addition, there is the innovative technology of (5) methane pyrolysis (also known as methane cracking or carbon-free hydrogen production), which is an innovative way to reduce carbon emissions while producing hydrogen. However, it should be noted that the hydrogen used in 2050 must be green hydrogen, not traditional gray hydrogen or blue hydrogen¹⁰⁶. Moreover, the efficiency of using non-dispatchable green power for water electrolysis to produce hydrogen still has room for improvement, and the development of high-efficiency hydrogen production technologies should be actively pursued in the future.

¹⁰⁶ Hydrogen produced from steam reforming of fossil fuels (such as natural gas) is referred to as gray hydrogen; gray hydrogen produced with carbon capture technology to prevent CO₂ from being released into the atmosphere is referred to as blue hydrogen.

(1) Water Electrolysis

Water electrolysis for hydrogen production is the process of using electricity to split water into hydrogen and oxygen. The advantage of this method is that it does not produce carbon emissions during hydrogen production. However, the water electrolysis process demands energy input, and if the power source remains traditional fossil fuels, there will still be carbon emissions. Therefore, it is necessary to combine renewable energy sources as the power supply. Using renewable energy to power water electrolysis for hydrogen production is a clean and safe carbon-free energy option. However, compared to traditional steam reforming technology, the cost is higher, especially since the electrolysis process requires catalysts and consumes a large amount of power¹⁰⁷. Therefore, the cost of using renewable energy for electrolysis will depend on the electricity bill of renewable energy. In addition, the efficiency of electrolytic hydrogen production needs to be improved. Depending on the technology and load factor, the efficiency of current electrolysis systems ranges from 60% to 81%. Producing 1 kg of H₂ requires approximately 48-50 kWh of electricity. It is estimated that in order to replace the hydrogen energy currently produced exclusively from natural gas (69 Mt H₂) (excluding hydrogen as a byproduct of the process)¹⁰⁸, the power demand would reach 3,600 TWh (3.6 trillion kWh), exceeding the current annual power generated in the European Union¹⁰⁹. In addition to the high cost of hydrogen production from water electrolysis and the need to improve hydrogen conversion efficiency, the U.S. Department of Energy also mentions that research challenges to be overcome in water electrolysis for hydrogen production include reducing the capital cost of water electrolyzer equipment and achieving system balance, as well as understanding the degradation process of electrolyzers to develop mitigation strategies to extend their service life¹¹⁰.

¹⁰⁷ Compared with water electrolysis, methane pyrolysis is energetically much more economical. From a thermodynamic perspective, it takes only 37.5 kJ to produce 1 mole of H₂ with methane pyrolysis, whereas water electrolysis is 286 kJ/mol H₂. For reference, see Sánchez-Bastardo, N., Schlögl, R. & Ruland, H. (2020). Methane pyrolysis for CO₂-free H₂ production: A green process to overcome renewable energies unsteadiness. *Chemie Ingenieur Technik*, 92: 1596-1609. <https://doi.org/10.1002/cite.202000029>

¹⁰⁸ US DOE (2020). Hydrogen Strategy. https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf

¹⁰⁹ According to the statistics, it is estimated that it requires 52 TWh of power to produce one Mt of hydrogen (52 kWh/kg H₂). For reference, see IEA (2019). *The future of hydrogen*. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

¹¹⁰ Office of Energy Efficiency & Renewable Energy (2021). Hydrogen production: Electrolysis.

In addition to power demand, water is also required as a raw material for hydrogen production through electrolysis. It takes approximately 9 liters of water to produce 1 kg of H₂, along with 8 kg of oxygen generated as the byproduct. Assuming Taiwan aims to generate 14.7 billion kWh of electricity through hydrogen produced via water electrolysis, it is equivalent to 6.62 million m³ of water needed as feedstock. Based on Taiwan's approximately 18 billion m³ of water consumption annually, it will take up about 0.04% of the total water consumption per year, or 0.38% of industrial water consumption. Therefore, to elevate the scale of hydrogen production via water electrolysis, it is necessary to take the resulting water demand into account. At present, there are researchers exploring the use of seawater as a source for water electrolysis as well, but challenges remain in addressing potential corrosion damage and chlorine generation caused by seawater.

Although the cost of water electrolysis for hydrogen production remains relatively high, it is expected that by 2030, with the large-scale production with water electrolysis technology, it will gradually become cost-competitive. However, if we aim to produce hydrogen this way, we still need to continue to raise the percentage of power generated from renewable energy sources in Taiwan (such as having more than 50% of variable renewable energy) to make it more suitable for hydrogen production application.

(2) Natural Gas (Methane) Steam Reforming

It is by far the most mature, widely used, and efficient hydrogen production technology. It mainly uses fossil fuels as a source, reacting them at high temperatures to form carbon dioxide and hydrogen. However, the hydrogen production process with such technology still generates carbon emissions, requiring further assistance from technologies like Carbon Capture, Utilization and Storage (CCUS) to reduce carbon, making it not the most ideal hydrogen production method.

(3) Byproduct in Industrial Processes

In the past, industries like petrochemicals, steelmaking, paper, and chlor-alkali have produced hydrogen as a byproduct of their processes. While the steelmaking industry is estimated to produce 20 billion m³ (1.8 Mt) of hydrogen, the byproduct

contains a high level of impurities, which requires further purification¹¹¹.

(4) Innovative Business Models of Imported Hydrogen

In consideration of the limited amount of green power in Taiwan in the future, the amount of green hydrogen produced from renewable energy domestically will be limited and can only be used for power dispatching. Hence, only by direct import of green hydrogen can we increase our energy supply. To import hydrogen, we may refer to the commercial collaboration model between Japan and Australia. For instance, we can participate in the collaboration between Australia and Japan, transport green hydrogen from Australia to Taiwan in the same way as it is transported to Japan, so as to replace part of the natural gas originally imported from abroad to achieve carbon reduction. In addition, if hydrogen is imported, shipping and related technologies will be required for the transportation.

(5) Methane Pyrolysis

Also known as carbon-free hydrogen production, the process involves natural gas pyrolysis technology, which separates natural gas into hydrogen and solid carbon (pure carbon) under oxygen-free conditions. The hydrogen is then directly combusted for power generation. Since no CO₂ is produced in the reaction, and the carbon is separated into solid carbon before combustion, there are no CO₂ emissions. The technology has significant potential for research and development and carbon reduction. Yet, the technology has not yet reached the stage of commercialization. For more details, please refer to Section 2.6, Carbon-free Hydrogen Production of this chapter.

1. Possible Innovative Models for Hydrogen Storage/Transportation

(1) Means to Hydrogen Storage

Hydrogen has the highest energy per unit mass compared to other fuels. However, its low density at ambient temperatures results in lower energy per unit volume. Therefore, safe and advanced hydrogen storage methods with high energy density (high pressure and low temperature) are required to reduce storage and transportation costs¹¹². Hydrogen can be physically stored as a gas or liquid. Gaseous storage, however, often

¹¹¹ Taiwan Institute of Economic Research (2016). "Overall Plan for National Hydrogen Energy Development" *Final Report*. <https://ws.ndc.gov.tw/Download.ashx?u=LzAwMS9hZG1pbmlzdHJhdG9yLzEwL3JlbGZpbGUvNTY1Ny8yNzU1OC83NGEzZWVhYy0xNTgwLTQwYzktOGUxNy04Y2RiNzE0MDQ0OGMucGRm&n=5YWo5ZyL5oCn5rCr6IO955m85bGV5LmL5pW06auU6KaP5YqDLnBkZg%3D%3D&icon=.pdf>

¹¹² Office of Energy Efficiency & Renewable Energy (2021). Hydrogen storage. <https://www.energy.gov/eere/fuelcells/hydrogen-storage>

requires high-pressure cylinders, while liquid hydrogen storage requires low temperatures and high energy consumption. Another type is material-based hydrogen storage technologies, including adsorbents, chemical hydrogen storage materials (such as liquid organic hydrogen carriers and chemical hydrides), and metal hydrides. In particular, liquid organic hydrogen carriers, such as MCH, offer advantages of convenient transportation and low energy consumption, making them worthy consideration. Nonetheless, MCH is toxic and requires adequate safety measures. An alternative is to use ammonia, which has lower chemical toxicity.

(2) Hydrogen Transportation Method – Blended Hydrogen/Natural Gas Pipeline Transportation

Currently, the transportation of small amounts of hydrogen in Taiwan is mostly through high-pressure tank trucks. When it comes to large-scale hydrogen transportation, high-pressure pipelines are required. In addition to building gas transportation pipelines, research and demonstration of hydrogen storage and transportation materials are also necessary. Furthermore, due to the limited green power in Taiwan, the self-produced green hydrogen is expected to be small-scale in the short term. Thus, a more feasible application is to produce hydrogen near the user-end or inject it into natural gas pipelines nearby, replacing part of the natural gas supply for nearby plants or consumers. That requires construction of relevant infrastructure (pressurization) and pipelines from water electrolysis plant to natural gas pipeline. Natural gas pipelines can withstand approximately 25% or less hydrogen blends^{113,114}. The concentration above this level requires improvement to the pipeline materials.

¹¹³ The report of NREL, U.S., in 2013 assessed the potential risks (Risk = Frequency of Pipeline Failure × Probability of Ignition × Consequences of the Fire) associated with blending different concentrations of hydrogen into natural gas for transmission pipelines. It was found that a 25% hydrogen blend posed a risk profile similar to that of a 100% natural gas pipeline. Please refer to Melaina, M. W., Antonia, O. & Penev, M. (2013). *Blending hydrogen into natural gas pipeline networks: A review of key issues*. <https://www.nrel.gov/docs/fy13osti/51995.pdf>

¹¹⁴ According to the International Energy Agency (IEA), among the EU Member States that allow hydrogen blending, the highest limit applies to Germany (10%), but only if there are no compressed natural gas filling stations connected to the network. Otherwise, the limits are Switzerland (2%), France (6%), Spain (5%), and Austria (4%). However, many jurisdictions have not yet allowed hydrogen to be blended into natural gas networks. See IEA (2020). *Current Limits on Hydrogen Blending in Natural Gas Networks and Gas Demand Per Capita in Selected Locations*. <https://www.iea.org/data-and-statistics/charts/current-limits-on-hydrogen-blending-in-natural-gas-networks-and-gas-demand-per-capita-in-selected-locations>

(3) Fuel Cells

Regarding the current development status in technologies related to hydrogen fuel cells in Taiwan, our NEP Phase I & II have included Proton Exchange Membrane Fuel Cells (PEMFCs) and Solid Oxide Fuel Cells (SOFCs) as part of their investment directions¹¹⁵. Domestic industries have also primarily focused on developing products/components pertaining to the two technologies. PEMFC manufacturers account for the majority, mainly developing small stationary systems. Meanwhile, the domestic SOFC component manufacturers have become major suppliers for Bloom Energy, a medium-to-large American fuel cell manufacturer¹¹⁶. Nevertheless, Taiwan still relies heavily on imports for core materials and components (such as membrane electrode assemblies, gas diffusion layers/electrodes, and proton exchange membranes) due to foreign patent restrictions¹¹⁷. In terms of market/industry, challenges remain, such as that the hydrogen fuel cell market has not fully formed, initial costs for equipment installation and fuel costs are relatively high, and that large-scale product promotion costs are also high. At present, the SOFC components suitable for centralized long-term power generation are mainly supplied to the international market. Fuel cell vehicles are still in the demonstration and verification stage, along with the lack of relevant infrastructure. Small passenger car markets face direct competition from electric vehicles^{118,119} (see 2.11 Energy Storage Analysis for further details). As such, Taiwan's fuel cell development strategy should prioritize the facet of industrial development, with the primary direction being to encourage domestic manufacturers to collaborate with international partners in establishing a fuel cell industry supply chain and to participate in the global market layout.

¹¹⁵ *Ibid.*, note 98.

¹¹⁶ Shih, H. L. (2021). Analysis of Taiwan fuel cell industry in 2021. IEKNet. https://ieknet.iek.org.tw/iekrpt/rpt_more.aspx?actiontype=rpt&indu_idno=5&domain=28&rpt_idno=512088239

¹¹⁷ Lan, C. H., Liu C. M., Huang S. Y., and Lee Y. J. (2013). The current status and trends of hydrogen energy and fuel cell industry development. Energy Knowledge Base. <https://km.twenergy.org.tw/ReadFile/?p=KLBase&n=20137309317.odt>

¹¹⁸ *Ibid.*, note 111.

¹¹⁹ CTCI Foundation (2016). *Analysis of international and domestic hydrogen energy application development and promotion policies*. <https://www.ctci.org.tw/8838/publication/10798/15783/>

2.5.5 Policy Recommendations

1. Develop Technologies Related to Hydrogen-Blended Natural Gas Combustion for Power Generation

In terms of technological development directions prior to 2030, the existing gas turbine designs can already tolerate a certain proportion of hydrogen blending (<10~60%)¹²⁰. Gas turbines that burn pure hydrogen still need further development, and key components required for high-concentration hydrogen combustion shall be tested. Large-scale commercialization of pure hydrogen combustion has not been achieved yet. Hence, it is necessary for Taiwan to plan, develop, and test hydrogen-blended natural gas combustion power generation technologies. In the short term, for example, a blend of 10%-20% hydrogen may be introduced into natural gas for power generation to help improve combustion efficiency and reduce carbon emissions in the power generation process. Previously, the gas-fired power generation technologies in Taiwan have mostly relied on package plant import. For hydrogen blended natural gas combustion power generation technologies, we still need to rely on the R&D experience of international giants. However, considering the increasing importance of hydrogen-blended or hydrogen-fired power generation technology in the coming decades, apart from introducing hydrogen-blended or hydrogen-fired power generation equipment, we may work on developing small-scale hydrogen-blended or hydrogen-fired power generation equipment to enhance our capabilities, which can be made available for industrial process application as well.

2. Import Green Hydrogen with Reference to The Collaboration Model of Japan and Australia in Place of Certain Portion of Natural Gas in Power Generation

At present, Japan and Australia have successfully tested and demonstrated the process of producing hydrogen via water electrolysis in Australia, storing it in the form of liquid organic hydrogen, and shipping it to Japan. The process is ready for scale-up once the cost of green hydrogen drops significantly. In addition, Japan is a leading developer of the technologies related to liquid hydrogen import, such as receiving terminals and transport vessels. Taiwan's potential for producing hydrogen from surplus renewable energy is limited before 2030. Therefore, to enhance carbon reduction through the use of green hydrogen, the long-term import of green hydrogen must be

¹²⁰ Siemens (2020). Hydrogen power with siemens gas turbines: Reliable carbon-free power with flexibility.

taken into consideration. Since Taiwan is located between Japan and Australia, replicating the Japan-Australia collaboration model and importing green hydrogen via maritime transport across borders would be a collaboration model that presents more economically benefits.

3. Introduce and Develop Infrastructure and Technologies Related to Hydrogen Import, Such as Hydrogen Receiving Terminals and Hydrogen Storage Materials

For a smooth transition to and deployment of a carbon-free hydrogen energy in Taiwan, and replacement of part of natural gas with imported green hydrogen for power generation, the top priority is to improve the planning of the hydrogen energy supply chain and the construction of related infrastructure, including hydrogen receiving stations and hydrogen storage materials, which are crucial keys to the import of hydrogen to Taiwan. Nonetheless, the related research and development has been relatively in short supply in Taiwan, so we may introduce infrastructure and technologies related to hydrogen import through international partnerships to effectively facilitate the carbon reduction efforts in power generation and other fields domestically.

4. Effectively Utilize Non-Dispatchable (Not Immediately Available in the Short Term) Green Power to Produce Green Hydrogen Domestically, Optimize Fuel Cells, And Develop Related Technologies for Hydrogen Applications in the Steelmaking and Petrochemical Industries

Most of the hydrogen produced in Taiwan at present comes from grey hydrogen produced by natural gas steam reforming, which is the cheapest hydrogen production process. However, if we want to avoid increasing carbon emissions, it is necessary for us to combine it with CCUS technologies to make it green. If we produce green hydrogen through water electrolysis using domestic green power, we have to consider whether the supply of green power is sufficient to support the energy required for large-scale green hydrogen production. Since the direct use of green power is the most efficient, the green power that cannot be used immediately can be stored through batteries, pumped storage hydropower, and hydrogen production via water electrolysis. Although some domestic academic and research institutions have planned to invest in green hydrogen production technologies such as water electrolysis to produce hydrogen, they are more of small-scale electrolysis systems for hydrogen production and lack experience in integrating new hydrogen production systems into existing industrial applications. Also, there is still room for improvement for the conversion efficiency, so

we need to consider collaborating with major international manufacturers to effectively utilize non-dispatchable green power (that cannot be used immediately in the short term) to produce green hydrogen domestically.

Among the applications of hydrogen energy, the use of hydrogen as fuel for fuel cells to power vehicles, especially heavy-duty vehicles for purposes like long-haul transportation, is one of the applications with carbon reduction potential for Taiwan. Also, using fuel cells for distributed power generation can provide additional benefits such as backup power for industries or disaster preparedness. Currently, many domestic research institutions and businesses have invested in the basics for the development of fuel cell technologies, which can provide benefits for industrial development. In terms of technological research and development, it is recommended to strengthen the upstream key components and materials R&D to fuel the fundamental momentum of the domestic fuel cell development. In terms of industrial promotion, the main direction is to integrate the R&D capabilities of domestic fuel cell manufacturers internally, and to jointly establish fuel cell supply chains with international partners externally for global market layout.

In addition, hydrogen can also be used as a reducing agent chemically or for heat generation, and its efficiency is higher than that of batteries in the chemical, steelmaking, and cement industries. Nevertheless, there comes with the additional need for the design and development of hydrogen-fired boilers. There is a special necessity for hydrogen as a reducing agent for the purposes like steelmaking and chemical reactions of hydrogenation. Hence, we should introduce and develop hydrogen applications in the steelmaking and petrochemical industries.

2.6 Methane Pyrolysis

Summary

Methane pyrolysis involves splitting natural gas under anaerobic conditions, resulting hydrogen and solid carbon, with the hydrogen being used directly for power generation. This hydrogen produced through pyrolysis, is also known as Turquoise Hydrogen (Turquoise H₂) because the process does not produce carbon dioxide (CO₂), instead separating carbon in solid form before combustion, thus eliminating CO₂ emissions. The European Union recently approved the inclusion of low-carbon natural gas power generation (<270 g/kWh) as one of the options for sustainable energy investment by 2035. If carbon reduction through pyrolysis can be maintained, this method could become a "quasi-green" power source, potentially addressing the current severe shortage of green energy. The solid carbon produced can also serve as a backup energy source during emergencies, alleviating Taiwan's inadequate energy reserves. Despite the drawbacks of relying on imported natural gas and utilizing only 55% of its calorific value, this technology remains highly valuable for development. Necessary technological advancements include:

- developing natural gas pyrolysis technology,
- developing electric turbines that can run on a mix of natural gas and hydrogen,
- developing electric turbines that can run on pure hydrogen, and
- developing ways to use the solid carbon by product.

This approach can surpass the traditional mindset of post-combustion CO₂ capture, paving the way for the development of zero-carbon power technology more suitable for Taiwan.

While this technology has significant potential to be further researched as well as potential capacity to cut carbon emissions, it has yet to reach commercial viability, necessitating further refinement of technical details and technoeconomic analysis. Therefore, in view of Taiwan's situation, we recommend the following actions:

1. Developing various pyrolysis technologies to split natural gas into hydrogen and solid carbon, and perform technoeconomic evaluations for different models.
2. Developing hydrogen-mixed or pure hydrogen-fueled power generation equipment, including fuel cells.
3. Exploring utilization pathways for pure carbon, such as material applications, land reclamation, sequestration, or as an emergency fuel reserve.

4. Developing by 2035 natural gas pyrolysis technology (methane pyrolysis) to replace 2-5% of natural gas power generation capacity (2020 baseline) with mixed combustion power generation, redesign combustion systems for full hydrogen combustion power generation, and complete the transition by 2050.

2.6.1 Introduction

The anaerobic pyrolysis of natural gas, known in this proposal as methane pyrolysis technology, represents an innovative technology under development by both our institute and researchers around the world. This technology allows natural gas to be broken down under anaerobic conditions, producing hydrogen and pure solid carbon. Although natural gas is used as the source, the reaction results in solid carbon rather than gaseous carbon dioxide, thus eliminating CO₂ emissions. The hydrogen produced can be directly mixed with or eventually replace natural gas for power generation. Current laboratory-scale conversion yield exceeds 95%¹²¹. The pyrolysis process yields very pure carbon byproducts, which can be utilized as industrial raw materials for charcoal, carbon fiber, high-temperature resistant materials, elastomers, and electrodes, and can be developed into large-scale construction materials. Additionally, it can be processed into various sophisticated carbon structures, such as graphite, graphene, carbon nanotubes, and diamonds. The large amounts of carbon produced can be used for land reclamation, sequestration, or as emergency fuel reserves. The hydrogen produced from methane pyrolysis may also be directly mixed with natural gas for co-firing (below 20%) in existing gas turbines¹²², enhancing combustion efficiency and reducing carbon emissions during power production (Figure 2.6.1).

Although this technology has not yet reached commercial capability, it is progressing rapidly towards commercialization and has significant potential for further research. For instance, a study by Pöyry Management Consulting (UK) (2019) concludes that hydrogen production from methane pyrolysis will be highly cost-effective and easily scalable in the future. The study estimates that by 2050, the EU's

¹²¹ A study published in the journal *Science* in 2017 by researchers from the University of California, Santa Barbara (UCSB) demonstrated that catalytic molten metals can directly convert methane into hydrogen and carbon. Using a 27% Ni–73% Bi alloy at 1,065°C, the research achieved a 95% methane conversion rate. Please refer to Gao, Y., Wang, X., Corolla, N., Eldred, T., Bose, A., Gao, W. & Li, F. (2022). Alkali metal halide-coated perovskite redox catalysts for anaerobic oxidative dehydrogenation of n-butane, *Science Advances*, 8, 30. <https://www.science.org/doi/10.1126/science.aao5023>

¹²² Mitsubishi Power (2018) The hydrogen gas turbine, successfully fired with a 30% fuel mix, is a major step towards a carbon-free society. https://power.mhi.com/special/hydrogen/article_1

hydrogen power demand will be approximately 3,969 TWh (including power, industrial process/non-process heat, and transport), with the majority (55%, or 2,197 TWh) supplied by hydrogen from pyrolysis of natural gas. Hydrogen production through traditional natural gas reforming with carbon capture and storage (CCS) will account for 30% (1,163 TWh), while water electrolysis will only account for 15% (609 TWh), primarily because the study suggests that only in regions of the EU where renewable energy costs are extremely low, such as the Iberian Peninsula or Northern Europe, will water electrolysis be cost-competitive with the other two technologies¹²³.



圖 2.6.1 天然氣無氧裂解產氫與碳，以及混燒應用

Figure 2.6.1 Schematic of Methane Pyrolysis Producing Hydrogen and Solid Carbon, and Its Mixed Combustion Applications

According to the hydrogen economy impact model for natural gas (methane) anaerobic pyrolysis established by Weger et al. (2017), when natural gas leakage rates are low, utilizing anaerobic pyrolysis of natural gas to produce hydrogen and applying it in fuel cells (or direct combustion) can reduce global carbon dioxide emissions by up to 27%¹²⁴. Additionally, as reported by Sánchez-Bastardo et al. in 2021, the current integration of Carbon Capture and Storage (CCS) systems enables both natural gas

¹²³ Pöyry Management Consulting (UK) (2019). Hydrogen from natural gas: The key to deep decarbonization. https://agnatural.pt/folder/documento/ficheiro/565_zukunft_erdgas_key_to_deep_decarbonisation.pdf

¹²⁴ Weger, L., Abánades, A. & Butler, T. (2017). Methane cracking as a bridge technology to the hydrogen economy, *International Journal of Hydrogen Energy*, 42(1), 720-731. <https://www.sciencedirect.com/science/article/pii/S0360319916333213>

steam reforming and anaerobic pyrolysis of natural gas to achieve similar conversion efficiencies (60% vs. 58%) (Table 2.6.1)¹²⁵. However, recent advances in anaerobic pyrolysis of natural gas have been rapid. Furthermore, the deployment of CCS in Taiwan faces technical, economic, and social challenges that need to be addressed.

Table 2.6.1 Energy Efficiency of Methane Pyrolysis and Other Hydrogen Production Technologies (with CCS in the Right Column)¹²⁶

Technology	Energy Efficiency in Transformation (%)	Energy Efficiency with CCS (%)
Coal gasification	60	43
Steam methane reforming	75	60
Biomass gasification	35~50	
Thermochemical water splitting	20~45	
Water electrolysis	50~70	
Methane pyrolysis	58	58

¹²⁵ Sánchez-Bastardo N., Schlögl, R. & Ruland, H. (2021). Methane pyrolysis for zero-emission hydrogen production: A potential bridge technology from fossil fuels to a renewable and sustainable hydrogen economy. *Industrial & Engineering Chemistry Research*, 60(32), 11855-11881. DOI10.1021/acs.iecr.1c01679

¹²⁶ *Ibid.*, note 131.

When comparing hydrogen production costs and the lifecycle carbon footprint¹²⁷ of hydrogen production (using existing grid power), the unit cost of hydrogen production via methane pyrolysis is higher than that of hydrogen production via natural gas reforming but lower than that of water electrolysis. Regarding the carbon footprint of hydrogen production, methane pyrolysis has a lower carbon footprint compared to both natural gas reforming and water electrolysis (Figure 2.6.2).

It is important to note that natural gas comprises 90% methane (CH₄), a short-lived but highly potent greenhouse gas. In recent years, international attention has increasingly focused on methane emissions¹²⁸, particularly fugitive leaks in the upstream and midstream segments of the natural gas supply chain. Since methane pyrolysis still relies on natural gas as a raw material, future efforts must ensure the mitigation of fugitive emissions in order to reduce the carbon footprint of methane pyrolysis technology (Box 2.6.1).

Moreover, while natural gas reforming technology is already mature and water electrolysis for hydrogen production has been developed for some time, methane pyrolysis is still in the developmental stage, even though it holds great promise. If hydrogen produced from pyrolysis of natural gas can be classified as green energy, this pathway could represent the optimal model for generating green electricity. For further details, see Box 2.6.2, Box 2.6.3, and Box 2.6.4.

Box 2.6.1 Current Status and Trends in International Control of Methane Emission Leaks

Global methane emissions primarily originate from natural wetlands and human agricultural activities, with energy-related methane emissions accounting for approximately 23% of the total¹²⁹. Given the role of natural gas as a transitional energy source in the energy transformation of many countries, methane emissions from the energy sector are expected to increase. Methane emissions throughout the natural gas lifecycle occur predominantly during the upstream extraction and

¹²⁷ A carbon footprint refers to the total amount of greenhouse gas emissions generated by an activity or product throughout its entire life cycle. This includes all stages from raw material extraction, manufacturing, distribution and sales, usage, to disposal or recycling. (Source: Product Carbon Footprint Information Network, 2022, Introduction to carbon footprint - What is a carbon footprint)

¹²⁸ Tollefson, J. (2022). Scientists raise alarm over “dangerously fast” growth in atmospheric methane. *Nature*. https://www.nature.com/articles/d41586-022-00312-2?utm_source=Nature+Briefing&utm_campaign=d6c58c6a9d-briefing-dy-20220208&utm_medium=email&utm_term=0_c9dfd39373-d6c58c6a9d-44990377

¹²⁹ IEA (2020) *Methane Tracker 2020*. <https://www.iea.org/reports/methane-tracker-2020>

processing stages (44%), particularly due to high-pressure venting demands during processing. Midstream transportation accounts for 35%, and downstream regasification and distribution comprises 21%¹³⁰.

Historically, there has been a lack of effective means of monitoring and control for methane emissions and leaks within the natural gas production chain, leading to the potential underestimation of methane emissions from the energy sector¹³¹. This issue has garnered increasing international attention. In November 2021, during the COP26 summit, over 100 countries (including half of the top 30 methane-emitting countries, such as Brazil) endorsed the Global Methane Pledge¹³² initiated by the United States and the European Union. This initiative aims to reduce methane emissions from natural gas extraction, processing, storage, and distribution. The following are some of the measures being promoted include:

- In 2015, the U.S. Environmental Protection Agency (EPA) established methane emission standards, allocating \$30 million to develop low-cost but highly sensitive technologies to detect methane emissions in oil and gas systems. Companies are required to investigate methane leaks from storage tanks, pipelines, and extraction wells, with monthly inspections mandated for large facilities¹³³.
- The European Union established the European Network of Network Operators for Hydrogen, which plans to cease offering long-term contracts to natural gas operators without ways to reduce carbon emissions starting in 2050¹³⁴.
- Agencies such as the International Energy Agency (IEA) and the U.S. Environmental Protection Agency (EPA) recommended developing Leak Detection and Repair (LDAR) systems, establishing procedures for the detection and repair of natural gas pipeline equipment, and regulating

¹³⁰ IEA (2021). Driving down methane leaks from the oil and gas industry. IEA, Paris.

¹³¹ A.R. Brandt et al., (2014). Methane leaks from North American natural gas systems. *Science* 343:6172.

¹³² *Global methane pledge*. <https://www.globalmethanepledge.org/>

¹³³ U.S. White House (2015). FACT SHEET: Administration takes steps forward on climate action plan by announcing actions to cut methane emissions. <https://obamawhitehouse.archives.gov/the-press-office/2015/01/14/fact-sheet-Administration-takes-steps-forward-climate-action-plan-anno-1>

¹³⁴ The EU hydrogen and decarbonised gas market package: Revising the governance and creating a hydrogen framework. <https://fsr.europa.eu/the-eu-hydrogen-and-decarbonised-gas-package-revising-the-governance-and-creating-a-hydrogen-framework/>

inspection frequencies and scopes. They also advocate for setting technical standards to govern methane emission standards for natural gas equipment¹³⁵.

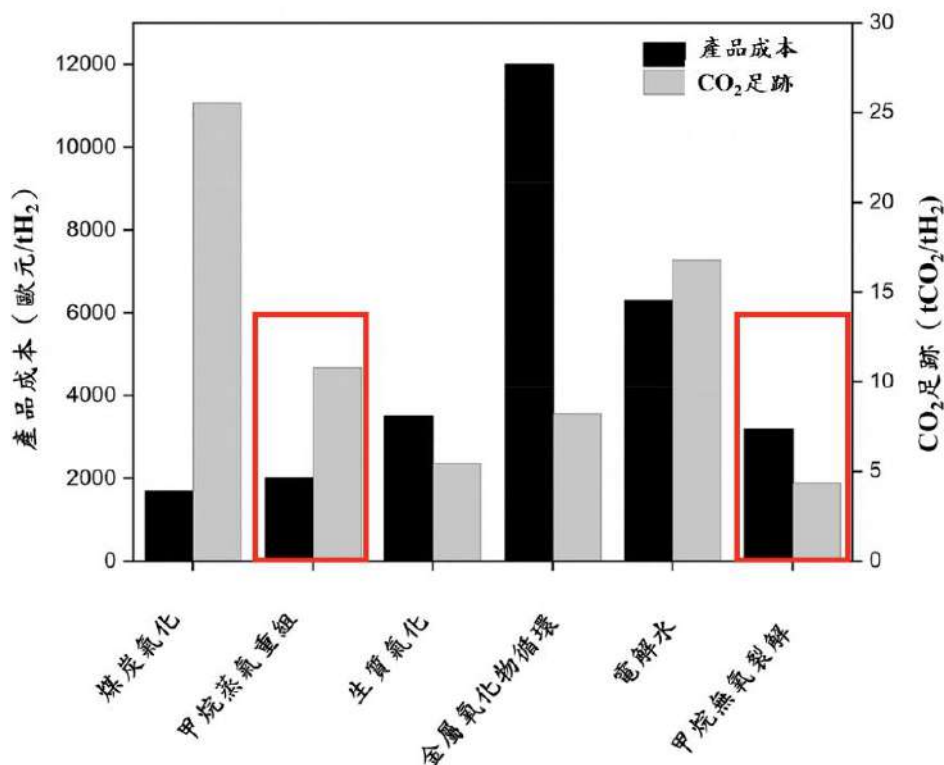


Figure 2.6.2 Costs and Lifecycle Carbon Footprints of Hydrogen Production Technologies^{136,137}

¹³⁵ EPA (2007) Leak detection and repair: A best practices guides.

¹³⁶ *Ibid.*, note 131.

¹³⁷ The life cycle carbon footprint of hydrogen production through water electrolysis and metal oxides looping primarily originates from the carbon emissions associated with existing grid electricity production. In contrast, the carbon emissions from the pyrolysis of natural gas include not only those from grid electricity production but also emissions from the extraction and transportation of natural gas. Although methane leakage from natural gas can result in a higher carbon footprint over the entire life cycle, this leakage can be mitigated through comprehensive infrastructure and effective leak detection and repair. Therefore, in the future, Taiwan can avoid related carbon emissions by requiring natural gas-producing countries to certify that there is no methane leakage during the extraction process.

Box 2.6.2 Optimal Utilization of One Kilowatt-Hour of Green Electricity

When one kilowatt-hour (kWh) of green electricity is available, it can be utilized in several ways:

1. **Direct Use:** Replacing carbon-emitting power.
2. **Storage for Later Use:** Stored in batteries or other energy storage devices for later use.
3. **Hydrogen Production via Water Electrolysis for Power Generation:** Electrolyzed water to produce hydrogen, which is used to generate power.
4. **Hydrogen Production via Water Electrolysis for Heat Generation:** Electrolyzed water to produce hydrogen, which is used to generate heat.
5. **Methane Pyrolysis for Hydrogen and Solid Carbon Production, Followed by Power Generation:** Anaerobic pyrolysis used to produce hydrogen and solid carbon from natural gas, and then use hydrogen for power generation.
6. **Pumped Hydro Storage for Later Power Generation:** Pumped hydro storage used to store energy for later power generation.

By directly using green electricity to replace power from natural gas or coal, CO₂ emissions can be reduced by 0.45 kg and 0.9 kg, respectively.

If immediate use is not possible, green electricity can be stored in batteries. With an efficiency of approximately 90%, one kWh of electricity becomes 0.9 kWh after storage¹³⁸. This would reduce CO₂ emissions by 0.41 kg and 0.81 kg compared to natural gas or coal. However, battery storage incurs costs and long-term storage is challenging.

Using one kWh of green electricity for water electrolysis, at the highest efficiency of 80%¹³⁹, can produce 0.02 kg of hydrogen. If this hydrogen is used to generate electricity with a maximum efficiency of 60%, it can produce 0.48 kWh of

¹³⁸ The carbon emissions per kilowatt-hour (kWh) for coal and natural gas are based on the greenhouse gas emission factors for thermal power units provided by Taiwan Power Company (2016 data) as shown in Table 2.1.2. The emission factor for coal is calculated at 0.9 kg CO₂ per kWh, while the emission factor for natural gas is set at half that of coal, at 0.45 kg CO₂ per kWh. However, as technology advances, these emission factors are expected to decrease further. For instance, the new combined cycle gas turbine units acquired by Taiwan Power Company in 2020 already achieve a generation efficiency of 64%, with potential for further improvement through future technological innovations. Additionally, the ultra-supercritical coal-fired units currently employed at Dalin Power Plant achieve a generation efficiency of 44.93%.

¹³⁹ *Ibid.*, note 83.

electricity. This would reduce CO₂ emissions by 0.21 kg and 0.43 kg compared to natural gas or coal. The efficiency of hydrogen production is low and hydrogen storage and transportation also present challenges. The advantage is the potential for long-term energy storage.

If hydrogen produced from one kWh of green electricity is used for heat generation to replace heat from natural gas, CO₂ emissions can be reduced by 0.16 kg¹⁴⁰. This assumes equal heat generation efficiency for natural gas and hydrogen combustion.

Using one kWh of green electricity for methane pyrolysis can decompose 0.6 kg (37.9 mol.) of natural gas into 0.151 kg (75.8 mol.) of hydrogen and 0.455 kg (37.9 mol.) of solid carbon. If the hydrogen is used for power generation with a maximum efficiency of 60%, it can produce 3.6 kWh of zero-carbon electricity. If this zero-carbon electricity is internationally recognized as green electricity, it would create a compounding cycle. The solid carbon produced can be used as industrial materials, construction materials, or for land reclamation. It can also serve as a backup energy source, addressing the issue of insufficient natural gas reserves.

Using one kWh of green electricity for pumped hydro storage, approximately 1.25 kWh of electricity is needed to pump water to generate one kWh of electricity later¹⁴¹. Therefore, one kWh of green electricity can yield 0.8 kWh of green electricity. This would reduce CO₂ emissions by 0.36 kg and 0.72 kg compared to natural gas or coal power generation.

¹⁴⁰ Using 1 kWh of green electricity for water electrolysis to produce hydrogen at the highest efficiency (80%), it is possible to generate 0.02 kg of hydrogen. Given that the higher heating value of hydrogen is 142 MJ/kg, the theoretical energy produced is 2.84 MJ. According to the 2020 statistics and analysis report on CO₂ emissions from fuel combustion by the Bureau of Energy, Ministry of Economic Affairs, the emission factor for imported natural gas in Taiwan is 56,100 kg CO₂/TJ (equivalent to 0.056 kg CO₂/MJ at 100% combustion efficiency). Assuming the combustion efficiency for both natural gas and hydrogen is the same (denoted as A), the actual heat energy produced by hydrogen combustion is $(2.84 \times A)$ MJ. The carbon emissions from natural gas combustion must be converted to $(0.056 \div A)$ kg CO₂/MJ. Therefore, the carbon emissions saved by the actual heat energy produced by hydrogen combustion $(2.84 \times A)$ MJ is calculated as $(2.84 \times A) \times (0.056 \div A)$ kg CO₂ = 0.16 kg CO₂.

¹⁴¹ Pumped storage hydroelectric power requires approximately 1.25 kWh of electricity to pump water in order to generate 1 kWh of electricity. Please refer to Sun Wenlin (2021). A new force for peak power backup: Deji Reservoir transforms into a large “energy storage battery”, aiming for operation by 2034.

Box 2.6.3 How to Achieve a "Compounding" Effect with Green Electricity?

Given Taiwan's current situation, where green electricity from wind and solar power is in short supply, utilizing one kilowatt-hour (kWh) of green electricity to pyrolyze natural gas (mainly methane, CH₄) can theoretically decompose 47.3 mol of methane into solid carbon and hydrogen. With an estimated efficiency of 80%, 37.9 mol. of methane can be decomposed into 37.9 mol. of solid carbon and 75.8 mol of hydrogen. Using this hydrogen for power generation, with an efficiency of 40-60% (via turbines or fuel cells), can produce 2.4-3.6 kWh of electricity.

Since hydrogen power generation does not emit carbon dioxide, the electricity produced through this pathway may be considered green electricity. This can be an effective method to "augment" green electricity, thereby addressing the shortage of green energy. The trade-off involves reliance on imported natural gas and utilizing only 55% of the calorific value of natural gas, which inevitably doubles the electricity production cost. However, when factoring in carbon prices, the cost difference will be reduced.

Box 2.6.4 Comparison of Water Electrolysis, Methane Pyrolysis (Decarbonized Hydrogen), and Steam Methane Reforming

The heat of combustion of hydrogen produced by water electrolysis ($2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$) theoretically equals the energy required for the electrolysis process. Even if the raw material cost is zero and the process has no losses, there is no added value. In practice, the efficiency of converting electricity to hydrogen and then back to electricity is below 50%. The advantage of this method is its ability to store energy for long-term, making it a viable energy storage option. However, issues related to hydrogen storage need to be resolved.

Methane pyrolysis requires only one-seventh of the energy needed for water electrolysis but needs methane as a source material. The energy contained in the hydrogen produced far exceeds the energy input required for the methane pyrolysis process, resulting in a net increase of usable zero-carbon energy. Additionally, the solid carbon produced can be used as an industrial raw material or as an emergency energy reserve. However, this method still relies on imported natural gas and produces less electricity. If the cost of natural gas is lower than the value of the

electricity produced, there is a net profit. Moreover, the electricity generated is green electricity. If the price of green electricity is more than twice the regular electricity price, this method is economically viable. Conversely, if natural gas prices soar and green electricity prices drop significantly, methane pyrolysis for hydrogen production and subsequent power generation will lose its competitiveness.

Another hydrogen production method is steam methane reforming, which has similar energy consumption and net energy gain to methane pyrolysis but produces a significant amount of carbon dioxide. To achieve net zero emissions, it requires carbon capture and storage (CCS).*

		Water	Methane	Steam
		Electrolysis	Pyrolysis (Decarbonized Hydrogen)	Methane Reforming
Raw Material		H ₂ O	CH ₄	CH ₄ , H ₂ O
Energy Input		2H ₂ O → O ₂ + 2H ₂	CH ₄ → C(s) + 2H ₂	CH ₄ + 2H ₂ O → CO ₂ + 4H ₂
Energy Required		572 kJ	76 kJ	126 kJ (per 2 moles of H ₂)
Energy Produced from H ₂ Combustion		2H ₂ + O ₂ → 2H ₂ O	2H ₂ + O ₂ → 2H ₂ O	2H ₂ + O ₂ → 2H ₂ O
		572 kJ	572 kJ	572 kJ
Net Energy Gain		572 - 572 = 0 kJ	572 - 76 = 496 kJ	572 - 126 = 446 kJ
Byproducts		None	Solid Carbon	Carbon Dioxide
Advantages		Hydrogen production, long-term energy storage	Green electricity production, load capacity	Mature technology, base hydrogen production
Disadvantages		No net green electricity gain	Relies on imported	Relies on natural

hydrogen issues	storage gas, needs refinement	technology gas, carbon capture and storage	requires

*Note: The values are theoretical and based on 2 mol. of H₂ as the reference.

2.6.2 Current International Developments

1. Pathways, Cases, Current Status, and Challenges of Methane Pyrolysis

There are currently three main pathways for developing methane pyrolysis: thermal decomposition, plasma decomposition, and catalytic decomposition (Figure 2.6.3).

Examples of thermal decomposition include the technologies developed by BASF and KIT/IASS in Germany, where reaction temperatures exceed 1,000°C. Plasma decomposition typically requires temperatures above 2,000°C and has been developed by Kvaerner in Norway and Monolith Materials in the United States. Catalytic decomposition has been developed by the Florida Solar Energy Center in the United States and Hazer Group in Australia, using catalysts to lower the reaction temperature below 1,000°C. Plasma decomposition and thermal decomposition are more advanced, currently at the pilot plant and production plant stages. In contrast, catalytic decomposition technology is at an earlier stage, somewhere between the laboratory and pilot plant phases¹⁴².

Type of Decomposition	Principle	Examples	Development Status (TRL)
Thermal Decomposition	Decomposition by heating the reactor walls to temperatures >1,000°C (Germany)	- BASF - KIT/IASS to large-scale research projects (TRL 3-4)	Laboratory-scale
Plasma Decomposition	Energy-dense plasma generation and high temperatures around 2,000°C	- Kvaerner (Norway) - Monolith Materials (USA)	Pilot plant to production plant stages (TRL 6-8)

¹⁴² Schneider, S., Bajohr, S., Graf, F. & Kolb, T. (2020). State of the art of hydrogen production via pyrolysis of natural gas. *ChemBioEng Reviews*, 7: 150-158. <https://doi.org/10.1002/cben.202000014>

Type of Decomposition	Principle	Examples	Development Status (TRL)
		- UOP, HYPRO process	
	Using catalysts to facilitate reactions at temperatures well below 1,000°C	Florida Solar Energy Center (USA)	Laboratory to pilot plant stages (TRL 3-4)
		- Hazer Group	

Figure 2.6.3 Current Development Status of Decarbonized Hydrogen Technology¹⁴³

2. Energy Consumption of Methane Pyrolysis

The challenge in developing decarbonized hydrogen technology primarily lies in energy consumption. The heat released from burning methane is 889 kJ/mole, but theoretically, only 76 kJ of thermal energy is required to decompose one mol (16g) of methane into two mol of hydrogen and one mole of carbon. The heat released from burning 2 mol of hydrogen is 572 kJ. Therefore, theoretically, the energy efficiency of methane pyrolysis for power generation can reach up to 59% of that of natural gas power generation¹⁴⁴, with the output being zero-carbon electricity. If the heat integration of power plants can be utilized, the efficiency can be further improved. For plasma pyrolysis, the efficiency of the plasma control systems must be increased. Currently, the energy consumption of methane pyrolysis is still higher than the theoretical value, but significant progress is expected in the coming years.

Comparing methane pyrolysis to burning natural gas plus carbon capture: if natural gas is directly used for power generation (assuming an efficiency of around 45%), approximately 0.44 kg of CO₂ is produced per kWh¹⁴⁵. Traditional carbon capture technology also requires substantial energy inputs. For example, using the calcium looping process for CO₂ capture, decomposing one mol of calcium carbonate

¹⁴³ *Ibid.*, note 148.

¹⁴⁴ Energy efficiency = $572 \div (889 + 76) = 59.2\%$

¹⁴⁵ The emission factor for imported natural gas in Taiwan is 56,100 kg CO₂/TJ. Since 1 TJ is equivalent to 277,778 kWh, the emission factor can be converted to 0.2 kg CO₂/kWh (under 100% combustion). If the power generation efficiency is 45%, then the CO₂ emissions per kWh would be $0.2 \div 0.45 = 0.44$ kg.

(CaCO₃) to release CO₂ requires 180 kJ, and the heat needs to be recovered to improve efficiency. Although heat recovery is feasible, it is complex in design and increases equipment investment costs. The captured CO₂ must be pressurized to a supercritical state for storage in geological formations, and the process also consumes considerable energy, while Taiwan lacks sufficient ready storage sites. Although some of the captured CO₂ can be converted into chemicals such as acetic acid, the quantity is insufficient to consume all of the CO₂ produced by Taiwan, with the remainder having limited utilization value.

In summary, from the perspective of energy consumption, storage, and reuse, methane pyrolysis is more efficient than burning natural gas with carbon capture, utilization, and storage (CCUS). However, methane pyrolysis is still in its early stages of development, and reaction efficiency needs to be improved. Additionally, suitable uses or disposal of the solid carbon by product need to be identified.

3. Using Carbon from Methane Pyrolysis

The carbon produced from methane pyrolysis is already “captured,” which is a significant advantage compared to the conventional CCUS (Carbon Capture, Utilization, and Storage) technologies, where carbon is in the form of gaseous CO₂ and must be pressurized to a critical state for geological injection.

Regarding potential applications for the carbon produced from methane pyrolysis, the Advanced Research Projects Agency-Energy (ARPA-E) of the U.S. Department of Energy has researched the market size and value of different types of carbon. High-value materials include graphene, diamonds, carbon nanotubes, and carbon fiber. Additionally, carbon can be used in larger quantities in industries such as cement, steel, aluminum, plastics, metallurgical coke, carbon black, graphite, and silicon carbide. For instance, graphene is highly valuable, up to \$100 million per ton, but the global market is less than 0.01 Mt. In contrast, the quantities of carbon used in the steel and plastics industries are larger, ranging from 100 to 1,000 Mt, with prices around \$1,000 per ton¹⁴⁶. As a raw material for cement, although the price of carbon is only about \$100 per ton, the volumes are much higher. Monolith Materials in Olive Creek, Nebraska, plans to use carbon from methane pyrolysis to produce carbon black for use in tires, industrial rubber, and specialty chemicals¹⁴⁷. C-Zero, a firm also in the U.S., is developing

¹⁴⁶ ARPA-E (2021). Methane pyrolysis for hydrogen: Opportunities and challenges. <https://www.energy.gov/sites/default/files/2021-09/h2-shot-summit-panel2-methane-pyrolysis.pdf>

¹⁴⁷ *Ibid.*, note 152.

technology to use carbon from methane pyrolysis in building structures, as detailed in Innovative Case 5 (1). Germany's BASF is exploring the use of carbon in steel and aluminum production, with positive test results¹⁴⁸.

However, given that methane pyrolysis can produce millions of tons of carbon annually, it is impractical to utilize all the carbon produced. Storage or sequestration methods include land reclamation or using carbon as a soil additive/environmental remediation agent. Since pure carbon is relatively stable, land reclamation is a viable option. Taiwan has experience in land reclamation, which could be evaluated for this purpose. The density of carbon is about twice that of water, allowing for potential permanent sequestration on the seabed, though the ecological impact must be further assessed. Adding carbon-based products to soil can improve seed germination, plant growth, and crop yield. If the carbon from methane pyrolysis can be used for soil improvement, it could positively impact plant growth. However, further research is necessary to verify its suitability for soil improvement and environmental purification, ensuring it does not negatively affect existing land and ecological systems¹⁴⁹.

The carbon produced can also serve as a reserve energy source, enabling carbon-based power generation during emergencies. This technical aspect can reference coal-fired power generation. For long-term use, integrating CCUS technology is necessary. In summary, unlike the current methods of converting gaseous CO₂ to storage that incur additional energy consumption, the utilization or storage of solid carbon has market value and represents a positive approach to carbon storage.

¹⁴⁸ ARPA-E (2021). Methane pyrolysis – A potential new process for hydrogen production with out CO₂ emission, BASF. ARPA-E methane pyrolysis annual program review virtual meeting. <https://arpa-e.energy.gov/sites/default/files/2021-01/16%20OK%20-%20ARPA-E%20Meeting%20Bode%20Flick%20Methane%20Pyrolysis%20web.pdf>

¹⁴⁹ *Ibid.*, note 131.

4. Issues and Challenges in Implementing Methane Pyrolysis

In summary, methane pyrolysis is more efficient than natural gas plus CCUS. However, the implementation of methane pyrolysis technology requires more detailed evaluation to confirm its feasibility from political, social, economic, technical, and environmental aspects. For example, although methane pyrolysis gas does not emit carbon, it still requires natural gas as a raw material. The amount of natural gas needed by methane pyrolysis to generate the same amount of electricity is higher than that for direct natural gas power generation. In 2020, the fuel input for natural gas power generation was approximately 14.26 million tons¹⁵⁰, generating 99.8 billion kWh of electricity¹⁵¹, which equates to 14,300 tons of natural gas per billion kWh. According to Appendix 2H, estimating the potential for hydrogen power generation via methane pyrolysis from a long-term net-zero emissions perspective by 2050, 38.88 million tons of natural gas could generate approximately 145.6 to 168.5 billion kWh of electricity, requiring 23,100 to 26,700 tons of natural gas per billion kWh, which is 1.6 to 1.9 times that of traditional natural gas power generation.

Therefore, using methane pyrolysis for power generation may increase Taiwan's reliance on natural gas imports, making it less favorable for achieving energy security goals such as diversification of energy consumption. Additionally, because the amount of natural gas required for anaerobic pyrolysis to produce the same amount of electricity is 1.6 to 1.9 times that of traditional natural gas power generation, the raw material cost (excluding revenue from carbon by-products and the cost of new fixed assets required for methane pyrolysis) will also increase, necessitating a rise in electricity prices. However, if future carbon pricing and the development of various uses for carbon can increase revenue, methane pyrolysis technology still has the potential to become competitive compared to traditional natural gas power generation.

Technically, methane pyrolysis requires high operating temperatures above 1,000°C. Therefore, the design and use of pyrolysis furnaces must consider potential corrosion effects from high-temperature reactions and develop suitable materials to ensure the safety of the reaction. Regarding environmental feasibility, as previously discussed, carbon storage or sequestration methods must undergo comprehensive

¹⁵⁰ Ministry of Economic Affairs Energy Bureau Energy Statistics Section (2022). Fuel inputs for power generation. <https://www.esist.org.tw/Database/Search?PageId=5>

¹⁵¹ Ministry of Economic Affairs Energy Bureau Energy Statistics Section (2022). Power generation data. <https://www.esist.org.tw/Database/Search?PageId=3>

ecological impact assessments.

5. Innovative Cases of Methane Pyrolysis

(1) **Catalytic Molten Metal.** University of California Santa Barbara (UCSB) has developed a catalytic molten metal technology for methane pyrolysis, using catalytic molten metals (27% Ni-73% Bi alloy) to achieve a 95% methane conversion rate at 1,065°C. In 2021, a UCSB spin-off company, C-Zero, received a \$11.5 million investment¹⁵² from Breakthrough Energy Ventures. Additionally, ARPA-E funded a project involving C-Zero, MIT, Stanford, and other universities looking at uses for the carbon created from methane pyrolysis. This project demonstrated the use of carbon to replace minerals and metals in building structures and thermoelectric systems. The goal is to develop carbon-based houses using carbon nanotubes (CNTs), threads, and sheets^{153,154}.

(2) **BASF.** In Germany, the chemical company BASF and partners are involved in a project funded by the German Federal Ministry of Education and Research (BMBF) to develop a test methane pyrolysis reactor. They have constructed and launched the reactor in Ludwigshafen^{155,156}. The plan is to start a pilot plant by 2025 and begin large-scale production by 2030.

(3) **Monolith Materials' Plasma Torch.** Monolith Materials in the United States employs plasma decomposition technology, using 100% renewable energy to perform methane pyrolysis with a plasma torch. This technology converts renewable natural gas (RNG) or renewable biogas into carbon and hydrogen, achieving net negative emissions. The plant is expected to be operational by 2024, becoming the world's largest methane pyrolysis facility¹⁵⁷.

(4) **Academia Sinica.** To reduce pollution from coal-fired power generation, Taiwan has increased its proportion of power generation using natural gas to 40%.

¹⁵² C-Zero (2021). Greentech Media: C-Zero raises \$11.5M to scale up “turquoise hydrogen”. <https://www.czero.energy/post/greentech-media-c-zero-raises-11-5m-to-scale-up-turquoise-hydrogen>

¹⁵³ ARPA-E (2020). Massachusetts Institute of Technology (MIT)- CarbonHouse. <https://arpa-e.energy.gov/technologies/projects/carbonhouse>

¹⁵⁴ *Ibid.*, note 152.

¹⁵⁵ BASF (2020). Climate protection with carbon management. <https://report.basf.com/2020/en/managements-report/responsibility-along-the-value-chain/environmental-protection-health-and-safety/carbon-management.html>

¹⁵⁶ BASF (2021). New technologies. <https://www.basf.com/hk/en/who-we-are/sustainability/we-produce-safely-and-efficiently/energy-and-climate-protection/carbon-management/innovations-for-a-climate-friendly-chemical-production.html>

¹⁵⁷ *Ibid.*, note 152.

However, the combustion of natural gas ($\text{CH}_4 + \text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$) still releases greenhouse gases such as CO_2 . Academia Sinica's Alpha Decarbonization Project aims to remove carbon from natural gas (methane) before combustion ($\text{CH}_4 \rightarrow \text{C} + 2\text{H}_2$), leaving clean hydrogen for power generation to achieve net-zero emissions. The technology pathways include thermal decomposition, plasma decomposition, and catalytic decomposition, each with its advantages, disadvantages, and challenges. Although international research on methane pyrolysis methods for high-purity hydrogen production has a long history, achieving large-scale commercial decarbonization has not yet been possible. Over the past year, the Alpha Decarbonization Project has tested all three anaerobic pyrolysis technologies, accumulating experimental data (Figure 2.6.4) and progressing to Technology Readiness Level 3 (TRL 3; i.e. laboratory R&D). The next step is TRL 4, involving prototype testing and validation in a lab environment. Despite only conducting a year of research, Academia Sinica has reached international standards and hopes to collaborate with industry to test optimal conditions for integrating natural gas power generation units. The goal is to achieve commercial



operation as soon as possible to help Taiwan achieve net-zero emissions by 2050.
Figure 2.6.4 Results of Carbon Production from Methane Pyrolysis by Academia Sinica¹⁵⁸

¹⁵⁸ Provided by the Alpha Decarbonization Project Research Team at Academia Sinica.

2.6.3 Policy Recommendations

1. Develop Various Methane Pyrolysis Technologies and Conduct Techno-Economic Evaluations of the Different Models

The three main pathways for methane pyrolysis—thermal, plasma, and catalytic decomposition—each have their advantages and challenges. Regardless of the method, the byproduct is very pure powdered carbon, which does not result in carbon emissions. Thus, research and development should be accelerated to commercialize these technologies. The hydrogen produced can be mixed with or eventually replace natural gas for power generation, while the powdered carbon byproduct can be used in material applications or stored. However, developing these various models will require additional energy. Therefore, related technological investment decisions should be based on comprehensive techno-economic evaluations, including energy consumption, carbon reduction benefits, and the technical and economic feasibility of various applications to select the most suitable application fields for Taiwan's development of methane pyrolysis.

2. Develop Mixed or Full Hydrogen Power Generation Equipment

Hydrogen produced from methane pyrolysis can be directly mixed with natural gas for co-firing with below 20% up to 60% hydrogen in existing gas turbines, improving combustion efficiency and reducing carbon emissions in the short term. It is anticipated that pure hydrogen-burning gas turbines will mature around 2030, allowing hydrogen power generation to gradually replace traditional fossil fuel power generation, significantly reducing carbon emissions. Therefore, while developing various methane pyrolysis technologies, it is necessary to also introduce or develop power generation equipment that can run on mixed or pure hydrogen. Furthermore, with the EU recently including low-carbon natural gas power generation (less than 270 g/kWh) as a sustainable energy investment option by 2035, continuous carbon reduction in decarbonized hydrogen technology may qualify it as a "quasi-green" power source, helping address the current severe shortage of green electricity.

3. Develop Pathways for Pure Carbon, Including Materials, Land Reclamation, Sequestration, or as a Backup Emergency Fuel

The powdered carbon byproduct from methane pyrolysis can be directly stored or used, which is a major advantage compared to the gaseous CO₂ captured by conventional CCUS technologies that must be pressurized to a critical state for

geological injection. Given the potential annual production of millions of tons of carbon from methane pyrolysis, planning and developing utilization pathways for pure carbon is crucial. Pure carbon is relatively stable and can be used in various material applications, such as industrial raw materials, advanced materials, and construction materials. Large quantities can be considered for land reclamation, permanent seabed storage, or as a backup fuel. However, the ecological impact of land reclamation and permanent seabed storage must be evaluated.

4. Develop Methane Pyrolysis Technology to Partially Replace Natural Gas Power Generation by 2030 and Transition to Full Hydrogen Power Generation by 2050

International projections estimate that pure hydrogen gas turbines will be ready around 2030. To achieve the 2050 net-zero emissions target, it is recommended to develop methane pyrolysis technology so that it can replace 2% to 5% of natural gas power generation (based on 2020 levels) by co-firing with natural gas by 2035. As methane pyrolysis technology matures and costs decrease significantly, and as power generation devices are gradually replaced with pure hydrogen turbines, the transition to full hydrogen power generation by 2050 can be realized.

Looking at the natural gas requirements for this policy, in 2021, Taiwan imported 19.44 million tons of natural gas. Assuming twice this amount for power generation by 2050, 38.88 million tons of natural gas could be needed for methane pyrolysis. At an 80% pyrolysis efficiency, 38.88 million tons of natural gas could produce 168.5 billion kWh of net electricity; at 60% efficiency, it could produce 145.6 billion kWh. Thus, the estimated full hydrogen power generation potential for 2050 is 145.6 kWh to 168.5 billion kWh. With a power plant capacity factor of 0.8, the required installed capacity would be approximately 20.8 GW to 24.0 GW (see Appendix 2H for details).

2.7 Biomass Energy

Summary

Biomass energy broadly refers to the energy obtained directly from or by somehow converting biomass. Since biomass is derived from materials that convert carbon dioxide from the atmosphere through photosynthesis, such as wood and sugarcane, burning biomass to produce heat is viewed as a carbon-neutral cycle. This is why biomass energy is considered a low-carbon energy option and a crucial pathway for many countries to achieve net-zero emissions. To develop biomass energy into a stable baseload power option, an alternative transportation fuel, and even a carbon sink, our country must use technology to overcome its low energy efficiency and Taiwan's limited feedstocks. The following angles are recommended for further development:

1. Development of New Technologies: (1) Utilizing pyrolysis technology to gasify biomass feedstock into hydrogen for power generation and solid carbon for sequestration, creating a carbon sink. (2) Employing biotechnology to enhance photosynthesis and single-carbon source utilization efficiency to increase the production efficiency of biological carbon sequestration, chemicals, and biofuels (such as aviation fuel).
2. Expansion of Biomass Feedstock Acquisition: (1) Efficiently collecting existing biomass resources from agriculture, forestry, animal husbandry, and municipal waste. (2) Cultivating short-rotation biomass crops (such as switchgrass) on non-arable land. (3) Importing biomass feedstock for subsequent utilization.
3. Improving Regulations and Environment: (1) Improving existing combustion power generation technologies. (2) Removing regulatory barriers to facilitate the transportation and disposal of biomass and waste.
4. Before fully going over to electric vehicles, import bioethanol to blend with gasoline (10-85%) as a transitional fuel for vehicles. This measure can address the social equity aspect of the net-zero transition while aiming for vehicle electrification longer term.
5. According to estimates, by 2050, Taiwan can increase the installed capacity of biomass power generation to 2.5 GW -3 GW, with an estimated power generation of approximately 12.2 kWh - 19.4 billion kWh.

2.7.1 Introduction

Biomass refers to feedstocks generated directly or indirectly through photosynthesis. Fossil fuel raw materials formed from ancient organisms are theoretically also biomass. However, since they have been sequestered for a long time, they are defined as non-biomass combustible materials, also known as “old carbon.” In contrast, carbon in biomass feedstocks comes from present-day atmospheric carbon dioxide, referred to as “new carbon.” Although burning biomass releases carbon dioxide, plants or crops absorb carbon dioxide during growth, resulting in no net increase in atmospheric carbon dioxide. Thus, biomass feedstocks can be considered effective products of direct air capture and a carbon-neutral energy option. When combined with appropriate carbon storage options, biomass can even become a negative carbon technology.

Existing biomass feedstocks come from energy-rich crops (such as corn and sugarcane for ethanol production, and palm trees for palm oil production). They can also be obtained from agricultural, forestry, and livestock residues, as well as urban waste¹⁵⁹, with 60-70% of urban combustible waste being attributable to biomass¹⁶⁰ (such as waste paper derived from wood). According to the "Renewable Energy Development Act" in Taiwan, energy derived directly or through processing domestic organic waste is considered biomass energy. Therefore, this section also includes energy produced from urban waste in the biomass energy category. Other innovative biomass feedstocks can be directly formed by photosynthetic microorganisms or developed through new technologies for microbial carbon fixation. Additionally, fallow land can be used to cultivate weeds traditionally deemed useless (such as switchgrass and miscanthus) as emerging biomass crops.

Biomass in its original state is solid, such as sugarcane, rice straw, branches, and urban waste. This type of biomass can be burned directly to produce thermal energy or converted into electrical energy, or further converted into liquid fuels (such as aviation fuel), or gaseous forms (such as biogas) for power generation or heat production. According to the International Energy Agency's (IEA) estimate of energy supply under

¹⁵⁹ The IEA defines "urban, food, agricultural, and industrial" organic waste as organic waste and separates it from "forestry residues."

¹⁶⁰ Part I of the "Waste Incineration Plant Transformation to Biomass Energy Centers" policy assessment report by the Environmental Protection Administration of the Executive Yuan (2012). <https://www.epa.gov.tw/DisplayFile.aspx?FileID=8BD164AEA5EB0DEE&P=5eee25bf-b45f-4e05-ba0a-a201552ca66c>

the 2050 net-zero emissions scenario¹⁶¹, the use of traditional biomass combustion (such as burning wood for cooking and heating) has significant air pollution impacts affecting many people's health, and such applications are expected to be phased out by 2050 and replaced by modern biomass energy. Modern solid biomass is projected to account for about 14% of global energy supply in the future, with modern liquid and gaseous biomass each accounting for an additional 3%. This positions modern biomass energy (20%) as comparable to solar energy (20%) and wind energy (16%).

Thus, many countries are actively developing biomass energy. For instance, Japan's 2018 "Basic Energy Plan" aims to increase the share of biomass power generation from 1.5% to 3.7% – 4.6% by 2030. The main strategy involves importing millions of tons of wood pellets. That said, limited resources have led to a competition for biomass fuel with the UK¹⁶².

Although the current share of biomass energy in Taiwan is low, continuous development of biomass sources and increasing biomass energy capacity will significantly contribute to achieving the 2050 net-zero emissions target. In particular, biomass energy can serve as a baseload power source. Maintaining a certain proportion of baseload power supply is crucial for a safe and stable power system as the proportion of solar and wind power increases in the overall installed capacity. Moreover, in the blueprint for the industrial and transportation sectors to achieve net-zero emissions, biomass energy, with its carbon-neutral nature and suitability for small to medium-scale applications, can partially or significantly replace existing fuels. For example, biomass feedstock can replace coal in boilers, and biojet fuel can be substituted for fossil jet fuel. Therefore, developing biomass energy is both important and necessary, but challenges, such as the current lack of a stable feedstock supply and low energy efficiency, need to be overcome.

¹⁶¹ *Ibid.*, note 12.

¹⁶² Taiwan Economic and Cultural Representative Office in Japan, Ministry of Economic Affairs (2019). Japan and the UK compete for biomass fuel. <https://info.taiwantrade.com/biznews/日英相互爭奪生質燃料-1826030.html>

2.7.2 Biomass Energy Development in Taiwan

Due to the low demand for thermal energy during winter and the predominant use of natural gas for cooking, the development of biomass energy in Taiwan is currently focused on power generation. In 2019, waste incineration facilities had an installed capacity of 632 MW, generating 3.63 billion kWh, the largest contribution. Biomass (including solid and gaseous forms) had an installed capacity of 77 MW, generating 0.17 billion kWh. All combined, this totals an installed capacity of 709 MW and total power generation of 3.8 billion kWh¹⁶³. Figure 2.7.1 compares the installed capacity of biomass energy in Taiwan and Germany over the past decade. Germany, which has the highest proportion of renewable energy¹⁶⁴, increased its biomass energy capacity from 5.8 GW in 2011 to 8.57 GW in 2021¹⁶⁵. In contrast, Taiwan's biomass energy capacity has stagnated at 0.72 GW over the same period¹⁶⁶. This indicates that while other countries have been actively developing biomass energy, Taiwan may have missed significant opportunities. Fortunately, in recent years, Taiwan started various demonstration projects (Box 2.7.1).

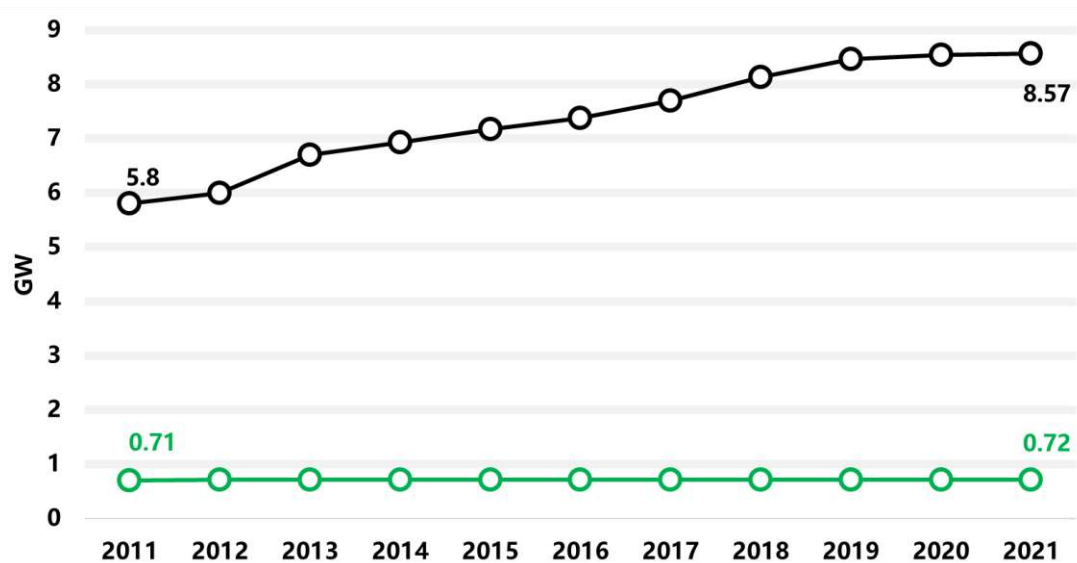


Figure 2.7.1 Installed Biomass Energy Capacity in Taiwan and Germany

¹⁶³ Green Energy & Environment Research Laboratories (2019). Renewable energy statistics. https://www.re.org.tw/information/statistics_more.aspx?id=4093

¹⁶⁴ Nhede, N (2020). Top ten countries with the highest proportion of renewable energy. Smart Energy International. <https://www.smart-energy.com/industry-sectors/smart-energy/top-ten-countries-with-the-highest-proportion-of-renewable-energy/>

¹⁶⁵ Net installed electricity generation capacity in Germany in 2021 (2021). https://energy-charts.info/charts/installed_power/chart.htm?l=en&c=DE&stacking=grouped

¹⁶⁶ Energy Administration, Ministry of Economic Affairs (2021). Renewable energy installed capacity statistics, monthly report for June 2021.

Box 2.7.1 Biomass Energy Demonstration Projects

1. **Urban Food Waste Biogas Power Generation:** The Waipu Biomass Energy Plant in Taichung processes food waste and rice straw to generate electricity. It handles 83 tons of food waste daily, undergoing 3 days of hydrolysis acidification and 30 days of anaerobic fermentation to produce biogas. At full capacity, it can generate 33.77 million kWh, providing electricity for 9,670 households for a year.
2. **Biogas from Animal Waste:** The Posko Biomass Energy Center in Hualien is Taiwan's first demonstration site for centralized livestock waste biogas power generation. It began operations at the end of June 2021, with an annual power generation capacity of 800,000 kWh.
3. **Agricultural Waste:** The Kaohsiung Agricultural Research and Extension Station's agricultural waste incinerator has a biochar power generation capacity of 0.1 MW. It processes wood and tree branches, producing biochar and wood vinegar for reuse while utilizing the heat generated from the biochar process for power generation.

Reasons for the slow development of biomass energy in Taiwan may be analyzed as follows:

1. Limited Biomass Resources and Difficulty in Collecting Agricultural, Forestry, and Livestock Residues

Taiwan produces about 6.46 million tons of combustible solid waste annually¹⁶⁷, primarily from well-operated urban general waste collection systems. This quantity is not increasing significantly. Other potential biomass energy sources include agricultural and forestry waste, with an annual total of nearly 5 million tons of solid agricultural waste¹⁶⁸ such as rice straw, corn cobs, and fruit and vegetable waste. Although the amount is substantial, agricultural fields, forests, and pastures are widely distributed, and there is currently no efficient collection mechanism for agricultural waste. As a result, agricultural and forestry waste not only doesn't contribute much to biomass energy but often is the cause of other environmental issues such as air and water

¹⁶⁷ Environmental Protection Administration, Executive Yuan (2021). Waste incineration plant management system, annual operation report. https://swims.epa.gov.tw/Statistics/Statistics_Year.aspx

¹⁶⁸ Directorate-General of Budget, Accounting and Statistics, Executive Yuan, R.O.C. (Taiwan) (2020). 109-year report on the compilation of green national income accounts.

pollution due to their improper disposal, including open burning.

Besides waste, traditional biomass sources also include wood. Taiwan has a forest cover rate of over 60%. However, due to forest conservation awareness, there is societal opposition to tree felling, limiting the development of the domestic timber industry. Consequently, the self-sufficiency rate for wood (used for papermaking, construction, etc.) is less than 2%, with most demand met through imports. Imported wood has a high carbon footprint, so restarting domestic forestry could effectively use wood for biomass energy while increasing carbon sinks through carbon sequestration in wood products (see Chapter 3 for more details).

2. Challenges with Energy Efficiency, Technology, Cost, and Uses

Primary biomass energy conversion technologies currently include solid biomass incineration, waste landfill, anaerobic fermentation of livestock manure for biogas/methane production, and the extraction of starch and oilseed crops. Incinerators are considered undesirable facilities, and any new or renovation projects face public opposition. Consequently, many incinerators are outdated and inefficient. In addition to updating and replacing equipment, it is necessary to invest in more efficient new technologies such as pyrolysis^{169,170,171}, gasification, biorefineries, and refuse-derived fuel (RDF) (Box 2.7.2).

The use of biogas/methane is mainly focused on power generation, but the scale of livestock farms in our country is relatively small. To install anaerobic fermentation and biogas power generation facilities, it is necessary to establish collection systems to reduce costs or consider other applications, such as integrating with natural gas pipelines.

¹⁶⁹ Bakenne, A., Nuttall, W., & Kazantzis, N. (2016). Sankey-Diagram-based insights into the hydrogen economy of today. *International Journal of Hydrogen Energy*, 41(19), 7744-7753. <https://doi.org/10.1016/j.ijhydene.2015.12.216>

¹⁷⁰ C. H. Bartholomew, R. J. Farrauto, *Fundamentals of Industrial Catalytic Processes* (Wiley, 2011).

¹⁷¹ Upham, D. C., Agarwal, V., Khechfe, A., Snodgrass, Z. R., Gordon, M. J., Metiu, H., & McFarland, E. W. (2017). Catalytic molten metals for the direct conversion of methane to hydrogen and separable carbon. *Science*, 358(6365), 917-921. <https://doi.org/10.1126/science.aao5023>

Box 2.7.2 Key New Technologies for Solid Biomass

Biomass energy technology has made significant progress after many years of research and development. Advances in technologies that integrate the biological, physical, and chemical fields can accelerate the efficient utilization of biomass energy. However, further R&D is still required. Pyrolysis and gasification can improve waste incineration. During pyrolysis, combustible materials first decompose at 300°C under anoxic conditions, and then form liquid or gaseous biomass energy in an inert environment at 800°C. Gasification involves the partial oxidation of solid combustibles at 700-900°C under precisely controlled oxygen concentrations, producing hydrogen, carbon monoxide, methane, etc. Biorefining technology can also produce value-added chemicals. The following provides a detailed explanation of pyrolysis technology:

Pyrolysis Technology

Pyrolysis involves the decomposition of biomass feedstock in a high-temperature, oxygen-free environment using catalysts, molten salts, or other physical and chemical methods to extract hydrogen. The remaining solid material is broadly known as biochar. This technology has existed for many years, but several issues remain to be resolved:

1. **Conversion Rate:** To improve the conversion rate, new catalysts or heat transfer media need to be developed. Additionally, reactor design and reaction parameters can be optimized.
2. **Energy Efficiency:** The pyrolysis process requires a high temperature, making heat loss a significant issue. Solutions include utilizing waste heat from boilers for thermal circulation, scaling up to reduce reactor surface area, and developing insulation materials to reduce heat loss.
3. **Hydrogen Utilization:** Some of the hydrogen created can be used to heat the reactor, with the excess mixed with natural gas for power generation. For now, it is advisable to install small natural gas power generators at pyrolysis plants to simultaneously generate electricity and provide thermal circulation. Initially, hydrogen can be mixed with natural gas at 10-60% for combustion, with a future shift to pure hydrogen power generation once pure hydrogen turbine materials are commercialized.
4. **Biochar Collection:** The solid biochar residue must be effectively

separated from the catalyst or heat transfer medium and collected.

5. **Biochar Utilization or Sequestration:** Biochar can be mixed into soil to improve its quality, depending on the soil properties. Another approach is burial for sequestration. Biochar has high stability and is easier to handle and transport compared to sequestering carbon dioxide. However, field conditions must be tested before implementation.

In the past, Taiwan developed bioethanol and biodiesel as alternative transportation fuels. However, due to insufficient feedstock, immature technology, and a lack of urgency to reduce carbon emissions, the results were not satisfactory. With the trend towards electrification of land transport, there is no longer a need for large-scale development of bioethanol or biodiesel. Nonetheless, importing small quantities of bioethanol or biodiesel as a transitional measure before full electrification of transport can help reduce carbon emissions and mitigate the impact on those groups affected by electrification.

However, there remains a necessity to develop chemical and biotechnological methods for biomass conversion, targeting chemical raw materials and aviation fuel. This will not only reduce petroleum usage but also potentially enable future technology exports.

3. Land Use Efficiency for Biomass Energy Production

In terms of land use efficiency, biomass energy generates less than 1 watt per square meter. In comparison, solar photovoltaics generate between 5 to 20 watts per square meter¹⁷², indicating a higher efficiency for solar photovoltaics. However, biomass energy has other advantages, such as maintaining soil arability, allowing the land to be converted to food production if necessary. It can also absorb atmospheric carbon dioxide and serve as a substitute for petroleum as a raw material for chemicals and aviation fuel. Nonetheless, additional carbon emissions are associated with the use of fertilizers during the plant growth process or fuel production processes. This issue can be addressed through biotechnological solutions, which are a key focus for future research and development.

¹⁷² *Ibid.*, note 69.

2.7.3 Potential and Limitations of Biomass Energy Development in Taiwan

Due to the diverse sources and applications of biomass energy, this proposal first evaluates the potential contribution of biomass power generation and then explores other possible biomass energy applications in Taiwan:

1. Incinerating Urban and Agricultural Waste to Generate Power

Taiwan has 24 urban waste incinerators with a total installed capacity of 632 MW¹⁷³, generating 3.6 billion kWh annually¹⁷⁴. Over the next 10-15 years, by improving combustion, boiler performance, and turbine efficiency, each incinerator can be transformed into a biomass energy center. This would increase power generation efficiency from around 20% to 30%, a 50% improvement, raising the installed capacity to 948 MW (with an annual power generation volume of about 5.4 billion kWh) by 2050. Additionally, according to the Executive Yuan Council of Agriculture¹⁷⁵, the total amount of solid agricultural waste in 2019 was approximately 5 million tons. If 70% of agricultural waste is recycled, and only the non-recycled 1.5 million tons are used for power generation at ~30% efficiency, there is a potential installed capacity of about 234 MW, generating 1.1 billion kWh¹⁷⁶ annually. Combining urban and agricultural waste, Taiwan's waste incineration installed capacity could reach 1.18 GW and about 6.5 billion kWh per year by 2050.

2. Biogas and Methane Power Generation from Livestock Manure and Food Waste

As Taiwan is no longer building new landfills, biogas power generation from landfills is decreasing annually. Therefore, our biogas estimates only include livestock manure and food waste. Preliminary considerations show that utilizing the manure from

¹⁷³ *Ibid.*, note 169.

¹⁷⁴ Taiwan Power Company (2021). Overview of renewable energy development. <https://www.taipower.com.tw/tc/page.aspx?mid=204>

¹⁷⁵ Directorate-General of Budget, Accounting and Statistics, Executive Yuan (2020). Report on the compilation of green national income accounts. Directorate-General of Budget, Accounting and Statistics, R.O.C. (Taiwan). <https://www.stat.gov.tw/lp.asp?ctNode=4867&CtUnit=1352&BaseDSD=7&mp=4>

¹⁷⁶ Using the estimated annual unutilized amount of solid agricultural waste of 1.5 Mt, with an estimated calorific value of 9000 MJ/t, and a conversion efficiency of 30%: $1.5 \times 10^6 \text{ t} \times 9,000 \text{ MJ/t} \times 0.2778 \text{ kWh/MJ} \times 30\% = 1.13 \times 10^9 \text{ kWh}$. The quantity of solid agricultural waste is referenced in the 108-Year Report on the Compilation of Green National Income Accounts. <https://www.stat.gov.tw/lp.asp?ctNode=4867&CtUnit=1352&BaseDSD=7&mp=4>

5.4 million pigs nationwide¹⁷⁷ could generate 200 million kWh annually (installed capacity of 72 MW¹⁷⁸). If agricultural waste with high carbon content (e.g., vegetable waste, rice straw, corn cobs) is co-digested with livestock manure (or wastewater sludge) with high nitrogen content, adjusting the carbon-nitrogen ratio to around 20-30:1, and the power generation potential could increase to 1 billion kWh (with installed capacity of 360 MW¹⁷⁹). Furthermore, according to Article 70 of the "Water Pollution Control Measures and Test Reporting Management Regulations," the biogas slurry and residue produced from anaerobic fermentation of livestock manure can be applied to farmland as fertilizer¹⁸⁰.

Another potential source of biogas is food waste. Currently, Taiwan's five food waste biogas power plants, scheduled for completion by 2024, will generate about 40 million kWh annually (with installed capacity of 14.4 MW¹⁸¹). Combining livestock manure and food waste, Taiwan's biogas power generation could reach an installed capacity of 370 MW and about 1.04 billion kWh by 2050.

3. Energy Crops

In addition to using residual resources from agriculture, forestry, and livestock, the agricultural sector can also use fallow or abandoned land to grow crops high carbon content, increasing natural carbon sinks to offset emissions. Taiwan has approximately 790,000 hectares of arable land, with around 220,000 hectares being short-term fallow and about 50,000 hectares as long-term fallow land¹⁸². Without affecting food production safety or ecology, half of the long-term fallow land could be used to grow herbaceous plants with short growth cycles and high carbon capture (e.g.,

¹⁷⁷ Central Livestock Association (2022). Pig population survey. <https://www.naif.org.tw/infoExamineList.aspx?frontTitleMenuID=37&frontMenuID=47>

¹⁷⁸ Council of Agriculture, Executive Yuan (2019). Office of the Biogas Power Generation Promotion Project. Biogas power generation benefit assessment. <https://www.biogas.com.tw/benefit/#>

¹⁷⁹ Chou, C.-Y., Liu, A.-C., & Zhang, N. (2020). Anaerobic digestion and co-digestion: Opening the door to agricultural circular economy with green technology converting livestock waste into biogas energy. <https://www.agriharvest.tw/archives/29786>

¹⁸⁰ Chen, C.-L., Lin, M.-J., & Liao, C.-Y. (2018). Guidelines for applying livestock wastewater as fertilizer on agricultural land. Special Publication No. 206. Taiwan Agricultural Research Institute,

Council of Agriculture, Executive Yuan. https://www.biogas.com.tw/technology/technology_more?id=f951dc40f4cc4ba7a0f56c312e8e47fe

¹⁸¹ Lin, Q.-Y. (2020, August 12). Composting and setting up biomass energy plants: The environmental protection administration promotes diverse treatment of kitchen waste. Environmental Information Center. <https://e-info.org.tw/node/226231>

¹⁸² Council of Agriculture, Executive Yuan (2021, July 30). Agricultural Land, Forest Land, and Fish Pond Area. *Agricultural Statistics Yearbook*. <https://agrstat.coa.gov.tw/sdweb/public/book/Book.aspx>

switchgrass¹⁸³). Switchgrass yields 250 tons per hectare annually; thus, 24,800 hectares could produce 6.205 million tons annually, with a power generation potential of 4.65 billion kWh, requiring an installed capacity of about 0.97 GW (assuming 30% power generation efficiency¹⁸⁴).

4. Going Carbon-Negative: Biomass Pyrolysis for Hydrogen and Carbon Sequestration

In the future, biomass pyrolysis for hydrogen production and carbon sequestration¹⁸⁵ can be further utilized. This is an example of Bioenergy with Carbon Capture and Storage (BECCS), a carbon-negative technology. This approach gasifies biomass into hydrogen and solid biochar. The hydrogen can be used for power generation, contributing to baseload power, while the solid biochar can be sequestered, creating a carbon sink. Since the hydrogen content of combustible waste is about 10% by weight¹⁸⁶, approximately 600,000 tons of hydrogen can be extracted annually from the 6.46 million tons of combustible waste in Taiwan. Assuming a 60% hydrogen generation efficiency from pyrolysis¹⁸⁷, about 360,000 tons of hydrogen can be obtained annually. One ton of hydrogen produces combustion heat of 142,180 MJ. Assuming a 60% power generation efficiency of hydrogen-powered turbines¹⁸⁸ (without considering the energy consumption of pyrolysis), 360,000 tons of hydrogen could generate up to 8.5 billion kWh¹⁸⁹, although the actual value needs to be verified. Considering that incinerators operate for about 200 days a year, converting them to hydrogen-powered turbines could provide an installed capacity of 2 GW¹⁹⁰.

The hydrogen/carbon atom ratio for herbaceous plants is approximately 1.5:1

¹⁸³ Li, Z. R., Li, J. Y., & Lin, Z. B. (2018). Cultivation and management techniques of *Pennisetum purpureum* Schumach No. 7. https://kmweb.coa.gov.tw/theme_data.php?theme=news&sub_theme=variety&id=55039

¹⁸⁴ Assuming the energy content is 9,000 MJ per ton and the power generation efficiency is 30%, the calculation for the energy output would be: $1.2409 \times 10^9 \text{ t} \div 2 \times 9,000 \text{ MJ/t} \times 0.2778 \text{ kWh/MJ} \times 30\% = 4.65 \times 10^9 \text{ kWh}$. Assuming a power plant operates for 200 days per year, we can estimate the annual energy output as follows: $4.65 \times 10^9 \text{ kWh} / 200 \text{ days} / 24 \text{ h/day} = 0.97 \text{ GW}$.

¹⁸⁵ Zeng, B., & Shimizu, N. (2021) Hydrogen generation wood chip and biochar by combined continuous pyrolysis and hydrothermal gasification. *Energies*, 14(13) 3793.

¹⁸⁶ Taipei City Government (2020). Quarterly report on waste analysis. Taipei City Environmental Quality Information Network. https://www.tldep.gov.taipei/Public/Download/TR_Report.aspx

¹⁸⁷ Ibid., note 131.

¹⁸⁸ Pasquariello, R (2020). Gas turbine innovation, with or without hydrogen. *Turbomachinery Magazine*. <https://www.turbomachinerymag.com/view/gas-turbine-innovation-with-or-without-hydrogen>

¹⁸⁹ $3.6 \times 10^5 \text{ t} \times 142180 \text{ MJ/t} \times 0.2778 \text{ kWh/MJ} \times 60\% \text{ (power generation efficiency)} = 8.53 \times 10^9 \text{ kWh}$

¹⁹⁰ $8.53 \times 10^9 \text{ kWh} \times 1,000 \text{ Wh/kWh} / 200 \text{ days} / 24 \text{ h/day} = 1.8 \text{ GW}$

¹⁹¹(hydrogen content is about 11.2% by weight), and the hydrogen/carbon atom ratio for methane is 4:1 (hydrogen content is about 25.1% by weight). Similarly, converting Taiwan's urban combustible waste, agricultural waste (1.5 million tons), energy crops from fallow land (about 6.205 million tons), and livestock or food waste biogas, etc., could contribute¹⁹² approximately 27.7 billion kWh of hydrogen power generation. Assuming a conservative plant completion rate of 70%, this approach could reach 19.4 billion kWh by 2050.

5. Other Potential Biomass Energy Applications

While vehicles can be electrified, it is almost impossible to electrify aviation and shipping. Current battery technology cannot support the long-range needs of aviation and shipping. Using biofuels to replace traditional aviation fuel could significantly contribute to achieving our 2050 net-zero emission target. Currently, some commercial flights have started using blended biofuel aviation fuel. Future development of liquid biofuels will primarily focus on aviation and marine fuel needs. Due to low land use efficiency and high production costs, advanced liquid biofuels are currently expensive. Recently, the price of aviation fuel in the US was about \$2.2 per gallon, while biojet fuel is about \$5.4 per gallon. Currently, advanced liquid biofuel technology is not cost-effective. However, as global carbon pricing starts to take effect, raising the cost of aviation fuel, the competitiveness of biojet fuel may improve. More R&D is needed on new catalysts and conversion microorganisms¹⁹³, reducing hydrogen usage efficiency in hydrogenation reactions, reducing power consumption in microbial carbon fixation, optimizing product separation technology, improving liquid fuel yields, and cost-effective mass production technologies¹⁹⁴.

In addition to power generation, modern solid biomass can replace coal in high-temperature industrial applications. This is a relatively convenient alternative fuel option for industries already equipped with boiler facilities, but the cost of solid biomass remains a major consideration for industrial transformation to succeed. Purified biogas-derived biomethane can replace part of the natural gas used in high-

¹⁹¹ Adamovics, A., Platace, R., Gulbe, I., & Ivanovs, S. (2018). The content of carbon and hydrogen in grass biomass and its influence on heating value. *Eng. Rural Dev*, 23, 1277-1281.

¹⁹² Note that the energy consumption of pyrolysis is not considered here.

¹⁹³ Liao et al. (2016). Fueling the future: Microbial engineering for the production of sustainable biofuels. *Nat Rev Microbiol*. 14, 288-304.

¹⁹⁴ Oh, Y. K., Hwang, K. R., Kim, C., Kim, J. R., & Lee, J. S. (2018). Recent developments and key barriers to advanced biofuels: A short review. *Bioresource Technology*, 257, 320-333.

temperature industrial applications and can be blended into natural gas pipelines for residential and commercial use, reducing natural gas consumption. However, the scale of pipeline and injection point construction is significant, and the cost-effectiveness needs careful evaluation. Additionally, new conversion microorganisms can be developed to convert methane into high-value-added chemicals.

In summary, the future options for biomass power generation in Taiwan, including general incinerators, agricultural waste and energy crop incinerators, livestock biogas, and food waste biogas, may achieve an installed capacity of 2.5 GW, generating about 12.2 billion kWh annually. If combined with pyrolysis for hydrogen and carbon sequestration technology, the installed capacity could reach 3 GW, generating 19.4 billion kWh.

2.7.4 Policy Recommendations

1. Develop New Technologies

Currently, the efficiency of biomass energy is limited. To enhance the overall capability, investment in more efficient technologies is required. The primary innovative technologies include:

(1) **Pyrolysis Technology.** Pyrolysis can transform traditional solid biomass utilization methods from carbon neutral to carbon negative. However, some aspects such as conversion rate, hydrogen utilization, energy efficiency, and biochar separation require further R&D.

(2) **Use Biotechnology to Enhance Photosynthesis and Single-Carbon Source Utilization,** so as to increase biological carbon sequestration as well as production of chemicals and biomass fuel (such as aviation fuel). With future international restrictions on fossil raw material extraction, producing chemical raw materials through biotechnology could also be a crucial direction for national technological development.

2. Expand Biomass Feedstock Acquisition to Stabilize Energy Supply

Biomass can serve as a baseload energy. However, ensuring a stable feedstock supply is critical. The following recommendations are proposed:

(1) **Effective Collection of Existing Agricultural, Forestry, Livestock Residues, as well as Urban Waste.** Taiwan currently lacks a systematic agricultural waste collection process. To avoid the higher costs of decentralized processing, future collection stations could be established in conjunction with the

development sites of pyrolysis technology. Purchasing incentives can be linked to power generation efficiency and the value of carbon sinks. For example, 5 million tons of agricultural waste could generate 340,000 tons of hydrogen¹⁹⁵ (producing 8 billion kWh¹⁹⁶) and 2.66 million tons¹⁹⁷ of biochar for reserve fuel or soil improvement. This technology could also solve the issue of air pollution caused by open air burning by farmers. Since pyrolysis technology requires additional energy inputs, further R&D is needed to optimize the process.

(2) Cultivation of Short-Term Biomass Crops on Non-Arable Land:

Although agriculture generates high carbon emissions from management, harvesting, and transportation, it also has the capability to sequester carbon. The agricultural sector can improve management techniques to reduce greenhouse gas emissions and utilize fallow or abandoned land to grow high carbon crops to remove atmospheric carbon dioxide (see Chapter 3 for more details). According to the Executive Yuan Council of Agriculture's 2021 statistics, Taiwan has about 790,000 hectares of arable land, with approximately 220,000 hectares of short-term fallow and 50,000 hectares of long-term fallow land¹⁹⁸. Without compromising food production safety or ecology, some fast-growing, high carbon content, and easy-to-harvest herbaceous plants can be cultivated. For example, the C4 plant *Pennisetum purpureum* (elephant grass) grows rapidly, can be harvested up to five times a year per hectare, and captures about 60 tons of CO per hectare annually, while increasing soil carbon storage. Compared to overgrown fallow land, choosing high carbon capture grass species is more beneficial for carbon reduction. Table 2.7.1 estimates the potential carbon capture using 105,000 hectares of fallow land (50,000 hectares long-term + 55,000 hectares short-term). *Pennisetum purpureum*, which is more suitable for agricultural land, can sequester 6.3 million tons of CO₂ annually.

Currently, *Pennisetum purpureum* is one of Taiwan's primary forage crops

¹⁹⁵ The hydrogen/carbon atomic ratio of herbaceous plants is approximately 1.5, with a hydrogen content of about 11.2% by weight, assuming a hydrogen yield of 0.6. Please refer to Adamovics, A., Platace, R., Gulbe, I., & Ivanovs, S. (2018). The content of carbon and hydrogen in grass biomass and its influence on heating value. *Eng. Rural Dev.*, 23, 1277-1281.

¹⁹⁶ $3.4 \times 10^5 \text{ t} \times 142180 \text{ MJ/t}$ (combustion heat of 1 ton of hydrogen is 142,180 MJ) $\times 0.2778 \text{ kWh/MJ} \times 60\%$ (power generation efficiency) = $8.1 \times 10^9 \text{ kWh}$

¹⁹⁷ The H/C atomic ratio of herbaceous plants is approximately 1.5, with a carbon content of about 88.8% by weight, assuming a carbon yield of 0.6.

¹⁹⁸ *Ibid.*, note 188.

due to its adaptability, high yield, and resistance to pests and diseases, making it a good cover crop or raw material for biochemicals. These characteristics make *Pennisetum purpureum* valuable for carbon sequestration and soil quality improvement. It can be grown across the various regions in Taiwan that have good water and nutrients, exhibiting good growth performance. *Pennisetum purpureum* is typically harvested every 8 to 10 weeks, leaving 5-10 cm of the base for regrowth. Given its potential beyond forage use, Taiwan's agricultural research institutions (such as the Livestock Research Institute) have been breeding varieties with different characteristics, such as *Pennisetum purpureum* No. 4 (yield 306.1 tons/ha/year) and No. 7 (yield 240.8 tons/ha/year¹⁹⁹), which can sequester 87.8 and 76.2 tons of CO₂ per hectare annually, respectively, making it a promising high-efficiency carbon capture plant. However, if *Pennisetum purpureum* is cultivated as a carbon reduction crop, nitrogen fertilizer use should be minimized due to its significant energy consumption and CO₂ emissions. Currently, intercropping *Pennisetum purpureum* with green manure crops like *Sesbania* can reduce chemical fertilizer use, maximizing plant carbon capture benefits under suitable agricultural conditions.

¹⁹⁹ *Ibid.*, note 189.

Table 2.7.1 Carbon Sequestration Plants Suitable for Idle Agricultural Land

Crop Type	Unit Carbon Sequestration Capacity (ton CO ₂ /ha/yr)	Carbon Sequestration Capacity for 50,000 ha Long-Term Idle Land (Mt CO ₂ /yr)	Carbon Sequestration Capacity for 55,000 ha Short-Term Idle Land (Mt CO ₂ /yr)	Maximum Carbon Sequestration (Long-Term + Short-Term) (Mt CO ₂ /yr)	Percentage of Total National Emissions (%)	Remarks
Bamboo	150.0	7.50	8.25	15.75	5.49	Taiwan Moso Bamboo
<i>Pennisetum purpureum</i> (Elephant Grass)	60.0	3.00	3.30	6.30	2.20	Five harvests per year
Corn	50.0	2.50	2.75	5.25	1.83	Two harvests per year
Wheat	17.6	0.88	0.97	1.85	0.64	-
Green Manure Crops (Sesbania, Sunn Hemp, Soybean)	30.0	1.50	1.65	3.15	1.10	Five harvests per year
a) Taiwan currently has about 220,000 hectares of short-term fallow land. This estimate uses only 1/4 of the short-term fallow land, approximately 55,000 hectares. b) The total greenhouse gas emissions in Taiwan in 2019 were approximately 287 Mt CO₂eq. Data provided by the Agricultural Biotechnology Research Center, Academia Sinica. Reproduced in this policy recommendation document.						

(3) Import Biomass Feedstocks. In the future, if carbon fees or carbon border taxes increase, our country can consider importing biomass feedstocks from abroad. Thailand, Malaysia, and Indonesia have abundant biomass resources. Besides hydrogen production for power generation, it can also increase carbon sinks. However, it is important to consider that the economic value of energy crops might drive deforestation, increasing carbon emissions instead of reducing them. The EU started restricting palm oil as a transportation biofuel in 2019 and plans to

ban it completely by 2030, due to concerns about deforestation in palm oil-exporting countries like Indonesia²⁰⁰.

3. Improving Regulations and Environment

Waste-to-energy is the primary source of biomass power in Taiwan. Sweden even imports waste for power generation²⁰¹. However, due to limited land and population density, incinerators are considered undesirable facilities in Taiwan. While importing waste is not feasible, inter-county waste processing might be a viable solution. Currently, various regulations govern waste processing responsibilities and certified operators, imposing many restrictions on inter-county waste processing. For example, cement plants have high-temperature incinerators that can use waste as fuel, but multiple regulations make that difficult. Reviewing these regulations to meet current and next-generation energy needs is urgent.

In terms of the supply chain, the collection, transportation, and classification of waste are significant challenges for many countries²⁰², hindering biomass energy utilization. Taiwan has a high rate of proper general waste disposal (nearly 95%), but converting agricultural waste to electricity requires government efforts in public communication, policy formulation, and in establishing an industrial ecosystem. This includes incentivizing farmers to collect waste, establishing a network of collection vehicles, and having power generation facilities capable of processing the collected waste. Given the challenges of large scale collection, establishing small, grid-connected power generation units could be a strategy for converting agricultural waste into electricity.

4. Bioethanol as a Transitional Vehicle Fuel

Although ethanol produced from corn or sugarcane has been proposed for the past half-century, it has not been able to compete with fossil fuels. With advancements in biotechnology and the urgent issue of climate change, countries like the US and Brazil have been heavily investing in R&D and mass production, leading to widespread use.

²⁰⁰ Bureau of Energy, Ministry of Economic Affairs (2019). EU passes legislation to phase out palm oil in transport biofuels by 2030. <https://www.re.org.tw/knowledge/more.aspx?cid=201&id=2883>

²⁰¹ Emma Bergman (2019). Why does Sweden import waste from other countries? <https://rioonwatch.org/?p=54109#:~:text=According%20to%20the%20Swedish%20Environmental,been%20reated%20through%20energy%20recovery.>

²⁰² Moya, D., Aldás, C., López, G., & Kaparaju, P. (2017). Municipal solid waste as a valuable renewable energy resource: A worldwide opportunity of energy recovery by using Waste-To-Energy Technologies. *Energy Procedia*, 134, 286-295.

Despite debates on food vs. fuel and the carbon footprint of bioethanol production, it is already blended with gasoline in many countries, available as E10 (10% ethanol), E20, and E85. E10 is widely used and effectively reduces carbon emissions. Ethanol-gasoline blends have higher octane numbers, but the energy content of E10 and E20 is about 96.5% and 93% of gasoline, respectively. Another concern is air pollution²⁰³ from volatile organic compounds, with nitrogen oxides (NOx) emissions increasing with higher ethanol blends but reductions in CO and total hydrocarbons. Special treatment of gasoline before blending can mitigate these issues.

With the rapid rise of electric vehicles, cellulosic ethanol has not developed as expected. Small vehicles are expected to be fully electrified by around 2040. However, given the high proportion of motorcycles in Taiwan, full electrification could impact many disadvantaged groups relying on motorcycles for their livelihood. Thus, importing low-carbon bioethanol to reduce emissions from gasoline vehicles can be a socially equitable transitional measure. Since transportation accounts for 12% of national emissions, using E10 and E20 could reduce emissions by 1-2%. With prices and performance similar to gasoline, and widespread use abroad, it is expected to be accepted domestically. E85 can also be promoted for non-electrified vehicles. Although Taiwan was once a sugar producer, it cannot compete internationally in recent years²⁰⁴, so importing bioethanol is recommended as a transitional measure to reduce carbon emissions, while aiming for full vehicle electrification in the long term. Future bioethanol production should focus on aviation fuel and chemicals. Although the overall carbon reduction benefits of bioethanol are debated, it largely depends on cultivation, harvesting, and production technology. If Taiwan imports bioethanol, choosing products with a lower carbon footprint than fossil fuels and adjusting the blend composition can reduce emissions.

²⁰³ Koten, H., et al. (2020). Effect of different levels of ethanol addition on performance, emission, and combustion characteristics of a gasoline engine. *Advances in Mechanical Engineering*, 12(7), 1-13.

²⁰⁴ Wen, Z.K. (2007). Current status of biomass energy development and discussion on the promotion of energy crops in Taiwan. <https://www.coa.gov.tw/ws.php?id=13518>

2.8 Hydropower

Summary

With plentiful rainfall and steep river descents, Taiwan has all the conditions, including water volume and water level differences, required for hydropower. Hence, hydropower has always been an important source of electricity in Taiwan and is one of the options for low-carbon energy. Hydropower can be divided into conventional hydroelectricity and pumped-storage hydroelectricity. As the climate changes, it is anticipated that Taiwan's precipitation patterns will also change with extreme fluctuations between drought and flooding. Thus, in the future, hydropower likely won't be able to serve as an adjustable power source during the dry seasons. It is recommended that Taiwan's management of hydropower move in the following directions:

1. For conventional hydroelectricity, in addition to regular dredging of weirs or retention basins to ensure the normal operation of the electricity turbines, it is recommended to use long-term flow data from hydrological observing stations at various river basins. Along with climate models, these can be used to project future trends of river flow changes and adjust operating models and improve the capacity factor of hydropower facilities.
2. Pumped-storage hydroelectricity can be used to stabilize the power supply system and support emergency power supply. At the same time, it can also be used as backup power. However, pumped-storage hydropower facilities may have a negative impact on river ecology. It is thus recommended to use existing reservoirs to set up pumped-storage hydropower facilities to save construction costs and time and minimize environmental and ecological impacts.
3. To promote small hydropower systems, it is necessary to take stock of river basins suitable for such facilities and resolve issues related to water rights and land acquisition in potential areas before one can determine the priorities for development. On the other hand, it is also necessary to evaluate Taiwan's grasp of key technologies and related industries to ensure the long-term maintenance and use of hydropower infrastructure.

2.8.1 Introduction

Hydropower has always played an important role in Taiwan's power supply. Hydropower can be divided into two categories: conventional and pumped-storage hydroelectricity. Based on power generation methods, conventional hydroelectric systems can be further divided into three types: impoundment, retention basins, and run-of-river. In addition to the traditional approaches, more and more people are paying attention to the approach of installing small hydropower systems in existing hydraulic facilities and irrigation channels. "Small hydropower" refers to systems below 20 MW that utilize irrigation channels or other water-related infrastructure (such as barrage dam reservoirs, hydropower plants, and irrigation channels). This approach allows people to add power-generating units to existing facilities, which reduces the environmental impact and helps to add more sources for the overall power supply.

Hydropower emits limited GHGs. The median value of lifecycle GHG emissions is 24g CO₂eq/kWh, only higher than wind and nuclear²⁰⁵. What is more, Taiwan's precipitation and rivers provide Taiwan with ideal conditions, including water volume and water-level differential, to develop hydropower. When the rivers have enough water, hydroelectric generation is stable for long periods of time with low costs. As a result, it can be used as a baseload power source. Generally speaking, hydropower will be an indispensable option for low-carbon energy to help Taiwan achieve the net-zero emissions goal by 2050.

2.8.2 Hydropower Challenges in Taiwan

To understand how existing hydropower contributes to Taiwan's total power supply, we have carried out a comprehensive review of relevant reports²⁰⁶. The review showed that in 2021, hydropower's installed electricity capacity accounted for approximately 7.9% of the total installed capacity of Taiwan's power supply, and actual

²⁰⁵ Schlömer S., T. Bruckner, L. Fulton, E. Hertwich, A. McKinnon, D. Perczyk, J. Roy, R. Schaeffer, R. Sims, P. Smith, and R. Wiser, (2014) Annex III: Technology-specific cost and performance parameters. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

²⁰⁶ Bureau of Energy, Ministry of Economic Affairs (2022). 2021 National electricity resources supply and demand report. https://www.moeaboe.gov.tw/ECW/populace/content/ContentDesc.aspx?menu_id=20851

power generation accounted for approximately 2.3%; Conventional hydroelectricity²⁰⁷ accounted for approximately 18.0% of the installed renewable energy capacity and 20.1% of actual renewable power generation. Table 2.8.1 provides detailed statistics. In addition, following the government's energy transition policy, Taiwan Power Company has included the development of small hydropower systems in its medium to long-term hydropower strategy. The following sections will briefly describe the current development of hydropower and challenges in Taiwan, including conventional hydroelectricity, pumped-storage hydroelectricity, and small hydropower systems.

Table 2.8.1 Statistics on hydropower in Taiwan in 2021^{208,209}

Category		Installed electricity capacity (GW)	Power generation (billion kilowatt)	Contribution to Taiwan's power supply in %		Contribution to renewable energy* in %	
				Installed electricity capacity	Power generation	Installed electricity capacity	Power generation
Hydro power	Conventional hydroelectricity	2.09	35	3.52	1.20	18.03	20.08
	Pumped-storage hydroelectricity	2.60	32	4.38	1.10	--	--
Taiwan's power supply		59.38	2,909	--	--	--	--
Taiwan's renewable energy		11.59	174	19.52	5.99	--	--

* Taiwan's renewable energy uses non-pumped storage hydropower

²⁰⁷ Taiwan Power Company (2022). Renewable energy overview (updated on June 27, 2022). <http://www.taipower.com.tw/tc/page.aspx?mid=204&cid=154&cchk=0a47a6ed-e663-447b-8c27-092472d6dc73>

²⁰⁸ *Ibid.*, note 錯誤! 尚未定義書籤。.

²⁰⁹ *Ibid.*, 213.

1. Conventional Hydroelectricity

Taiwan has 45 existing conventional hydropower units. In addition, 3 conventional hydropower units are under planning and development with an expected additional capacity is 119 MW. Conventional hydroelectric generating units require a sufficient amount of water to generate electricity. When Taiwan experienced a severe drought in April and May 2021, the water level of Sun Moon Lake, a reservoir for both water storage and power generation, was so low that the hydroelectric generating units could not operate properly to supply power²¹⁰, prompting an orange alert for Taiwan's power grid (which means that the electricity supply was under constraint and the backup capacity rate was less than or equal to 6%). In other words, when facing drought or other conditions that lead to insufficient water supply, the hydroelectric generating units cannot function properly, which may result in a power shortage.

Looking at Taiwan's climate and natural environment, we can see that Taiwan experiences uneven distribution of precipitation throughout the year. Over the years, Taiwan's precipitation during the rainy season accounted for 78% of annual precipitation, so the amount of water varies significantly during the rainy and dry seasons²¹¹. Studies²¹² also show that as global warming accelerates, the intensity and frequency of extreme rainfall events may increase, and the frequency of agricultural and ecological droughts will also increase. In other words, in the future, precipitation patterns may fluctuate between extreme dry and wet spells. Studies in Taiwan²¹³ point out that Taiwan's precipitation pattern is similar to the global trend. In the future, the precipitation pattern of "extremely wet or extremely dry" will likely be more prominent. Moreover, Taiwan has short and rapid rivers as well as small watersheds. During the dry season with low precipitation, Taiwan could face water scarcity, and hydropower

²¹⁰ Wenlin Sun (2021). How does water shortage affect power supply? Trivial yet important issues related to hydropower- The drought crisis of Taiwan's largest energy storage battery "Sun Moon Lake." Environmental Information Center. <https://e-info.org.tw/node/231256>

²¹¹ Water Resources Agency, Ministry of Economic Affairs (2020). 2019 special issue on Taiwan's hydrological environment. <https://www.wra.gov.tw/cl.aspx?n=6253>

²¹² IPCC (2021). IPCC AR6 (final draft of WGI AR6) *Sixth Assessment Report on Climate Change (IPCC AR6)*.

²¹³ The Taiwan Climate Change Projection Information and Adaptation Knowledge Platform (TCCIP) (2017). *Climate Change in Taiwan: Scientific Report 2017 (Volume 1 Physical Phenomenon and Mechanism)*.

facilities, in turn, would not be able to help balance electricity loads.

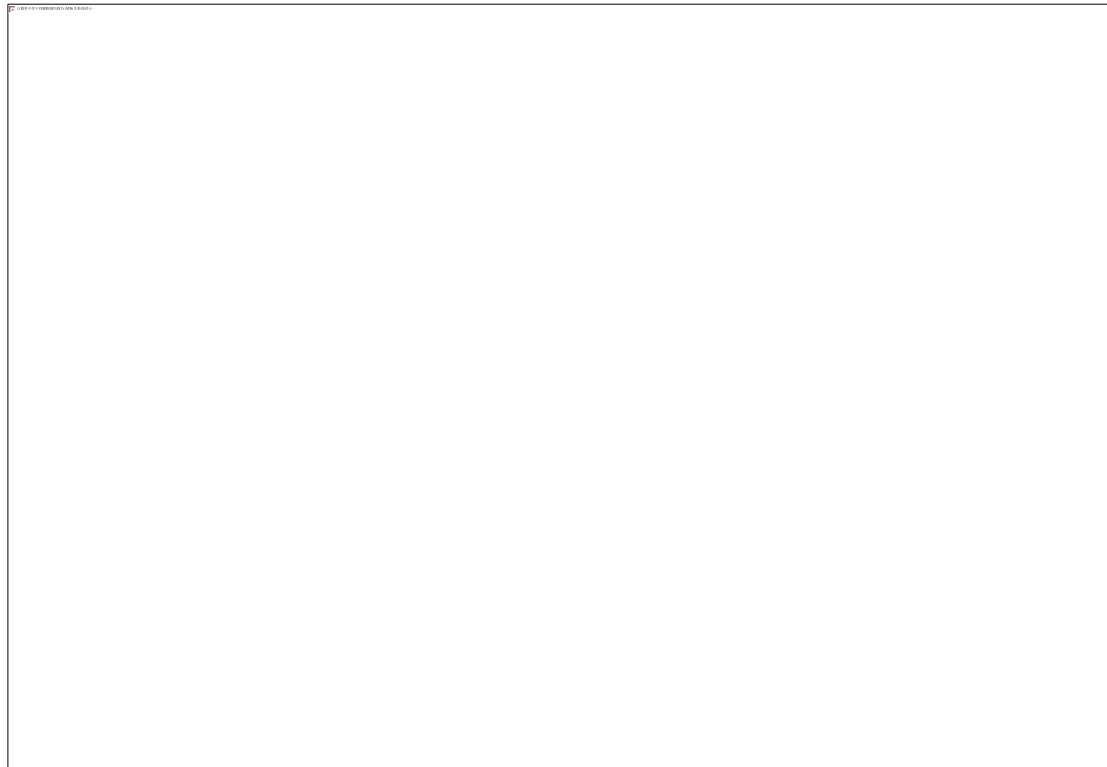


Figure 2.8.1 Distribution of Hydropower Facilities in Taiwan²¹⁴

2. Pumped Storage Hydroelectricity

Currently, Taiwan has 2 pumped-storage hydropower power plants^{215,216}. Both are located in the Sun Moon Lake area. One is Minghu and the other one is Mingtan. The Mingtan pumped-storage power plant was completed in 1995 and is the larger pumped-one, with an installed capacity of 1.6 GW. Since its completion, Taiwan has not built another pumped-storage power plant (see also Figure 2.8.1). The Dajia River Guangming hydroelectric plant currently under development is expected to start commercial operation in 2030. The planned installation capacity for the power plant is 350 MW (after the Chi-Chi earthquake in 1999, the installation capacity has been reduced to ensure that the power plant can be environmentally friendly and can use ecologically friendly construction methods).

Following Taiwan's renewable energy policies, Taiwan Power Company has

²¹⁴ *Ibid.*, note 錯誤! 尚未定義書籤。.

²¹⁵ Taiwan Power Company (2020). Pumped-storage hydroelectricity of Sun Moon Lake has become a model: A glorious history continues. *Taipower Journal* Vol. 690. <https://tpcjournal.taipower.com.tw/article/3969>

²¹⁶ Jinghua Lin (2021). Taipower plans to invest 26 billion NTD for the third pumped-storage hydropower plant. *Liberty Times*. <https://ec.ltn.com.tw/article/paper/1427614>

conducted feasibility studies of using pumped-storage hydropower plants as both a stable and emergency power supply²¹⁷. The Company plans to build a new pumped-storage hydropower plant to be a backup storage power plant that utilizes solar power. Basically, during the day, renewable energy (i.e. solar energy) can be used to generate electricity and pump water to the upper reservoir. During the peak hours in the evening, the water is released to generate electricity. As for site selection, Taiwan Power Company is considering using an existing reservoir as a potential site as the existing dam can be used as the upper reservoir, and they will only need to build another dam to be the lower reservoir. This approach can significantly reduce costs and construction time.

As mentioned above, a pumped-storage hydropower plant generates power by utilizing two water reservoirs at different elevations, so water is pumped from the river and discharged back into the river. It can be anticipated that the recharge and discharge process will affect the river ecology in the long run. As a result, environmental protection groups in Taiwan expressed concerns that the establishment of a pumped-storage hydropower plant could damage the river ecology, and they have repeatedly called on the government to stop the development of pumped-storage hydroelectricity²¹⁸.

3. Small Hydropower Systems

Small hydropower systems are hydropower systems set up in existing irrigation channels or other hydraulic facilities (such as dams, reservoirs, hydropower plants, and irrigation canals) to generate energy of less than 20 MW. As such systems utilize existing facilities, they can minimize impacts to the environment and help increase sources of power supply. To understand the planning and development of small hydropower systems, the information provided by the Water Resources Agency (WRA) of the Ministry of Economic Affairs (MOEA) at the briefing on small hydropower systems in 2018 was used here²¹⁹. At present, there are a total of 112 potential sites in Taiwan that can be used to develop small hydropower (based on the assessment report

²¹⁷ Wenlin Sun (2021). New force to support peak hour demand. Deji Reservoir is going to be transformed into a large “energy storage battery” and is scheduled to be opened in 2034. Environmental Information Center. <https://e-info.org.tw/node/231418>

²¹⁸ Liangqi Lin (2021). Environmental groups expressed concerns over the construction of a pumped storage hydropower plant. *China Times*. <https://www.chinatimes.com/newspapers/20210124000377-260102?chdtv>

²¹⁹ Water Resources Agency, Ministry of Economic Affairs (2018). Briefing on small hydropower systems.

on small hydropower systems put together by the WRA of the MOEA in 2018 and research data provided by Taiwan Power Company and the Council of Agriculture of the Executive Yuan in 2017). Among them, potential sites connected to natural rivers require environmental impact assessment, so 65 potential sites are considered priorities. Also, according to data provided by Taiwan Power Company²²⁰, it is estimated that small hydropower systems in Taiwan can potentially generate approximately 43.26 MW. A more detailed explanation is provided below:

(1) At present, there are a total of 24 potential sites for small hydropower systems with a total installation capacity of approximately 35.8 MW, and these systems are scheduled to start commercial operation from 2020 to 2024;

(2) The information includes small hydropower systems to be developed (with 10 potential sites and an installation capacity of approximately 3.94 MW); micro-hydropower systems (i.e. hydropower systems set up in existing irrigation channels or other hydraulic facilities to generate energy of less than 100 kW. At present, there are 8 potential sites with an installation capacity of approximately 0.38 MW); and small hydropower systems not yet included in the aforementioned small hydropower development plan. In addition, information on small (micro) hydropower systems provided by the 2010 “Survey and Potential Analysis of Agricultural Irrigation Channels for Renewable Energy by the Council of Agriculture of the Executive Yuan, (micro) hydropower (with 63 potential sites and a potential installation capacity of approximately 3.14 MW) is also included.

Apart from the small hydropower development plan proposed by Taiwan Power Company, civil society groups in Taiwan have also paid close attention to the development of small hydropower. The Taiwan Small Hydropower Green Energy Alliance (also referred to as the Small Hydropower Alliance) was established in 2021. According to the estimates of the Small Hydropower Alliance^{221, 222, 223} Taiwan’s

²²⁰ Jhenyong Wang (2017). Developing clean and renewable energy—Development of micro (small) hydropower industry. 2017 Symposium on Development Strategies of Water Industry (organized by Water Industry Promotion Association of Taiwan, WIDPA, Jhengyong Wang was the chief engineer of Taiwan Power Company at the time).

²²¹ Jhengjhong Hong (2021). Short-term development strategy of Taiwan's small hydropower energy industry. <https://cnews.com.tw/111210525a01/>

²²² Gufan Chen (2021). Estimates of the short-term development potential of small hydropower in Taiwan. <http://cnews.com.tw/111210426a01/>

²²³ Yige Chen (2021). Support green energy! Taiwan Small Hydropower & Green Energy Alliance announced its latest strategy. *Commercial Times*. <https://ctee.com.tw/industrynews/technology/465636.html/>

installed capacity potential of small hydropower within the following 3 to 5 years is about 2.6 GW. The estimates are significantly different from the estimates proposed by Taiwan Power Company; hence, more in-depth studies and evaluations may be needed. The installed electricity capacity of one small hydropower system may be limited, but such a system presents little impact on the environment and can be used to support the demand for household electricity in nearby areas. If power generated by small hydropower systems can be incorporated into the grid or the systems can be properly planned and configured with microgrid technologies, small hydropower systems may be used to supply power in small regions on weekdays and reduce the demands during peak hours. During large-scale blackouts caused by natural disasters, small hydropower systems can also provide power in certain areas. If small hydropower systems succeed in forming a supply chain in Taiwan and become a source of green power, they can help Taiwan reduce carbon emissions.

2.8.3 Potential and Limitations of Hydropower in Taiwan

According to the aforementioned description of the current development of conventional hydroelectricity, pumped-storage hydroelectricity and small hydropower systems, it is estimated that by 2050, installed electricity capacity of conventional hydroelectricity and small hydropower systems combined can reach approximately 2.26 GW, and pumped-storage hydroelectricity can reach approximately 2.95 GW. As for total power generation, conventional hydroelectricity and small hydropower systems combined can generate 3.391 billion kilowatt-hours and pumped-storage hydroelectricity can generate 3.583 billion kilowatt-hours. To further increase the installed electricity capacity and power generation of pumped-storage hydroelectricity, an assessment has been carried out, and the results showed that a seawater hydropower plant has the potential of an installed electricity capacity of 1 GW and a power generation capacity of 1.2 billion kilowatt-hours (see Appendix 2I).

As for the limitations to developing hydropower, site selection and construction of hydropower facilities (such as barrage dams, reservoirs, hydropower plants, etc.) have been quite difficult, and such facilities may have a considerable impact on the ecological environment and society, it is thus necessary to evaluate their impacts on the natural environment and social needs separately to gain public approval. Moreover, due to climate change, the frequency and scale of droughts are likely to increase; hence, it is necessary to obtain information on the seasonal variations of water in rivers,

reservoirs, and irrigation channels for more flexible strategies for water resource management and hydropower plant maintenance. Such an approach will help stabilize the power supply and adjust the electricity load. For example, during a severe drought, when there is not enough water to generate electricity, desilting and dredging can be carried out to clean reservoirs. In addition, desilting tunnels can be opened during typhoons to use the water to scour deposited sediment to the downstream areas, effectively desilting reservoirs and extending their lifespans and performance.²²⁴ In the long term, if Taiwan wants to improve the capacity factor of hydropower facilities²²⁵, it is necessary to update data collected by hydrological stations in various river basins, including information on hydrological flow and flood volume. At the same time, data on the natural flow of various dams and hydropower plants, flood frequencies and corresponding flood volumes, and probable maximum flood must be analyzed. In combination with climate models, such data can be used to estimate flow changes for the planning and design of various hydro infrastructure.

As for the development of small hydropower systems, the most important task is to take stock of waterways suitable for such systems, i.e. waterways with suitable upstream and downstream differentials and stable water supply conditions. At present, businesses seem to prefer adding small hydropower systems to existing irrigation channels; hence, in addition to providing incentives for the installation of small hydropower systems, the Council of Agriculture of Executive Yuan can work with the Irrigation Agency to evaluate how small hydropower systems may affect water use and land use. In addition, Taiwan Power Company also pointed out that before installing small hydropower systems²²⁶, supporting measures such as connecting the generated power to the grid or using the systems for the microgrid, should also be taken into consideration. Hence, as the government promotes small hydropower systems and evaluates potential sites, relevant technologies and settings at various stages, including power generation, transmission, and use, should all be taken into consideration. On the one hand, this helps to improve relevant regulations; on the other hand, one can examine

²²⁴ Taiwan Power Company (2021). New mindset on climate change adaptation: A sustainable future of hydropower. *Taipower Journal* Vol. 706. <https://tpcjjournal.taipower.com.tw/TPMM/2021/706/#p=1>

²²⁵ Minghong Wu, Jhenyong Wang, Cingmin Wu (2015). Current status of hydropower development, environmental challenges and future prospects. *Journal of Civil and Hydraulic Engineering*, 42(4).

²²⁶ Taiwan Power Company (2021). Small hydropower systems as new green: Power plant's strengths and creativity. *Taipower Journal* Vol. 693. <https://tpcjjournal.taipower.com.tw/article/4151>

the feasibility of specific operations and management of relevant facilities and continue to enhance communication with farmers, landowners and other stakeholders.

2.8.4 Policy Recommendations

Although the contribution of hydropower to the share of the power supply will see limited growth in the future, hydropower can indirectly stabilize baseload power and the grid. At the same time, hydropower can store energy generated by other renewable energy. Therefore, even though the power generation capacity is not large, hydropower plays an indispensable role in Taiwan's power system. However, with climate change, precipitation patterns in Taiwan may fluctuate between extreme dry and wet spells. Hence, it is important to develop mid- to long-term hydropower strategies to help Taiwan achieve the goal of net-zero emissions by 2050. Our recommendations are as follows:

1. For conventional hydroelectricity, in addition to regular dredging of weirs or retention basins to ensure the normal operation of power generation units, in the long run, water resources should be managed in response to changes in river flow due to climate change and adjust the operation and maintenance strategies of hydropower plants flexibly. It is recommended that measured flow data collected by hydrological stations over the years in various river basins can be used in combination with the climate model to estimate trends of flow changes to adjust operations and evaluate the possibility of increasing the capacity factor of hydropower facilities.
2. Pumped-storage hydroelectricity can help stabilize the power supply system and strengthen emergency power supply. At the same time, it can also be used as a form of energy storage. However, pumped-storage hydroelectricity may have negative impacts on river ecology. It is thus recommended that existing reservoir sites be used to develop pumped-storage hydroelectricity to save construction costs and time. Such an approach can also balance the demand for electricity and concerns for environmental and ecological impacts. In sum, it is important to carry out an appropriate assessment of the potential influence and impact of development and consider diverse information, including socioeconomic development trends and regional development, to facilitate effective communication with the public.
3. Technologies to develop small hydropower systems have become

increasingly mature. At the present stage, it is important to take stock of suitable waters for the installation of small hydropower systems and sort out issues related to potential areas, such as water rights and land acquisition. It is also important to evaluate Taiwan's development of key technologies and the feasibility of industrial development to ensure the long-term maintenance and use of relevant equipment. A more comprehensive evaluation of the benefits brought by small hydropower systems in the aspects of environmental friendliness, domestic livelihood, and post-disaster responses is needed, but its development potential deserves our attention.

2.9 Ocean Energy

Summary

Taiwan is surrounded by sea and is blessed with abundant marine energy. The waters not far from the eastern coastline reach depths of around 1,000 meters and the Kuroshio (Black Current) flows close to the coast. The Kuroshio is the second strongest current in the world, with high fluid velocity, stability and considerable marine current energy. In addition, the annual water temperature variation between the surface seawater and deep seawater near the eastern coast of Taiwan can reach 20°C to 24°C, which makes the area suitable for developing ocean thermal energy conversion (OTEC). This involves using pipes to draw up deep seawater, which consumes little energy. The power generation process does not need fuel, does not produce any waste, and emits almost no greenhouse gases. At the same time, the power generation process will not cause air, water, or noise pollution. Moreover, OTEC can generate power all year round, so it can serve as a baseload power. In short, in order to achieve the goal of net-zero emissions by 2050, marine current power and OTEC can be included in Taiwan's carbon-free energy options. It is recommended that Taiwan's research and development (R&D) and promotion of ocean energy power generation include the following:

1. Carrying out precise hydrological and geologic surveys and exploration of areas with potential for ocean energy as soon as possible. To install marine current power generators, it would be necessary to obtain more accurate data on the marine environment, hydrology and marine terrains. Hence, precise surveys of potential areas should be carried out to gain a better understanding of the physical and biogeochemical characteristics of the Kuroshio to prepare an appropriate plan to deploy power generators, improve the efficiency of the power generation system, and reduce the impact on the ecology during the development process.
2. Investing in R&D to harness ocean energy for power generation and technology of grid connection. One must select suitable paths carefully to lay the cables and improve mooring and anchoring technology to cope with environmental challenges like tension on the mooring line. The plan should also include cable landing points and connections to the high-voltage network on land

to ensure that the electricity generated can be successfully integrated into the grid to increase power supply sources.

3. Launching a pilot power plant project and bring in international technology. Feasible sites that could be used to set up a pilot power plant utilizing marine current energy need to be identified so we can create and design a suitable operation model. At the same time, it is necessary to work with international partners to help Taiwan improve its technology in harnessing ocean energy for power generation and grid connection technology. Moreover, Taiwan needs to promote the R&D of power grid stabilization technology through field testing for a stable and safe power supply.

4. Increasing incentives by promoting infrastructure. Port facilities will be needed for working vessels to berth, so the port needs to be big enough to accommodate research and construction vessels, and the throughput capacity and wharf space of the port need to be taken into consideration when making plans for the infrastructure. The port should be located in areas close to the power generation site for quick response and better efficiency.

2.9.1 Introduction

The ocean contains a lot of energy. As the ocean absorbs the heat from the sun, the uneven heating of the surface seawater results in differences in seawater density and causes the seawater to flow. At the same time, the heating process creates temperature differences between surface and deep seawater. On the other hand, the moving air on the ocean's surface creates waves, while changes in the moon's gravitational pull generate tidal force. Therefore, approaches to harness ocean energy, based on the type of energy to be used, can be roughly divided into five types: marine current energy, ocean thermal energy conversion (OTEC), wave energy, tidal current energy, and ocean salinity energy. According to the report of the International Energy Agency's Ocean Energy Systems (IEA-OES) Technology Programme^{227,228}, theoretically, the theoretical annual energy potentials of various forms of ocean energy mentioned above are as follows: marine current energy (including tidal current and marine current) 800 billion

²²⁷ IEA-OES (2007). *Annual report 2007*. <https://www.ocean-energy-systems.org/publications/oes-annual-reports/>

²²⁸ He Wuji, Luo Shengzong, Lui Weixian (2015). Taiwan Ocean Energy. *Science Monthly* (Issue 401). http://scitechreports.blogspot.com/2015/05/blog-post_26.html

kilowatts, OTEC 10,000 billion kilowatts, wave 8,000 to 80,000 billion kilowatts, tidal current energy 300 billion degrees and ocean salinity energy 2,000 billion kilowatts.

Taiwan is surrounded by sea, with a coastline of 1,448 kilometers. According to an analysis report by the Institute of Industrial Technology (ITRI)^{229, 230} on high potential areas of ocean energy, Taiwan's marine current energy (including the Kuroshio), OTEC, and wave energy have the potential to produce gigawatts of power. In comparison, tidal current energy could only produce megawatts of power, so the industry scale is less promising. Ocean salinity energy is still in the stage of theoretical analysis and laboratory testing²³¹. Generally speaking, the coast of Taiwan offers abundant ocean energy to support its development. If ocean energy is included in Taiwan's carbon-free energy options, it could help Taiwan move one giant step forward towards reaching the goal of net zero emission by 2050.

2.9.2 Current International Development

According to the International Renewable Energy Agency (IRENA), at present, technology to harness tidal current energy and wave energy, among all other forms of ocean energy, has attracted more attention²³². Worldwide, the total installed electricity capacity of power generation facilities using ocean energy is 534.7 MW. More specifically, the installed capacity of tidal energy is 532.1 MW, which includes 521.5 MW from tidal barrage power, 10.6 MW from tidal stream, 2.31 MW from wave energy, 0.23 MW from OTEC, and 0.05 MW from ocean salinity energy. A report from Ocean Energy Europe (OEE)²³³ shows that at the time when the European Union (EU) set its target for ocean energy development, the cumulative installed capacity of wave power equipment in 2020 was merely 12 MW, and the cumulative installed capacity of tidal energy was 27.9 MW; however, by 2021, the EU increased wave energy to 3.1 MW and tidal energy to 2.9 MW. With policy support in the following years, it is expected that the EU will reach the target of 100 MW total installed capacity by 2025.

As for power generation, the International Energy Agency (IEA) estimated that

²²⁹ Industrial Technology Research Institute (2018). Taiwan's ocean energy power generation goals and strategies (PowerPoint Presentation).

²³⁰ Green Energy and Environment Research Laboratories of ITRI (2018). Ocean energy development strategies (PowerPoint Presentation).

²³¹ Bureau of Energy, Ministry of Economic Affairs (2019). Hydropower and ocean energy. Renewable energy. <https://www.re.org.tw/knowledge/more.aspx?cid=202&id=681>

²³² IRENA (2020). Ocean energy technologies.

²³³ OEE (2021). Ocean energy: Key trends and statistics 2020.

the total power generation of global ocean energy has increased by approximately 13% in 2019²³⁴. However, since the IEA's Sustainable Development Scenario (SDS) estimates that power generated by ocean energy needs to grow by 23% by 2030, there is a gap between the reality and the ideal goal. On the other hand, statistics from the OEE^{235,236} showed that the total power generated by tidal energy in Europe reached 60 GWh in 2020. The growth was quite significant when we consider the fact that power generated by tidal energy in 2018 was only about 40 GWh.

At present, most ocean energy power generation facilities generating 10 kW to 1 MW of power are located in the United Kingdom, Canada, Australia and China²³⁷. Most of them are demonstration projects and small commercial projects whose cost of power generation is expensive and have not yet reached economies of scale. In 2020, a total of 31 countries around the world have invested in the research and development of ocean energy technology²³⁸. European countries like Finland, France, Ireland, Italy, Portugal, Spain, Sweden and the UK are leading the development of ocean energy. At the same time, countries outside of Europe, including Australia, Canada, and the United States, have also invested in the development of technology to harness ocean energy. Like the European countries, these countries also play an important role in the R&D of ocean energy and manufacturing of relevant facilities.

²³⁴ IEA (2021). Ocean Power. <https://www.iea.org/reports/ocean-power>

²³⁵ Ibid., 錯誤! 尚未定義書籤。

²³⁶ Taiwan Institute of Economic Research (2021). Ocean energy--An emerging renewable energy that cannot be ignored and needs to be supported. <https://www.tier.org.tw/comment/tiermon1000.aspx?GUID=26c61d2e-832f-480e-b8b7-3feda34d02f2>

²³⁷ Ibid., 錯誤! 尚未定義書籤。

²³⁸ Ibid., 232.

2.9.3 Challenges for Ocean Energy in Taiwan

Taiwan's R&D efforts to harness ocean energy in recent years have concentrated on the (2014-2018) Offshore Wind Power and Marine Energy Projects of the National Energy Program Phase II (NEP-II). If we examine NEP-II's focus on the R&D of ocean energy, we can identify two main tasks: (1) ensuring Taiwan has offshore construction and maritime engineering capability; (2) completing pilot demonstration projects to use Kuroshio and wave for power generation. In 2019, Taiwan passed the Basic Ocean Law to coordinate and integrate the maritime powers and responsibilities of various government agencies to jointly promote maritime affairs. The *Nation Ocean Policy White Paper* was released in 2020 to present Taiwan's ocean development policies. Many countries around the world have taken steps to promote the development of ocean energy. As an island country located near the Kuroshio, Taiwan has if in a favorable position to develop ocean energy. Preliminary studies have confirmed that the southeastern coast of Taiwan has the potential to develop marine current energy. Hence, the Ocean Affairs Council (OAC) followed the example of NEP-II²³⁹ to invest in the R&D of ocean energy for Taiwan's energy transformation. According to relevant research reports in Taiwan, such as the outcome report of the Offshore Wind Power and Marine Energy Projects (2014 to 2018) under NEP-II²⁴⁰, current problems of developing ocean energy in Taiwan are as follows:

1. Ocean current generation. In Taiwan, to use ocean currents for power generation, it would be best to find locations where the Kuroshio passes close by. After all, the Kuroshio is only 20 kilometers away from the main island of Taiwan, and its current is relatively stable and contains considerable kinetic energy²⁴¹. To develop technology for marine current power generation, a Kuroshio power generation test station was established for NEP-II. The development of a 20kW Kuroshio turbine was completed as a pilot demonstration, and offshore performance testing was also carried out. Through an industry-academia collaboration, the Ministry of Science and Technology (now the National Science and Technology Council) funded a project to research "kW-level Kuroshio pilot

²³⁹ Ocean Affairs Council (2020). *2020 nation ocean policy white paper*.

²⁴⁰ Mao-Hsiung Chiang (2019). The Plan to Promote and Manage the Offshore Wind Power and Marine Energy Center of National Energy Program (V) Final report of research project subsidized by the Ministry of Science and Technology.

²⁴¹ Marine Industry and Engineering Research Center (2022). Ocean energy power generation. National Academy of Marine Research. <https://www.namr.gov.tw/ch/home.jsp?id=111&parentpath=0,6>

power-generating equipment” and establish of an open sea test platform. The project was jointly carried out by a team from National Sun Yat-sen University and Wanchi Steel Industrial Co. Ltd and aimed to verify the performance of the marine current power generation system. With the efforts of the team, the 50kW marine current power-generating equipment has been upgraded to 400kW in 2020. The National Academy of Marine Research continued the testing in 2021. Hopefully, by 2025, they will be able to complete the R&D and testing of a 2MW ocean current power generator for commercial operation. Meanwhile, the National Academy of Marine Research has worked to select a suitable national testing site for ocean current energy²⁴². At present, Cielan (Fugang) and Chenggong Xingang Fishing Port in Taitung have been selected to be the bases for ocean current power generation and pilot field testing²⁴³. The future plan is to designate the area as an international testing site to facilitate international cooperation and accelerate technological advancement²⁴⁴.

2. Ocean Thermal Energy Conversion (OTEC). As the Kuroshio passes by the coast of eastern Taiwan, the surface seawater temperature of this area stays above 24°C all year round. The slope off the eastern Taiwan coast is quite steep. Hence, the 1,000-meter isobath along the shore of Hualien and Taitung is about 3 to 5 kilometers away from the coastline. The temperature here drops to about 4-5°C, so there is a temperature difference of over 20 degrees between the surface seawater and the deep seawater. After assessment, it is determined that the area has the potential to develop OTEC. Moreover, the area does not experience large fluctuations in temperature between day and night and between winter and summer, so compared with the other forms of ocean energy, OTEC would be relatively stable and can be used as a baseload power. OTEC does not emit carbon dioxide (CO₂) and it does not compete for vital resources like food and land. Moreover,

²⁴² Marine Science and Information Research Center (2020). Planning and Assessment of a Marine Current Energy Test Site in Taiwan National Academy of Marine Research. https://www.namr.gov.tw/ch/home.jsp?id=50&parentpath=0,7&mcustomize=research_view.jsp&dataserno=202006010008

²⁴³ Yude Li (2022). The new green energy for the island country--What is ocean energy? What is the next step for Taiwan's technology? Environmental Information Center. <https://e-info.org.tw/node/234462>

²⁴⁴ Dinghong Hong (2021). Another breakthrough in marine current power generation! Completion of the plan for the national-level test site and base port. *Liberty Times*. <https://news.ltn.com.tw/news/life/breakingnews/3410410>

May to November is the best time for OTEC²⁴⁵, so OTEC can help Taiwan meet the high demand for electricity in the summer. The practical experience of an ongoing “Taitung Deep Seawater Test Pipe Project”²⁴⁶ shows that the principle of connecting pipes can be applied to draw deep seawater so the process does not consume energy. However, local characteristics need to be taken into consideration to choose suitable construction methods to install cold water pipes to draw deep seawater. Here, the Heping OTEC Plant to be built by Taiwan Cement Corporation (TCC) can be used as an example²⁴⁷. TCC plans to collaborate with CPC Corporation and rely on CPC’s drilling technology. At the same time, TCC also plans to work with technical teams in Taiwan²⁴⁸ to use high density polyethylene pipes (HDPE) to reduce offshore construction costs and improve water extraction efficiency. Generally speaking, Taiwan’s pipe-laying techniques are getting mature. However, on-site positioning is needed before, during, and after construction according to the local marine environment. Regular monitoring is also needed to effectively monitor the pipelines.

3. Wave energy. Examining Taiwan’s wave pattern data²⁴⁹, we can see that wave energy along the northeastern and eastern offshore waters and outlying island areas (west waters of Penghu) is relatively high and can reach up to 15-20 kW/m, followed by the wave energy along the east and northwest coasts at about 5-15 kW/m. The wave energy along the southwest and southern coasts is below 10 kW/m. During the R&D process of wave power generation systems, NEP-II set up a wave energy test site, built a 20kW pilot wave power generator and completed the open sea testing. However, more study will be needed to enhance the generator’s typhoon resistance before considering commercialization.

4. Tidal power. The western coast of Taiwan has mostly flat sandy beaches that are not suitable for building tidal pools. In comparison, the offshore islands of

²⁴⁵ Cianru Lin (2016). The rise of "ocean energy"! Industry, government, and academia focus on the potential of OTEC on the east coast. Environmental Information Center. <https://e-info.org.tw/node/201963>

²⁴⁶ Jin-Yuan Liu (2021). Feasibility assessment of deep seawater extraction technology and potential sites (project commissioned by the National Academy of Marine Research).

²⁴⁷ Bohong Sie (2022). Taiwan Cement works with CPC to expand the geothermal power plant in Taitung. *United Daily News*. <https://udn.com/news/story/7238/6328424>

²⁴⁸ Kwangyin Liu (2022). A SME Xizhi helped Taiwan Cement realize its dream to harness ocean energy and get 80% of orders from Philippines power plants. How? *Commonwealth Magazine*. <https://www.cw.com.tw/article/5120941?template=transformers>

²⁴⁹ Simin Lyu (2015). Wave energy is here! Can Taiwan make it? *Sci-Tech Vista*. <https://scitechvista.nat.gov.tw/Article/C000003/detail?ID=d11281e1-ce53-40d9-8bc1-96a1d5942044>

Kinmen and Matsu, with a tidal range of up to 5 meters, are suitable to develop tidal power. However, a tidal range of up to 6 to 8 meters would ideally be more suitable for developing tidal power, so more assessment would be needed to verify the potential of tidal power²⁵⁰.

Table 2.9.1 shows an estimation of various forms of ocean energy considering the coastal environment of Taiwan, the characteristics of various forms of ocean energy, as well as the technical levels and capacity factors achievable by 2050. With the exception of tidal power, whose estimated energy production is at the MW level, other forms of ocean energy, including ocean current energy, OTEC, and wave energy, are expected to reach the GW level. In total, the potential energy production of the four forms of ocean energy could reach 9.6 GW (including Kuroshio power generation). As mentioned earlier, with the exception of tidal power, whose power generation will be below 1 billion kilowatt-hours, the potential power generation of the other three forms of energy can reach 1 to 6 billion kilowatt-hours²⁵¹. Overall, ocean energy would be extremely helpful to help Taiwan increase its share of renewable energy in the electricity mix and achieve its goals of carbon reduction. Figure 2.9.1 shows the locations of high potential areas in Taiwan.

²⁵⁰ *Ibid.*, 232.

²⁵¹ Bureau of Energy, Ministry of Economic Affairs and Industrial Technology Research Institute (ITRI) (2021). Technical and scientific inspection procedures of Taiwan's energy sector and preliminary inventory of technologies in the 5+1 fields (PowerPoint Presentation). (Unpublished information)

Table 2.9.1 Assessment of Taiwan's Potential Ocean Energy^{252,253,254}

Form of ocean energy	Potential capacity (GW)	Power generation potential*	Baseload power	Potential sites
Marine current power	4 (Kuroshio) +0.2	Medium	No	Kuroshio near the eastern coast (the assessment covers four sites including Suao, Hualien, Green Island and Orchid Island) Fugueijiao, Penghu Channel
OTEC	2.8	Medium	Yes	Off the coast of Hualien and Taitung in eastern Taiwan
Wave power	2.4	Medium	No (seasonal and cyclical changes, but with high energy density)	Offshore at the northeastern coast, Fugueijiao, Penghu, Yunlin-Changhua Ridge
Tidal power	0.2	Low	No	Kinmen, Matsu

*The power generation potential is estimated based on the achievable technical level and capacity factors by 2050: high > 6 TWh, medium=1-6 TWh, low < 1 TWh

²⁵² *Ibid.*, 錯誤! 尚未定義書籤。

²⁵³ *Ibid.*, 232.

²⁵⁴ *Ibid.*, 錯誤! 尚未定義書籤。

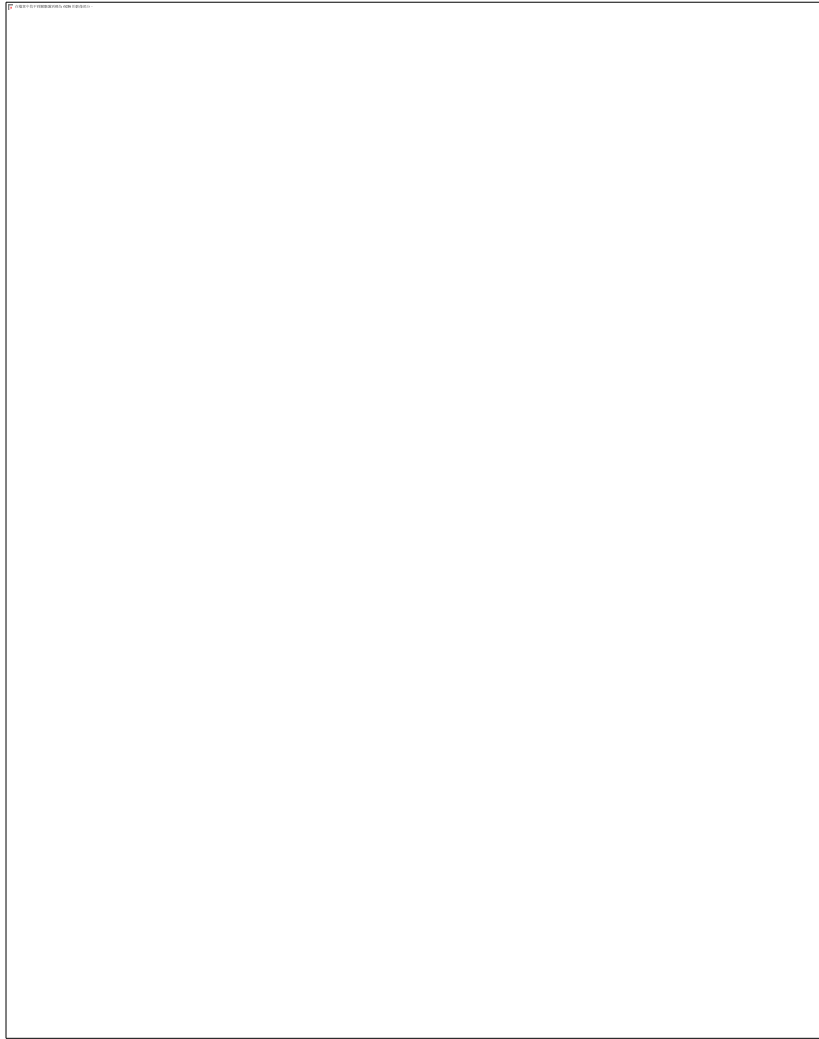


Figure 2.9.1 High Potential Areas of Ocean Energy in Taiwan²⁵⁵

2.9.4 Ocean Energy—Potential and Limitations

Ocean energy technology is considered a forward-looking technology, so the assessment of potential ocean energy in our recommendations assumes that Taiwan can harness 40% to 80% of the development potential from the three forms of ocean energy with high development potential and high potential for power generation. The initial estimations show that the installed electricity capacity can reach 3.8 to 7.5GW. It is important to point out that the capacity factors of these three forms of ocean energy vary greatly from one to the other. The capacity factors of marine current power and

²⁵⁵ *Ibid.*, note 錯誤! 尚未定義書籤。.

OTEC are higher, while the capacity factor of wave power is lower²⁵⁶. Since Taiwan does not have any actual ocean energy installations, conservative parameters have been used for the estimation. It is estimated that the annual power generation is approximately 21.2 to 42.4 billion kilowatts²⁵⁷. The potential and limitations of each form of ocean energy are elaborated as follows:

1. Ocean current energy has the advantage of sufficient energy supply, stability, large-scale commercialization potential and cost competitiveness. Kuroshio power generation also has a lot of development potential. However, the technical safety and cost of marine current energy generation still need to be evaluated because the potential site of Kuroshio power generation will need to be located on a steep slope on the seabed with a water depth of more than 300 meters, so deep water marine engineering will be a key factor affecting the development progress.
2. OTEC can provide constant power 24 hours a day, so compared with other renewable sources that are intermittent, OTEC can be used as a baseload power. At the same time, OTEC is a GW-level carbon-free energy option. Suitable sites in Taiwan are located in eastern coastal areas, including Hualien and Taitung. Apart from assessing the potential impact of typhoons and earthquakes, it is also essential to evaluate and adopt appropriate pipe-laying methods for construction in the eastern coastal area and gradually overcome the challenges related to maritime engineering, such as the use of large-diameter cold water pipes ($D > 5$ m) and floating platforms.
3. High potential areas for wave energy generation are found near the northeastern coast of Taiwan. The near-shore potential can reach up to over 13 kW/m and it is estimated that offshore potential would be higher. Taiwan is equipped with construction capabilities, but in addition to enhancing typhoon resistance of the power generators, it is also necessary to assess the potential

²⁵⁶ The capacity factor of marine current power generation is about 70 to 95%, the capacity factor of OTEC is about 90 to 95%, and the capacity factor of wave power is about 25 to 32%. Source of data: Minesto, Ocean energy, <https://minesto.com/ocean-energy>; IRENA 2014. Ocean thermal energy conversion technology brief. Lavidas; G. 2020. Selection index for Wave Energy Deployments (SIWED): A near-deterministic index for wave energy converters. *Energy* 196 (1).

²⁵⁷ If the development volume is 40%, the electricity capacity of marine current power would be 1.68GW and possible power generation would be about 10.3 billion kilowatts (with a capacity factor of 70%); the electricity capacity of OTEC would be 1.12GW and possible power generation would be about 8.8 billion kilowatts (with a capacity factor of 90%); the electricity capacity of wave power is about 0.96GW and possible power generation would be about 2.1 billion kilowatts (with a capacity factor of 25%). In total, the power generated would be about 21.2 billion kilowatts.

impact on fisheries and maritime navigation.

4. For tidal power, Kinmen and Matsu are considered suitable locations, and Taiwan has the construction capacity. However, large-area cofferdams will be needed to develop tidal power. Considering the fact that the development potential and power generation potential are not high, it is not cost-effective. Nevertheless, tidal power may help to meet the demand for power on offshore islands, so a comprehensive evaluation may be needed.

2.9.5 Policy Recommendations

The ocean covers more than two-thirds of the earth's surface and contains considerable energy. If we consider the characteristics of various ocean energy power generation technologies and high potential areas of ocean energy along Taiwan's coasts, ocean current power has strong development potential, and Taiwan has the technical foundation needed, while OTEC can be used as a baseload power supply. Hence, industry, academia and research institutes in Taiwan should keep track of international developments and accelerate R&D via international cooperation. Other technologies, such as wave power and tidal power, are highly non-periodic and there are ups and downs. The development potential of tidal power is also low, so it is not cost-effective to develop tidal power when we compare it with the former two forms of ocean energy. When we take all aspects into consideration, we can see that for Taiwan to achieve the goal of net-zero emissions by 2050, marine current power and OTEC should be included in our carbon-free energy options.

After carrying out a more detailed analysis of various conditions required to set up ocean energy power generators, including different characteristics of ocean current power and wave power, we know that the selection of the locations will be a vital first step. Hence, precise and accurate investigation of potential locations and exploration of marine resources are necessary to understand the physical conditions of the waters as well as the marine geological and ecological characteristics of the base. Moreover, if all steps and infrastructure related to the construction of open sea test sites, including environmental impact assessment, power output equipment, mooring systems, etc., are planned together, it will help to accelerate the verification process and technical research. The threat of typhoons and earthquakes due to Taiwan's geographical location should also be taken into consideration in the investigation and research, including the design of generators to improve their durability and resilience. To install ocean current

generators, Taiwan needs to carry out precise hydrological and geological surveys focusing on the Kuroshio. Proper planning to deploy power generators can help improve the efficiency of power generation efficiency; at the same time, proper planning can reduce the impact on the marine ecological environment.

When selecting where ocean energy sites, plans for grid connection and pilot power plants should also be factored in. Power plant site selection, operating models, and integration of power generation systems should be integrated. As Taiwan has limited practical experience in this area, international technology should be introduced to meet the needs of the pilot power plants for field testing. It is recommended that an assessment should be carried out to check the availability of generating units, the safety of on-site development, the cost-effectiveness of power generation, and the impact on marine ecology, so we can identify major bottlenecks for the construction of the power equipment and find appropriate solutions to ensure that renewable energy can be integrated into the grid to supply stable and safe power.

Finally, the installation of ocean energy power generators will require a sufficient number of professional construction vessels of appropriate tonnage for maritime engineering, and these working vessels also need port facilities for berthing. Hence, in addition to accelerating the research and development of ocean energy power generation technology, it is also necessary to construct relevant infrastructure to increase incentives for deploying ocean energy power generating units. To select suitable locations for relevant infrastructure, one must make sure that the location has sufficient space to provide enough throughput capacity. The port should be located near the power plant to respond to the needs of maritime engineering and improve the efficiency to deploy the generators.

2.10 Smart Grids

Summary

Taiwan has set a current goal of reaching a 20% share for renewable energy (mostly solar PV and wind power) in total power generation by 2025. If Taiwan is to reach its target of net zero carbon emissions by 2050, the share of renewable power generation will need to be increased compared to the current power mix. Solar and wind power systems are often unpredictable, affected by weather, uptime, and seasonal changes. When large amounts of these intermittent power sources are connected to existing grids, the stability and security of the power system will be impacted. To ensure the security and stability of the power supply, deploying smart grid technology across the country is an important task for Taiwan. The following measures are recommended:

1. Continue installation of low voltage smart meters in the power system to monitor electricity usage data across Taiwan. Integrate IT, AI, and big data analysis technologies to increase the operating efficiency of the power system and the safety and stability of the grid.
2. Changes to the environment and climate will affect the stability of the power supply. Weather forecasting should incorporate AI technology for daily renewable power generation forecasts, allowing more accurate scheduling for traditional power generation.
3. Install GW-scale energy storage infrastructure to compensate for the intermittency of renewable power generation, in addition to existing pumped hydropower storage and dispatch of IPP generation.
4. Allow users to participate in demand response planning, providing more diverse ancillary services to meet the demand for flexible power dispatch after the connection of large amounts of renewable energy to the grid.
5. Gradually transition Taiwan's power system to a distributed structure; facilitate the integration of low-carbon and renewable energy sources through smart grid and virtual power plant technologies, and establish advanced power distribution management systems to ensure the stability of the power supply and improve efficiency.

2.10.1 Introduction

Developed countries in Asia are planning to increase the share of renewable energy in their total power generation in order to meet their 2050 net zero goals. South Korea's draft carbon neutrality plan published in October 2020 called for a renewable energy share of up to 70% in the power mix by 2050²⁵⁸, while Japan's green growth strategy for carbon neutrality by 2050 called for the renewable energy share to be increased to 50-60% by 2050²⁵⁹. Taiwan's government has set a current target of reaching a 20% share for renewable energy by 2025²⁶⁰, but a further increase will be necessary to achieve the target of net zero emissions by 2050.

However, solar and wind power generation systems are often unpredictable, affected by weather, uptime, and seasonal changes. When large amounts of these intermittent power sources are connected to existing grids, the stability and security of the power system will be impacted. The scale and performance of the existing traditional grid is insufficient to meet future needs, as renewable energy grows and grid connections continue to increase. In the foreseeable future, Taiwan's power system will face three major problems. First, renewable energy is unstable and intermittent. As the share of renewable energy grows, smarter dispatch of traditional baseload generation and other power sources will be necessary to balance supply and demand. Second, large-scale electricity generation units have life cycles of more than 20 years. As these generation units are retired or replaced, the risk of extreme climate disasters and the need for carbon emissions reduction must be considered. How continuous generation can be maintained to improve grid resilience and the power supply stability is an important question. Third, there is a strong public consensus to reduce pollution and carbon emissions. Consumer participation in energy saving and the development of new technologies must be promoted to improve the efficiency of the power system. To maintain the efficacy and stability of the power supply and achieve an increased share of renewable energy generation, Taiwan must build a smart grid system that meets its needs.

Smart grid systems use information and communications technology (ICT) to collect data on electricity supply on the generation end and usage on the user end. The

²⁵⁸ Ministry of Environment, Korea (2021). Korea's carbon neutrality implementation plan for 2021.

²⁵⁹ National Atomic Energy Institute (2022). International net zero target response strategies and global scenario assessment.

²⁶⁰ Ministry of Economic Affairs (2019). *Renewable Energy Development Act*.

data is used to optimize electricity distribution, improving energy efficiency through digitalized and automated features. Smart grid features across the electricity supply process include: (1) generation and smart dispatch; (2) grid management (transmission, distribution, and storage); and (3) demand-side management (sale of electricity)²⁶¹. Key technologies include integrated communications technologies across the power network, advanced metering infrastructure (AMI), power distribution automation, system control, and decision planning. The US Department of Energy has allocated US\$4.5 billion to smart grid infrastructure since 2010, installing more than 15 million smart meters. It initiated several smart energy and smart grid projects starting in 2019, promoting future-ready grid integration technologies such as AI, big data analysis, and machine learning. All of these facilitate more efficient, safe, and stable grid operations²⁶². After the blackouts of 2021 in Taiwan²⁶³, public concern has grown over the government's renewable energy installed capacity targets and the effect on the power grid. Using smart grid technology to optimize the electricity supply for high efficiency, safety, and stability is now an urgent priority.

2.10.2 Developments Overseas

Countries around the world are actively working to reduce carbon emissions and increase the use of renewable energy. These countries now face the challenge of building an efficient and stable new energy system. The European Technology & Innovation Platform of Smart Networks for Energy Transition (EUTIP SNET) has pointed out that integrated energy storage and power conversion are essential to accelerating the energy transition. In addition, the power system can be the nexus for coupling various energy sources to realize the decarbonization of the entire energy system²⁶⁴. Effective integration of renewable energy in traditional power systems will require strategies including strengthening demand-side management, deploying energy storage systems alongside renewable energy, installing smart grids, and building

²⁶¹ Bureau of Energy, Ministry of Economic Affairs (2020). Overall smart grid plan. https://www.moeaboe.gov.tw/ECW/populace/content/Content.aspx?menu_id=9922

²⁶² DOE (2010). What the smart grid means to Americans. <https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/ConsumerAdvocates.pdf>

²⁶³ Ministry of Economic Affairs (2021). Review report on May 13 and May 17 blackouts. https://www.moea.gov.tw/MNS/populace/news/News.aspx?kind=1&menu_id=40&news_id=96815

²⁶⁴ European Technology & Innovation Platform of Smart Networks for Energy Transition (2018). Integrating smart networks for the energy transition: Serving society and protecting the environment.

distributed smart energy management systems²⁶⁵.

An International Energy Agency (IEA) report points out that the global pathway to net-zero carbon emissions requires an increase in grid investments to US\$1 trillion by 2040, due to the rapid electrification of various sectors, growth in electricity demand, addition of renewable energy, and replacement of older grids²⁶⁶. Current developments in smart grid technologies focus on advanced metering infrastructure (AMI), integration of distributed energy systems, ICT, and smart network management to coordinate transmission and distribution²⁶⁷.

Many developed countries are using power equipment installed over 100 years ago. These countries urgently need to invest in smart grid development to maintain the quality and reliability of the electricity supply. The Institute for Electric Innovation (IEI) in the US reports that US power companies have installed 98 million smart meters as of the end of 2020, and forecasts that the number of smart meter installations will reach 115 million by the end of 2021, covering over 75% of American households²⁶⁸. EU energy efficiency legislation has set targets for all member states to reach a smart meter penetration rate of 80% by 2020; Norway, Denmark, and Spain all forecast that their smart meter penetration rate will reach 100% by 2020²⁶⁹. In Asia, Japan is focusing on maintaining the stability of the power supply after the connection of large amounts of renewable energy to the grid, as well as household and municipal energy management planning. It will initiate the full buildout of smart meters in 2024, with the installation of 80 million devices²⁷⁰. Widespread deployment of smart grid technologies will allow the rapid gathering and application of electricity-related data through the internet of things. South Korea is also planning to complete the deployment of smart grids in larger cities by 2020, and across the entire country by 2030²⁷¹.

²⁶⁵ Lin, F.-C. (2017). Innovate technology developments in system integration: Blueprint for 2017-2021. Smart Grid Center. [http://www.smart-grid.org.tw/userfiles/vip1/01_系統整合創新技術發展-智慧電網的佈局與應用_106_-115_年藍圖規劃_\(更新\).pdf](http://www.smart-grid.org.tw/userfiles/vip1/01_系統整合創新技術發展-智慧電網的佈局與應用_106_-115_年藍圖規劃_(更新).pdf)

²⁶⁶ IEA (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector*, 2021.

²⁶⁷ *Ibid.*, 261.

²⁶⁸ IEA, Electric company smart meter deployments: Foundation for a smart grid (2021 Update). 2021/04.

²⁶⁹ European Commission (2011). Energy efficiency plan 2011. <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0109:FIN:EN:PDF>

²⁷⁰ Energy Knowledge Database (2014). Current developments in Japan's smart meter system market. https://km.twenergy.org.tw/Knowledge/knowledge_more?id=1132

²⁷¹ Huang, Y.-C. & Chiang, C. -W. (2013). Analysis of Korea's smart grid demonstration project development strategy, IEK. https://ieknet.iek.org.tw/iek rpt/rpt_more.aspx?rpt_idno=153751315

2.10.3 Current Issues in Taiwan's Smart Grid Development

Taiwan's Ministry of Economic Affairs (MOEA) launched the Overall Smart Grid Plan in 2012, aiming to build out Taiwan's smart grid in three phases over 20 years (2011 through 2030): preliminary deployment, promotion and spread, and wide adoption. Since the plan was put into action, important projects have been undertaken including power distribution automation, smart technology deployment in power substations, and smart meter installation²⁷². However, with the government spearheading energy transition policies, rapid growth in intermittent renewable energy sources could affect the overall balance of supply and demand and impact electricity dispatch in the traditional power grid. To achieve the goal of maintaining a stable electricity supply while reaching 27 GW in renewable energy generation capacity connected to the grid and a 20% share for renewables in power generation by 2025, the MOEA adjusted its targets in 2020. The updated plan includes the incorporation of advanced technologies such as energy storage and big data analysis to improve the operational stability of the power system, strengthen the resilience of the power grid, and allow users to participate in energy saving²⁷³. Plans call for developing high-power batteries for short-term storage before 2025 and high-energy batteries for longer-term storage after 2025 to help flatten the peaks and valleys of renewable generation, as well as using demand response and variable rates to redistribute user loads and improve the stability of the power system²⁷⁴.

2.10.4 Specific Measures and Targets for Smart Grid Development in Taiwan

Taiwan's centralized power system is characterized by large generation units and highly concentrated loads²⁷⁵. Existing large-scale power plants are mostly centralized and located far from users. Voltage is stepped up from the generation side before entering transmission lines, and then stepped down when supplied to users. This often results in significant power loss. With electricity demand rapidly growing in urban areas

²⁷² Ministry of Economic Affairs (2020). Overall smart grid plan. https://www.moeaboe.gov.tw/ECW/populace/content/Content.aspx?menu_id=9922

²⁷³ *Ibid.*, 272.

²⁷⁴ Ministry of Economic Affairs (2020). Public infrastructure plan to strengthen grid operation flexibility. https://www.moea.gov.tw/MNS/cord/content/ContentMenu.aspx?menu_id=25358

²⁷⁵ Chen, Y.-H., Lu, S.-Y., Chen, L.-W. & Tsuo, C.-D. (2014). *Taiwan Economic Research Monthly*. Current developments and outlook for Taiwan's smart grid industry. Issue 9, Vol. 37, pp.13-24.

and science and industrial parks, the load is geographically concentrated; however, power substations are considered undesirable facilities and frequently encounter local protests against their construction, leading to regional power supply bottlenecks. Long-distance transmission of electric power across the large grid system also poses challenges with real-time tracking of load changes and faults, increasing the risk of system failure through chain reactions. Complex large-scale grids and overly centralized generation facilities are also vulnerable to attack, endangering national security. The deployment of smart grids and the buildout of a distributed power system (see Table 2.10.1) has therefore become a guiding principle for Taiwan's energy policy, based on both security and energy considerations. Microgrids can be considered regional smart grids, incorporating both distributed power generation and municipal power. Microgrids can integrate renewable energy sources and nodes, operating either in normal mode or island mode. If municipal power is suddenly cut off, the microgrid can adjust voltage and power to maintain a stable local power supply. Deployment of microgrids is now under way in Taiwan's outlying islands and remote areas.

Table 2.10.1 Comparison of Traditional Grids and Smart Grids²⁷⁶

Feature	Traditional Grids	Smart Grids
Generation	Low number of large power plants	Small electricity suppliers
Network Design	Centralized	Distributed
Scale	Large, connected by power lines	Small and regional
Transmission	One-way	Two-way
Role of Users	Consumers only	Active participants in the grid system
Meters	Electronic or mechanical; requires human readers	Digital; remote reading
Equipment Repair	Manual inspection and testing	Remote inspection and testing
Faults	Faults must be identified manually	Automatic repairs and immediate restoration
Usage Data	Difficult to forecast	Real-time management

²⁷⁶ Chang, C.-L., Chinese Institute of Engineers (2020). Smart grid development and renewable energy monitoring. Issue 1, Vol. 93, pp. 39-49. http://www.cie.org.tw/cms/JournalFiles/10903_chapter05.pdf

To reach the energy transition goals set by the government, Taiwan will need to add renewable energy generation capacity every year and connect the new capacity to the grid. As solar and wind generation are highly dependent on weather conditions, a large gap between forecasted renewable generation and actual loads will result in major impacts on power dispatch and the stability and safety of the electricity supply²⁷⁷. Rolling blackouts may be necessary during severe shortfalls.

Solar farms begin generating power at 7 AM, and generation rapidly diminishes starting at 2 PM. As solar power is unable to provide for all-day loads, the addition of solar energy to the grid results in the so-called “duck curve” (see Box. 2.10.1). In a power system, baseload generation such as coal and nuclear are more appropriate for long-term consistent output, while gas (or oil) and pumped hydropower are better suited to immediate startup in response to rapid changes in the electricity load. In current circumstances, the power system could employ combined cycle gas generation units to ramp up and ramp down generation on short notice. Under the projected power mix for 2025 (20% renewables, 30% coal, 50% gas), traditional generation units will be gradually ramped down at a rate of 3 GW per hour starting at 9 AM, and ramped up at a rate of 2.5 GW per hour starting at 3 PM²⁷⁸. In a scenario where the share of renewable energy exceeds 50% by 2050, additional storage and demand response capacity must be added to maintain grid stability, as renewable energy will be unable to keep up with load demand. In addition, if electricity generated from renewable sources exceeds load demand, the storage or conversion of electricity into other forms of energy, such as storage systems, hydrogen, or hydropower, should be considered. This will eliminate the need to ramp down generation in the power system.

²⁷⁷ Wu, C.-C. & Cheng, Y.-H., Chinese Institute of Engineers (2020). The impact of connecting large amounts of renewable energy to the grid and power dispatch response strategies. Issue 1, Vol. 93, pp.77-88. http://www.cie.org.tw/cms/JournalFiles/10903_chapter09.pdf

²⁷⁸ Taiwan Power Company (2020). Current status of the overall smart grid plan, 1st meeting of the Executive Yuan Energy and Carbon Reduction Office, 2020.

Box 2.10.1 Renewable Energy Power Compensation²⁷⁹

When the power system includes large amounts of renewable energy, traditional power plants must take on the role of balancing the overall load. As solar generation grows during the daytime, baseload generation will ramp down (this is the duck's belly). After sunset, solar generation will decrease, requiring a rapid ramp-up in baseload generation (the duck's neck). How to rapidly adjust the baseload output in response to the enormous amount of solar power generated during the daytime is an important challenge.

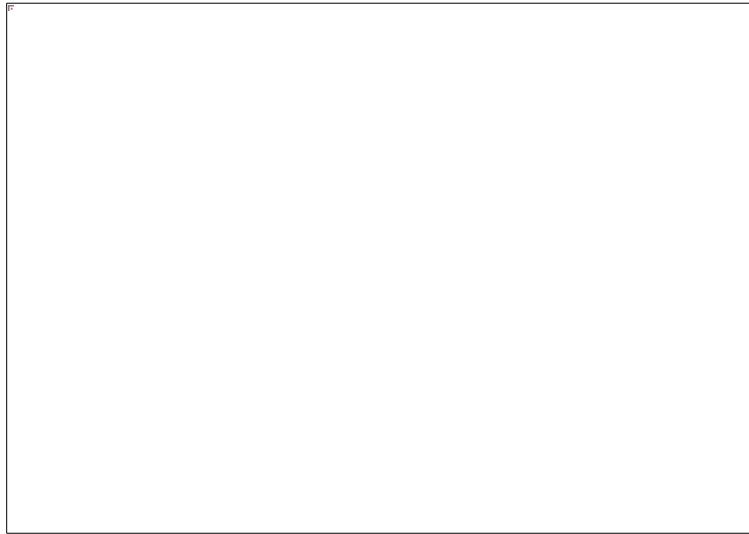


Figure 2.10.1 The Duck Curve

The development of energy storage technology in Taiwan must be planned in conjunction with the deployment timeline and scale of carbon-free energy. Energy storage systems installed at sufficient scale, integrated with the power grid, will even out the peaks and valleys of the electricity supply. This will allow the overall power system to incorporate renewable energy in a more flexible and resilient way, while maintaining the safety and stability of the power grid.

Many factors must be considered in grid-scale energy storage systems. Taiwan's current grid-scale energy storage is chiefly comprised of pumped hydropower, including the Daguan II and Mingtan Power Plants. The total capacity of these storage systems is 2.6 GW, chiefly used to support peak load usage, provide backup power

²⁷⁹ Taiwan Power Company (2021). Smart electricity usage in the evening peak, cover story, Issue 704. <https://tpcjournal.taipower.com.tw/article/4846>

when major generation units trip, and balance the output of intermittent renewable energy sources²⁸⁰ (for a description of common storage devices, see Chapter 2.11 on energy storage). With the rapid growth of renewable energy, a variety of battery technologies have also been developed, including lithium and flow batteries. Lithium-ion batteries are now a mature technology used in electronic products, and further applications include electric vehicles, energy storage systems for renewable generation, and energy storage systems for smart grids. Lithium-ion batteries are superior in energy and power density to other storage battery technologies, an advantage considering the limited space allocated to energy storage equipment installation. Other advantages of lithium-ion batteries include long cycle life and high power conversion rates. With many projects demonstrating their use in renewable energy storage, lithium-ion batteries have become the main solution for energy storage in smart grids. As countries around the world increase the share of renewable energy every year, action should be taken to assess the feasibility of grid storage. Electrolysis of water to produce hydrogen is another form of energy storage, but this solution offers far lower energy efficiency than lithium-ion batteries and cannot generate electricity on short notice. Hydrogen's advantage is as a long-term energy storage solution. However, it is impossible to predict if Taiwan's green electricity generation will ever be so high that long-term storage is an option.

In addition, as the installed capacity of renewable energy grows as a share of total capacity, real-time generation forecasts for renewable energy must be improved, incorporating weather forecasts and real-time output monitoring to improve the precision of electricity dispatch and maintain the stability of the power system²⁸¹. Energy storage systems, demand response, and the ancillary service market must also be integrated to reach net zero by 2050 (see Box 2.10.2). If renewable energy can reach 20% of total generated power by 2025, the Executive Yuan has set a goal of 1,500 MW in energy storage capacity (including storage equipment and ancillary services). The systems will be constructed by both Taipower and private companies, with all capacity purchased and dispatched by Taipower. The 1,500-MW target will include 1,000 MW

²⁸⁰ Liu, Y.-C., Tseng, Y.-C., Lu, Y.-F., Shen, C.-C. & Chung, J.-C. (2015). R&D status and developments in grid-scale energy storage technology. Issue 2, Volume 2, pp. 169-190.

²⁸¹ Wu, C.-C., Taiwan Power Company Department of Electricity Dispatch (2018). Challenges and opportunities posed by the connection of renewable energy for electricity dispatch. <https://www.ctci.org.tw/media/6359/01> 再生能源併聯運轉對電力調度-吳進忠.pdf

in system-side storage (500 MW each for high-power and high-energy battery systems) and 500 MW in generation-side storage (solar PV systems with integrated energy storage)²⁸² to maintain electricity supply during the second usage peak in the evening. The target also includes 3 GW in demand response participation to strengthen the ability to ramp up and ramp down loads, helping the system respond to the intermittency of renewable energy and any unexpected incidents in the generation units.

Box 2.10.2 Demand Response and Ancillary Services^{283,284}

Demand response refers to the use of pricing mechanisms or discounts to incentivize users to change their electricity usage patterns. This could help flatten usage peaks or reduce excess electricity during off-peak hours, maintaining the reliability and stability of the supply. Ancillary services provide reserve capacity within extremely short timeframes (measured in seconds) or relatively long periods (measured in hours). The source of this reserve capacity may include generation units, energy storage systems, or demand response.

To ensure that the stability and reliability of the overall power system can be maintained even after large amounts of renewable energy is connected to the grid, various performance specifications of renewable energy must be improved and real-time dispatch capabilities must be strengthened. Taiwan's current dispatch centers include two Central Dispatch Control Centers (in Taipei and Kaohsiung), six Area Dispatch Control Centers, and 21 Distribution Dispatch Control Centers²⁸⁵. The dispatch control centers are tasked with analyzing load changes and issuing accurate renewable energy generation forecasts based on weather forecasting, seasonal usage patterns, and economic conditions, so that reserve capacity from ancillary services may be leveraged as needed. The mean absolute percent error for day-ahead forecasts is currently 6-8%. Within the power system, voltage adjustment capabilities must be strengthened at the point of interconnection, as must the system's frequency support

²⁸² Ministry of Economic Affairs (2020). Public infrastructure plan to strengthen grid operation flexibility. https://www.moea.gov.tw/MNS/cord/content/ContentMenu.aspx?menu_id=25358

²⁸³ Chen, T.-Y., Taiwan Power Company Taipei North Branch (2018). Demand response load management measures. <https://www.taipower.com.tw/upload/135/2022021615570940851.pdf>

²⁸⁴ Chung-hua Institution for Economic Research (2021). *On the current development and competition regulations of electric power trading platforms*. <https://www.ftc.gov.tw/upload/c8bfc9a4-a8d9-4265-a742-a6e24b1c1af9.pdf>

²⁸⁵ Taiwan Power Company (2021). Electricity dispatch rules. <https://www.taipower.com.tw/upload/5570/2021033011461244698.pdf>

capabilities and abnormal voltage and frequency ride through. In terms of regulating the ramp-up and ramp-down of renewable energy, sufficient energy storage systems must be deployed for the ramp rate to ensure the stability and safety of the system. Between the smart grid and energy storage systems, power control systems are required for two-way power conversion. The development of next-generation power conversion systems is a key technology. Currently, wide bandgap semiconductor power devices use advanced materials such as silicon carbide and gallium nitride. Compared with traditional silicon-based components, silicon carbide components exhibit advantages such as good frequency cutting capability, low switching loss, and high operating frequency. This could improve the stability of the grid system and reduce power conversion losses²⁸⁶. Finally, the dispatch control centers must be equipped with various types of reserve capacity to maintain the dynamic balance between electricity generation and load within the power system. Electricity market mechanisms should also be established, allowing the procurement of ancillary services through the market in response to the impact of large amounts of renewable energy on the grid²⁸⁷.

As of August 2021, Taiwan's renewable energy installed capacity includes approximately 6 GW in solar generation and 850 MW in wind generation; real-time monitoring is available for approximately 3.5 GW of solar generation and 260 MW of wind²⁸⁸. As the intermittency of renewable generation will affect dispatch across the entire power system, Taipower is currently planning to build a platform for renewable energy generation data. The platform will integrate renewable energy monitoring, estimates, and forecasts to help dispatchers understand the output of renewable generation in real time²⁸⁹.

Strengthening grid resilience is a key objective for power system management. Taiwan's energy system is currently dominated by centralized power plants and substations; a single incident (whether naturally occurring or due to human error) could create nationwide blackouts. Grid protection plans should therefore be updated to

²⁸⁶ M. E. Levinshstein, S. L. Rumyantsev, and M. S. Shur, Eds (2001). *Properties of Advanced Semiconductor Materials GaN, AlN, InN, BN, SiC, SiGe*. New York: Wiley, 2001, pp.31-47.

²⁸⁷ *Ibid.*, 281.

²⁸⁸ Taiwan Power Company, Power supply and demand, power generation of each generating unit. <https://www.taipower.com.tw/tc/page.aspx?mid=206&cid=406&cchk=b6134cc6-838c-4bb9-b77a-0b0094afd49d>

²⁸⁹ Chang, C.-L., Chinese Institute of Engineers (2020). Smart grid development and renewable energy monitoring. Issue 1, Vol. 93, pp. 39-49. http://www.cie.org.tw/cms/JournalFiles/10903_chapter05.pdf

improve grid resilience. AI technologies should be introduced in protection coordination mechanisms to improve the accuracy of protective relay determinations, preventing impacts throughout the power grid caused by a single fault. In addition, deploying smart meters across Taiwan is another way to strengthen grid resilience. Taipower completed the deployment of high-voltage smart meters in 2014, covering 60% of electricity use nationwide. It is currently focusing on the deployment of low-voltage smart meters. As of 2020, smart meters have been installed for 1.09 million households, with deployment forecasted to grow to 3 million households by 2024 and 6 million households by 2030. This will cover 85% of electricity usage nationwide²⁹⁰. To reduce downtime during outages and greatly shorten the time needed to restore power, Taipower has also initiated the deployment of distribution automation switches. A transmission equipment maintenance system will be established, integrating GIS systems and real-time monitoring data. The system will lower average transmission system downtime from 1.62 hours currently to under 1.39 hours by 2030. The deployment of automated power lines will grow from 71% of all users currently to 95% by 2030²⁹¹. The installation of distributed energy systems is also a key solution to reduce the impact of renewable energy intermittency on power quality. Taipower's traditional energy storage units, such as the Daguan and Mingtan pumped hydropower plants, provide about 2.6 GW in storage capacity; the MOEA's Bureau of Energy (now Energy Administration) is also building energy storage equipment for solar PV stations in Longjing, Taichung and Yongan, Kaohsiung²⁹².

Users equipped with low voltage smart meters can currently obtain usage data on a 6-hour delay, and use the data to calculate their optimal electricity rate plan. In the future, Taipower will continue to accelerate the deployment of low voltage smart meters, with the goal of allowing users to obtain usage data on a 2-hour delay by 2030. Taipower could also adjust electricity rate plans as required by the regulatory authorities, raising user awareness of and participation in electricity saving. User participation in demand response plans can also flatten usage peaks through shifting or reducing usage²⁹³. To achieve the goal of net zero emissions by 2050, Taipower will leverage AI and big data

²⁹⁰ Taiwan Power Company (2022). AMI smart meter deployment website. <https://ami-meter.taipower.com.tw/views/home.php>

²⁹¹ *Ibid.*, 272.

²⁹² Huang, Y.-C., Chen, C.-C. & Go, F.-K. (2017). Grid-level energy storage system analysis in Taiwan simulation using TIMES Model. *Journal of Taiwan Energy*, Issue 1, Vol. 4, pp. 45-58.

²⁹³ *Ibid.*, 272.

analysis for preventative maintenance and renewable generation forecasts. For example, AI decision-making and big data analysis can be used for solar and wind power to build prediction models on the relationship between sunlight hours and power output, which can be used for system dispatch and scheduling for traditional generation²⁹⁴.

Taiwan's power system is dominated by centralized power plants. The system includes generation sources, transmission networks, distribution networks, and users. With much of the generation capacity concentrated in the south and usage concentrated in the north, line losses resulting from long-distance transmission leads to poor usage efficiency and power quality. The concentration of the load in certain cities and industrial zones has also led to problems with transmission bottlenecks and frequent faults. To accelerate the development of renewable energy, a gradual transition from the current centralized power supply to distributed supply should be initiated. After such a transition, the system will be simplified to consist of only generation sources and users, with perhaps the addition of the distribution network. This will greatly improve usage efficiency and power quality, and allow regional self-sufficiency in electricity. The development of microgrid technologies will also mitigate regional grid supply issues stemming from the voltage fluctuations caused by the connection of large amounts of renewable energy sources to the grid. The distributed grid will also reduce the energy loss (approximately 10%) resulting from complex long-distance power lines that are necessary under a centralized network.

Taipower's real-time electricity usage data shows that Taiwan's northern and southern regions use the most electricity, at 10.68 GW and 10.74 GW respectively; the central and eastern regions use 9.4 GW and 0.39 GW respectively²⁹⁵. As energy usage and supply varies across regions, each region will have a different deployment strategy for renewable energy and smart grids. The northern region has high usage but little generation available, relying on transmission from the south to meet peak usage demand. It can serve as the energy demand hub focusing on demand response strategies. The central and southern regions are rich in wind and solar respectively, so energy storage systems and virtual power plants should be the priority (see Box 2.10.3). The eastern region is rich in geothermal and ocean energy, which can fully meet regional usage

²⁹⁴ Taiwan Power Company (2022). Renewable energy generation forecasts: Decoding wind and solar. Cover story, Issue 691. <https://tpcjournal.taipower.com.tw/article/4029>

²⁹⁵ Taiwan Power Company (2022). Power information of today. <https://www.taipower.com.tw/tc/page.aspx?mid=206>

demand and reduce the need for transmission; power lines for excess electricity may be needed if generation grows. In the future, Taipower's regional offices can also collaborate with county and city governments to establish regional energy management and supply centers.

As regions plan their distributed energy systems, they can build mid-size or large renewable energy power plants that provide ancillary services to the grid. In conjunction with energy storage, this can smooth out the renewable energy curve and maintain power quality and the stability of the electric power supply²⁹⁶. In addition, city-scale virtual power plants can also be developed. Users in major urban areas can be incentivized to participate in the power system by installing renewable energy and energy storage equipment. This will broaden demand response sources to stabilize urban power supply. As for the development microgrids, Taiwan's microgrid projects include disaster prevention grids, outlying island grids, and community grids. The National Atomic Research Institute under the Executive Yuan's Atomic Energy Council has built a community microgrid demonstration site in Longtan, Taoyuan. The site is capable of independent operations to supply electricity, and of balancing electricity supply and demand in conjunction with Taipower's dispatch control center²⁹⁷. In the future, microgrids can be further expanded to integrate regional electricity resources, ultimately covering entire cities.

Box 2.10.3 Virtual Power Plants²⁹⁸

Virtual power plants integrate user-end energy management systems, distributed energy systems, and energy storage systems to provide short-term power dispatch to meet peak load demands. They can also be used with variable electricity rates to incentivize different usage patterns, balancing supply and demand in the power system.

²⁹⁶ Lin, F.-C. (2018). Regional electricity supply challenges and responses in Taiwan's energy transition. <https://www.ctci.org.tw/media/6334/主題4台灣能源轉型之區域供電挑戰與因應.pdf>

²⁹⁷ Taiwan Power Company (2018). Small is new big: The future of the electricity grid. Feature, Issue 672. <https://tpcjournal.taipower.com.tw/article/2887>

²⁹⁸ Chen, Y.-H., Lu, S.-Y. & Lin, F.-C. (2013). An introduction to the concept and operations model of virtual power plants. *Power Electronics Journal*, Issue 11, pp. 46-53.

2.10.5 Policy Recommendations

Based on the government's plans to increase the share of renewable energy generation by 2025, it can be anticipated that large amounts of renewable energy will be connected to the current power system by 2050. This will have an enormous impact on the power system. Changes in the climate will also affect the stability of the power supply and increase the difficulty of generation and load forecasts. In response to the intermittency and unpredictability of renewable energy, Taiwan must continue the deployment of low voltage smart meters to resolve bottlenecks in the traditional power system, with the goal of covering 100% of Taiwan's electricity users in the future. Advanced ICT technology and equipment, management systems, and big data analysis must also be introduced to improve the operating efficiency and power quality of the electricity system and the safety and stability of the grid. Weather forecasting models must be integrated with generation system models and AI algorithms to predict current and next-day power generation, so that traditional generation can be properly scheduled to compensate for the intermittency of renewable energy. In addition to adding pumped hydropower for rapid response and dispatching IPP generation capacity, Taiwan should also continue to install GW-scale energy storage infrastructure. As usage demand grows annually, Taiwan must continue to strengthen electricity dispatch capabilities. Measures in the future could include increasing the added value of AMI technology, improving household energy management systems, opening demand response participation to more users, establishing appropriate market mechanisms or trading platforms for electricity, and establishing a sufficient amount of diverse ancillary services for the dispatching system. All of this will help electricity dispatch to meet real-time needs after the connection of large amounts of renewable energy, allowing a balance to be maintained between generation and load in the power system. In the future, infrastructure deployment and electricity dispatch in Taiwan's overall power system should transition from centralized to distributed, and from supply-side management to demand-side management. The integration of renewable and low-carbon energy sources should be facilitated through building smart grids and virtual power plants, and advanced distribution management systems should be built to improve supply efficacy. This will allow Taiwan to meet its 2050 net zero targets.

2.11 Energy Storage

Summary

The high proportion of wind and solar energy in Taiwan's renewable energy mix presents significant technical challenges due to their intermittent nature. The power supply from these sources fluctuates greatly based on seasonal changes, climatic conditions, and the Earth's rotation, leading to potential instability in the entire grid and difficulties in transmission and regulation. To mitigate these impacts and maximize the use of renewable energy, it is essential to establish appropriate energy storage systems that can act as buffers, smoothing out supply peaks and valleys, and preventing the intermittency of renewable energy from affecting grid stability.

One viable option for energy storage is the use of batteries. Batteries are not only suitable for grid energy storage but also play a critical role in electric transportation vehicles. Batteries have the advantage of a longer lifespan and smaller size, making them particularly well-suited for use in passenger cars. In contrast, hydrogen/fuel cells, due to their higher energy density, are more appropriate for long-haul transportation, such as trucks.

Given Taiwan's development status and international trends, the following measures are recommended:

1. Build sufficient grid-scale battery energy storage systems to support high proportions of renewable energy.
2. Develop key energy storage technologies required for transportation electrification, such as battery storage for passenger cars and hydrogen/fuel cell power generation for large vehicles.
3. Develop high-energy-density, high-safety grid-scale storage technologies, such as all-solid-state lithium batteries and flow batteries.
4. Develop environmentally friendly battery materials, designs, and recycling technologies.
5. Encourage private sector investment in energy storage system R&D, installation, and expansion.

2.11.1 Introduction

Energy storage is an essential auxiliary service within the power system, integrated with smart grids (refer to Section 2.10 of this chapter), and functions as an energy carrier providing charge and discharge services. It helps to mitigate the impact on grid stability caused by the significant variability of renewable energy sources, which are highly intermittent. By smoothing out fluctuations in power supply and demand, energy storage systems maximize the utilization of renewable energy.

In Taiwan, where wind and solar energy are the primary focus of renewable energy development, the power supply from these sources can fluctuate significantly due to changes in seasons, weather, and time of day. Since renewable energy accounted for only 5.99%²⁹⁹ of Taiwan's energy mix in 2021, achieving the target of net-zero emissions by 2050 will necessitate a substantial expansion of renewable energy. Driven by this policy, the share of renewable energy generation is expected to continue growing, leading to significant fluctuations in instantaneous power integrated into the grid.

Given Taiwan's isolated power system, which cannot rely on cross-border power transmission and regulation with neighboring grids, the country must rely on its own generation and dispatch planning to maintain a balance between power supply and demand and ensure system frequency stability³⁰⁰. Failure to do so could lead to grid congestion, regional voltage instability, and even severe frequency fluctuations that could disrupt the entire power system³⁰¹. Alternatively, if Taiwan is to maintain grid stability, it might have to forgo integrating the excess instantaneous power generated by renewable energy, leading to significant economic waste and the loss of the original intent behind using renewable energy as a means to “accelerate power decarbonization” by replacing traditional, high-pollution, high-emission fossil fuel power sources. To achieve the goal of “Accelerating Power Decarbonization,” it is crucial to establish sufficient energy storage systems and integrate them with the grid to accomplish peak

²⁹⁹ Energy Statistics Section, Bureau of Energy, Ministry of Economic Affairs (2022). 1-01 energy indicators. https://www.esist.org.tw/publication/page01_detail?Id=30de463d668https://www.esist.org.tw/publication/monthly_detail?Id=1b14a5cffb2dhttps://www.esist.org.tw/publication/monthly_detail?Id=1b14a5cffb2d

³⁰⁰ Wu, G.-B., Wu, C.-C., Tsai, H.-T., Chen, C.-Y. & Liang, P.-F. (2020). Current and future development of frequency regulation service in international independent power systems. https://km.twenergy.org.tw/Publication/thesis_down?id=266

³⁰¹ Wu, J.-Z. & Cheng, Y.-H. (2020). The impact of large-scale renewable energy integration on the grid and power dispatch strategies. *Engineering*, Issue 1, Vol. 93, pp. 77-88. http://www.cie.org.tw/cms/JournalFiles/10903_chapter09.pdf

load shifting (Box 2.11.1).

Grid-scale energy storage systems involve multiple factors. Currently, pumped hydropower is the dominant form of energy storage, but with the rapid growth of renewable energy, various storage systems and batteries have been developed. Battery storage is particularly advantageous for its ability to charge and discharge rapidly, adjust to instantaneous power changes to maintain grid stability, and perform peak load shifting³⁰². While traditional pumped hydropower can also store excess energy, its installation is limited by geographical requirements, and the increasing risk of water shortages due to global climate change can further impact its storage capacity. Therefore, alternative solutions must be considered.

Battery storage is less constrained by natural geographical conditions and offers a wide range of storage technologies that can meet different discharge duration requirements, from seconds to hours, or even days. Due to their longer lifespan and relatively smaller size, batteries are the preferred option for energy storage in vehicles, particularly for passenger cars. Hydrogen produced through electrolysis can also be used as a form of energy storage, but its energy efficiency ranges from only 25% to 45%, which is significantly lower than that of lithium-ion batteries, and it cannot meet short-term storage needs. Its main advantage lies in its potential for long-term energy storage. However, whether Taiwan will have sufficient green electricity to necessitate long-term storage is still uncertain. In the event of an oversupply of green electricity, the more likely solutions would be battery storage and reducing the load on gas-fired power units. Furthermore, hydrogen/fuel cells, due to their high energy density, are more advantageous for long-haul transportation, such as heavy trucks.

³⁰² Peak load shifting refers to charging batteries with renewable energy during periods of low electricity demand and releasing stored energy to the grid during peak load periods for use.

Box 2.11.1: Renewable Energy Time-Shift Benefits with Energy Storage Systems

The intermittency of renewable energy poses a serious threat to grid stability. Energy storage can smooth out energy flows and help achieve a balance between power supply and demand. For example, when solar power generation peaks at noon, and demand for electricity is lower than the supply, energy storage can effectively store the excess energy and deploy it or connect it to the grid later, based on the power system's load requirements. This achieves the time-shift benefits of renewable energy power plants, such as solar PV plants. As a result, renewable energy, when combined with energy storage, becomes dispatchable, allowing for a separation between power generation and supply.

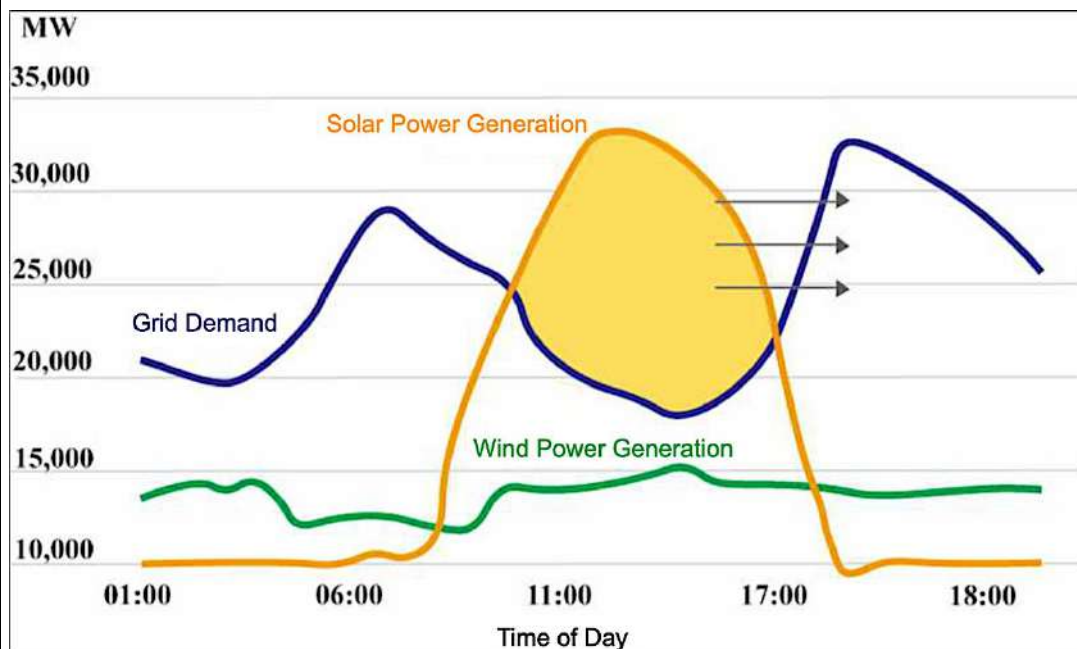


Figure 2.11.1 Renewable Energy Time-Shift Benefits with Energy Storage Systems³⁰³

Grid-scale energy storage systems not only expand the grid's capacity to integrate renewable energy and reduce the need for additional peak-load generation units or capacity but also assist in frequency and voltage regulation during power generation. In the event of a power supply imbalance caused by unexpected incidents in the transmission system, energy storage can replace traditional backup generation units (such as thermal power plants) to supply power instantly, preventing a rapid decline in

³⁰³ Auclimate (2018). Battery storage: The answer to renewable energy intermittency. <https://auclimate.wordpress.com/2018/04/17/battery-storage-the-answer-to-renewable-energy-intermittency/>

system frequency and maintaining power supply quality. Additionally, in the event of a complete power outage caused by a system failure, energy storage systems can automatically restore power, delaying the need for transmission and distribution system investments and stabilizing voltage to ensure grid safety. For end-users, installing energy storage systems can also provide time-of-use rate management functions, such as reducing the demand contract capacity between large electricity users and power companies, increasing self-consumption rates, and serving as backup power³⁰⁴. Thus, energy storage is a suitable auxiliary service technology for accelerating the decarbonization of the power system.

Recently, the significant decline in the upfront costs of energy storage investments, increasingly favorable regulatory frameworks, the completion of early-stage projects, and knowledge-sharing have driven a rapid expansion of battery storage systems globally³⁰⁵. In the United States, for example, the cost of utility-scale battery storage dropped by nearly 70% from 2015 to 2018³⁰⁶. Many U.S. local governments now require public utilities to source a certain percentage of their electricity from renewable energy. Coupled with federal tax incentives, renewable energy has expanded rapidly, and with continuous improvements in energy storage technology, it is starting to challenge the dominance of traditional natural gas power plants as the cost of electricity from renewable sources quickly drops. For instance, Vistra, a company that owns 36 natural gas power plants in the U.S., recently abandoned plans to build new gas power plants and instead shifted its investments to developing solar power plants and energy storage in Texas and California as part of its business transformation³⁰⁷.

Although the global outlook for energy storage systems is promising, in practice, battery storage systems still face several challenges: the complexity of the systems, along with the high integration requirements, results in higher installation costs; long-term charge and discharge operation may cause overheating, potentially leading to fires

³⁰⁴ Wang, J.-G., Chiu, P.-C., Hsu, H.-C. & Liu, C.-C. (2019). *Opportunities and challenges for the energy storage industry under the trends of energy transition*, CTCI Foundation. <https://www.ctci.org.tw/8838/publication/10798/42530/>

³⁰⁵ IRENA (2019). Innovation landscape brief: Utility-scale batteries, International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Utility-scale-batteries_2019.pdf

³⁰⁶ U.S. Energy Information Administration (2020). Utility-scale battery storage costs decreased nearly 70% between 2015 and 2018. <https://www.eia.gov/todayinenergy/detail.php?id=45596>

³⁰⁷ Blunt, K. (2021). Natural gas, America's no. 1 power source, already has a new challenger: Batteries. *The Wall Street Journal*. <https://www.wsj.com/articles/batteries-challenge-natural-gas-electric-power-generation-11620236583>

or explosions; and the liquid electrolytes in mainstream lithium-ion batteries are prone to evaporation and leakage issues. Additionally, the environmental issues associated with large quantities of discarded batteries remain a significant challenge. Therefore, innovative approaches are needed to address these challenges to successfully expand the application of battery storage systems.

The ICT industry is one of Taiwan's existing strengths, providing a solid foundation for developing battery storage technologies. The battery industry can also play a critical role in Taiwan's economic development and national security. Besides serving as a complementary power system option for zero-carbon electricity, it can also help mitigate natural disasters, reduce the risks of cyber and military attacks, and create jobs in the industry. Moreover, it can support the electrification of transportation to reduce carbon emissions in the transportation sector. Therefore, when assessing Taiwan's potential for developing zero-carbon energy, energy storage system technologies must be incorporated as a complementary part of the carbon reduction strategy, to explore how advancements and deployments in these technologies can contribute to and enhance Taiwan's carbon reduction efforts.

2.11.2 International Development Status

Energy storage technologies can be broadly categorized into four types based on their principles: (1) Gravity/Mechanical Technologies, (2) Electrochemical Technologies, (3) Electromagnetic Storage, and (4) Other Storage Technologies (Hydrogen/Fuel Cells). The various sub-technologies are illustrated in Figure 2.11.2.

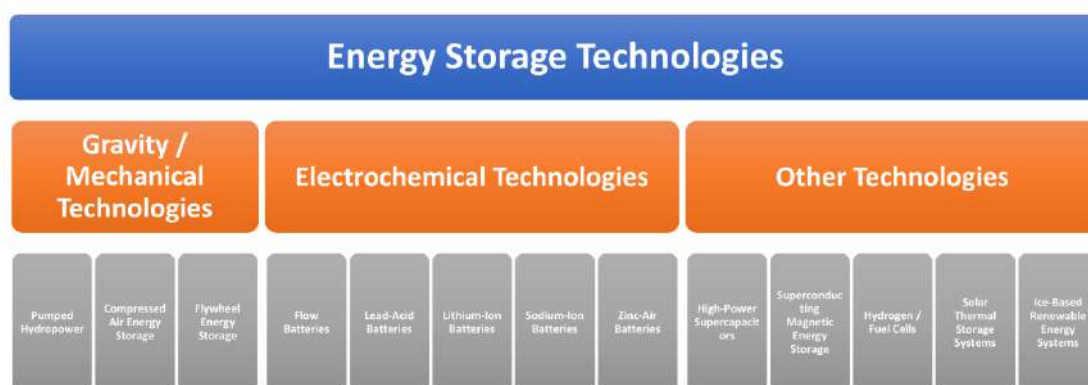


Figure 2.11.2 Types of Energy Storage Technologies

Almost all energy storage systems can be applied to grid-scale storage, including pumped hydropower, compressed air energy storage, flywheel energy storage, flow batteries, lead-acid batteries, lithium-ion batteries, sodium-ion batteries, zinc-air

batteries, high-power supercapacitors, superconducting magnetic energy storage, hydrogen/fuel cells, solar thermal storage systems, and ice-based renewable energy systems. Suitable energy storage systems for mobile applications, such as vehicles, include lithium-ion batteries, flow batteries, lead-acid batteries, sodium-ion batteries, zinc-air batteries, high-power supercapacitors, hydrogen/fuel cells, and flywheel energy storage, as detailed in Table 2.11.1.

It is crucial to identify the projects for which Taiwan has the strongest technical capabilities and that are most suitable for implementation. Starting with more mature technologies, pumped hydropower (a non-battery type) under gravity/mechanical technologies, lead-acid and lithium-ion batteries under electrochemical technologies, as well as solar thermal storage and ice-based renewable energy systems under other technologies, are currently the most advanced options. Pumped hydropower offers advantages such as technical maturity, low cost, and large-scale deployment, but site selection is constrained by geographical conditions. Furthermore, as Taiwan's rainfall patterns trend towards extremes due to climate change, water shortages during dry seasons could impact the functionality of hydroelectric facilities, limiting their load-regulating capabilities. Therefore, optimizing domestic hydroelectric operations remains essential. For a detailed analysis, see the section on hydroelectric power (Section 2.8).

Lead-acid batteries have a short lifespan and poor depth of discharge. If not properly recycled, they can cause pollution and are expected to be gradually replaced by lithium-ion batteries. Lithium-ion batteries, with their longer lifespan, relatively smaller size, and greater environmental friendliness, have become the mainstream technology in international development; however, as their application expands, it is crucial to manage the risk of overheating, which can lead to explosions and fires, necessitating continuous improvements in manufacturing technology. The installation capacity of solar thermal storage systems in Taiwan is nearing saturation, while the modular capacity of ice-based renewable energy systems is small, requiring large-scale installation to achieve the effects of peak load shifting.

Another emerging battery technology that has recently gained attention is the all-vanadium flow battery, a type of flow battery that utilizes the redox reactions of vanadium ions for charging and discharging. This energy storage battery offers advantages such as the electrolyte being resistant to degradation, the ability to store energy for 8 to 10 hours, a long service life, no risk of overheating or combustion, and

high safety. It has already begun to be used by power companies for capacity management and frequency regulation. For example, in 2020, the California Energy Commission (CEC) selectively funded four energy storage projects using vanadium flow batteries from the UK's Invinity Energy Systems plc as long-duration storage options³⁰⁸. It's a potential direction for research and investment for Taiwan.

For less mature technologies or those that Taiwan has not traditionally engaged with, several examples are noteworthy. Compressed air energy storage, a gravity/mechanical technology, involves using excess electricity during off-peak times to compress air, which is then stored in underground tanks under high pressure. When needed, the stored energy is released via turbines. In 2021, Canadian startup Hydrostor launched a massive compressed air energy storage project in California, with two plants capable of storing over 10 GWh of electricity³⁰⁹. However, this technology requires suitable geological conditions, and Taiwan must conduct thorough evaluations to determine if such conditions exist domestically.

Flywheel energy storage involves accelerating a flywheel (or rotor) to high speeds, storing energy in the form of rotational kinetic energy³¹⁰. It has a long lifecycle and a certain energy density, but its primary applications remain in areas where battery replacement is impractical or maintenance costs are high, such as in space exploration, automotive, and railway sectors. Additionally, large-scale application of flywheel energy storage requires significant financial investment.

In the field of electrochemical technologies, sodium-ion batteries are currently being actively developed and manufactured by China's CATL, the world's largest electric vehicle battery manufacturer^{311,312}. These batteries offer the advantage of low cost for large-scale use and reliance on sodium salts derived from seawater, reducing dependence on lithium resources. However, sodium-ion batteries have lower energy density and shorter lifecycles, presenting commercialization challenges. They are

³⁰⁸ Largue, P. (2020). California Energy Commission opts to fund vanadium flow batteries, Smart Energy International. <https://www.smart-energy.com/storage/california-energy-commission-opts-to-fund-vanadium-flow-batteries/>

³⁰⁹ Irving, M. (2021). World's largest compressed air grid "batteries" will store up to 10GWh, New Atlas. <https://newatlas.com/energy/hydrostor-compressed-air-energy-storage/>

³¹⁰ Mechanical energy storage: The emergence of flywheel battery. <https://scitechvista.nat.gov.tw/Article/C000003/detail?ID=5f965866-0fc9-4d63-ab42-5dc045c5db9d>

³¹¹ Sung, W.-C. (2021). *CATL's patent strategy for sodium-ion battery anode materials*, Patent Search Center. <https://www.psc.org.tw/upload/17/2021120914485134203.pdf>

³¹² Bloomberg News (2021). Tesla battery supplier CATL debuts cheaper sodium-ion batteries. <https://www.bloomberg.com/news/articles/2021-07-29/catl-debuts-sodium-ion-batteries-amid-raw-material-cost-spike>

expected to be more suitable for automotive applications as power batteries in the future. Zinc-Air Batteries offer a cost advantage over lithium batteries due to the use of zinc as the material. However, currently their power output and scalability cannot compete with lithium and lead-acid batteries. Zinc-air batteries are mainly used in off-grid rural areas and are still relatively in the research and development stage^{313,314}.

In the field of electromagnetic storage technologies, high-power supercapacitors offer advantages such as fast charge and discharge speeds and a high number of usage cycles. However, they have high development costs, large size, and low capacity density. Taiwan currently has small-scale supercapacitor technology but lacks the capabilities for grid-scale capacitor technology. Superconducting magnetic energy storage technology allows for long-term energy storage with minimal losses, high energy density, and fast response speed. However, superconducting coils must be maintained at low temperatures to sustain superconductivity, limiting their application scope.

In other storage technologies, hydrogen/fuel cells, particularly hydrogen storage, are seen by the International Energy Agency (IEA) as having future potential under scenarios with a high proportion of renewable energy. With a high energy density (compressed hydrogen at 40 kWh/kg)³¹⁵, hydrogen energy can provide long-duration storage. However, there are considerable challenges in developing high-density and safe hydrogen storage and transportation technologies. Additionally, hydrogen production must adhere to carbon-neutral principles; if hydrogen is produced locally through the electrolysis of water using green electricity, the supply and demand dynamics of the green electricity must be carefully assessed. Essentially, green electricity is most efficient when used immediately, and if it cannot be used immediately, it should be stored in batteries, pumped hydropower, or hydrogen produced through electrolysis. If there is a surplus of green electricity over the long term, it could support large-scale green hydrogen production through electrolysis. For a detailed analysis, refer to Section 2.5 on “Hydrogen Energy.” Hydrogen/fuel cells, with their high energy density, are advantageous for long-haul transportation and are more suitable for large-

³¹³ E360 (2018). How a new zinc-air battery could transform the grid. <https://e360.yale.edu/digest/how-a-new-zinc-air-battery-could-transform-the-grid-nantenergy>

³¹⁴ Tsai, C.-L. (2019). A brief overview of the research progress on zinc-air flow fuel cells, *Science Monthly*. <https://www.scimonth.com.tw/archives/2037>

³¹⁵ The Copenhagen Centre on Energy Efficiency (2019). Analysis of hydrogen fuel cell and battery efficiency (Presentation). https://c2e2.unepdtu.org/kms_object/analysis-of-hydrogen-fuel-cell-and-battery-efficiency-presentation-27-02-2019/

scale, long-duration grid-scale storage applications compared to battery storage.

For a detailed comparison and evaluation of the advantages and disadvantages of various energy storage technologies mentioned above, see Table 2.11.1. For suitable application fields for each energy storage technology, refer to Appendix 2J.

Table 2.11.1 Comparison and Evaluation of Various Energy Storage Technologies^{316,317}

Principle	Energy Storage Technology	Advantages	Disadvantages	Durability (Years)	Applicable Field(s)	Does Taiwan Have Technical Capability or Installation Potential?
Gravity/ Mechanical Technology	Pumped Hydropower	Technically mature; high storage capacity; can support peak loads immediately; easy to scale up	Low energy density; site constraints; long charge/discharge reaction time	> 20 years	Grid	★★★
	Compressed Air Energy Storage	Technically mature; low cost; large scale and flexible; integrates with gas turbines	Requires suitable geological conditions; not suitable for small capacity applications; affected by natural gas prices	20 years	Grid	- (No suitable geology available)
	Flywheel Energy Storage	High energy density and flexibility for short-term applications;	Low storage capacity; prone to overheating; sensitive to	>20 years	Grid, UPS, Vehicles	- (Not installed)

³¹⁶ Sandia National Laboratories (2019). Energy storage systems. <https://www.osti.gov/servlets/purl/1643349>

³¹⁷ Canadian Energy Research Institute (2019). Electricity storage systems: Applications and business cases. <https://ceri.ca/files/publications/427>

Principle	Energy Storage Technology	Advantages	Disadvantages	Durability (Years)	Applicable Field(s)	Does Taiwan Have Technical Capability or Installation Potential?
		high energy for long-term applications; can integrate with AC motors	vibrations			
Electro-chemical Technology	Flow Battery	All-vanadium flow batteries are flexible scale-wise; stable storage capacity; no heat dissipation issues; long cycle life	Zinc-bromine technology must meet specific power specifications High cost; efficiency decreases with rapid charge/discharge; acidic electrolytes pose pollution risks	20 years	Grid, Vehicles	★ (Research stage - prototype testing)
	Lead-Acid Battery	Technically mature with a well-established recycling system; low cost	Short lifespan; poor depth of discharge; poor performance when not entirely charged; acidic electrolytes could cause pollution	5~10 years	Grid, Vehicles	★★★

Principle	Energy Storage Technology	Advantages	Disadvantages	Durability (Years)	Applicable Field(s)	Does Taiwan Have Technical Capability or Installation Potential?
	Lithium-Ion Battery	Diverse chemical compositions; rapidly declining costs due to production scale-up; high efficiency and energy density	Currently high cost; safety issues with overheating; limited cycle life; requires better manufacturing technology for optimal performance	10 years	Grid, Vehicles	★★★
	Sodium-Ion Battery	High-temperature applications are relatively mature; low-temperature applications are still in development, but it's relatively safe and has potential for low-cost deployment	High cost for high-temperature applications with combustion concerns; low efficiency and high cost for low-temperature applications; poor cycle performance	10 years	Grid, Vehicles	- (High-temperature sodium-sulfur not installed; low-temperature in development)
	Zinc-Air Battery	High depth of discharge; safe for long-term use	Still in the research stage, low efficiency; low cycle life and charge/discharge rate	10 years	Grid, Vehicles	★ (Research stage)

Principle	Energy Storage Technology	Advantages	Disadvantages	Durability (Years)	Applicable Field(s)	Does Taiwan Have Technical Capability or Installation Potential?
Electro-magnetic Storage	High-Power Supercapacitor	High charge/discharge speed; high cycle count	High development cost; large size; low capacity density	>10 years	Grid, Vehicles	- (Small-scale supercapacitor technology available; lacks grid-scale capability)
	Super-conducting Magnetic Energy Storage	Long-term energy storage with minimal losses; high energy density; fast response speed	Superconducting coils require low temperatures to maintain superconductivity; high cost; increases energy consumption; limited system installation	<10 years (Low-temperature system lifespan)	Grid	- (Lacks relevant technical capabilities)
Other Energy Storage Technologies	Hydrogen Energy/Fuel Cells	Suitable as a medium to long-term energy storage option	High-density and safe hydrogen storage/transport technology presents significant challenges; hydrogen production technology must lower costs to be competitive	10 years	Grid, Vehicles	★ (Battery capacity and hydrogen storage density are in need of improvements; costs need to be lowered; related applications are not yet developed)

Principle	Energy Storage Technology	Advantages	Disadvantages	Durability (Years)	Applicable Field(s)	Does Taiwan Have Technical Capability or Installation Potential?
	Solar Thermal Storage System	A widely used renewable energy source; advantageous in areas with good sunlight conditions	Technology is well developed; domestic installation capacity is nearly saturated	20 years	Grid	★★★ (Technology is very mature)
	Ice-Based Renewable Energy System	Helps shift peak electricity demand; reduces power plant capacity requirements and carbon dioxide emissions	Small modular capacity; higher cost compared to general air conditioning, requires large-scale installation to achieve peak load shifting effects	15 years	Grid	★★★ (Technology is very mature)

In terms of the development direction and goals for battery storage technology, international organizations have also established relevant development indicators and made forecasts. For example, the U.S. Department of Energy set the Energy Storage Grand Challenge Roadmap in 2020³¹⁸, aiming to reduce the long-term stationary application costs of battery storage by 90% by 2030, compared to 2020 baseline levels, achieving a levelized cost of \$0.05 USD/kWh. As increasing battery energy density is one method to reduce costs, the U.S. Department of Energy's Battery500 Consortium, launched in 2017, focuses on developing next-generation lithium metal anode batteries

³¹⁸ U.S. Department of Energy (2020). *Energy storage grand challenge roadmap*. <https://www.energy.gov/sites/default/files/2020/12/f81/Energy%20Storage%20Grand%20Challenge%20Roadmap.pdf>

that can provide up to an energy density of 500 Wh/kg (for use in vehicles). By 2020, the consortium announced interim results, achieving an energy density of 350 Wh/kg and extending cycle life to over 350 cycles³¹⁹.

South Korea's 5th Science and Technology Forecast Survey predicts that between 2025 and 2027, it will be possible to develop energy storage systems (ESS) with high capacity and long life using low-cost metals³²⁰. As a result, emerging storage technologies that do not rely on lithium and other rare earth or precious metals as battery materials will require continued attention and assessment for long-term strategic planning.

In late 2020, the European Union proposed new legislative proposal aimed at setting requirements for battery sustainability (such as carbon footprint rules, minimum recycled content, performance and durability standards), safety, battery marketing and service labeling, and waste management conditions. For example, the proposal stipulates that recycled materials must account for a certain proportion of the primary materials in batteries. Starting from January 2030, the mandated proportions for recycled cobalt, lead, lithium, and nickel in batteries will be at least 12%, 85%, 4%, and 4%, respectively. The plan is to adjust these ratios to 20% cobalt, 10% lithium, and 12% nickel by January 2035, with the proportion of lead remaining unchanged^{321, 322}. Therefore, in addition to pursuing higher energy density and cost-effectiveness in battery storage, it is also necessary to pay attention to the development of supporting technologies as required by international trends, such as the use of environmentally friendly materials, and focus on environmental-friendly design and recycling technologies.

Hydrogen energy/fuel cells generate electricity through the reaction of hydrogen within the fuel cell. As long as hydrogen fuel is continuously supplied, the fuel cell can continuously generate electricity. The application of hydrogen energy through fuel cells is mainly in two categories: one is through fuel cells to convert hydrogen energy into

³¹⁹ US DOE (2020). Battery 500: Progress update. <https://www.energy.gov/eere/articles/battery500-progress-update>

³²⁰ KISTEP (2017). South Korea's 5th Science and Technology Forecast Survey (2016~2040). <http://www.kistep.re.kr/en/c3/sub4.jsp?brdType=R&bbIdx=11502>

³²¹ Science and Technology Industry Information Management Office, Science & Technology Policy Research and Information Center, National Applied Research Laboratories (2020). The EU has proposed legislation requiring carbon footprint batteries to enter the EU market. <https://iknow.stpi.narl.org.tw/Post/Read.aspx?PostID=17338>

³²² European Parliament (2022). New EU regulatory framework for batteries-Setting sustainability requirements. [https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI\(2021\)_689337](https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2021)_689337)

industrial electricity, providing power as needed (stationary storage devices); the other is to use fuel cells to convert hydrogen energy into power sources for transportation, especially for long-distance, heavy-load vehicles.

The main types of fuel cells that can use hydrogen as fuel are: solid oxide fuel cells (SOFC), molten carbonate fuel cells (MCFC), phosphoric acid fuel cells (PAFC), alkaline fuel cells (AFC), and proton exchange membrane fuel cells (PEMFC). Among these, solid oxide fuel cells operate at the highest temperature, ranging from 700°C to 1000°C, while alkaline fuel cells and proton exchange membrane fuel cells operate at lower temperatures, both below 100°C. Due to differences in power output, different hydrogen fuel cells are suitable for different application fields. For example, the two main types of hydrogen fuel cells developed by Taiwanese manufacturers, proton exchange membrane fuel cells and solid oxide fuel cells, have distinct applications. Proton exchange membrane fuel cells are suitable for everything from personal electronic devices to vehicle power/auxiliary power, while solid oxide fuel cells are suitable for vehicle power/auxiliary power to distributed generation equipment (see Figure 2.11.3).

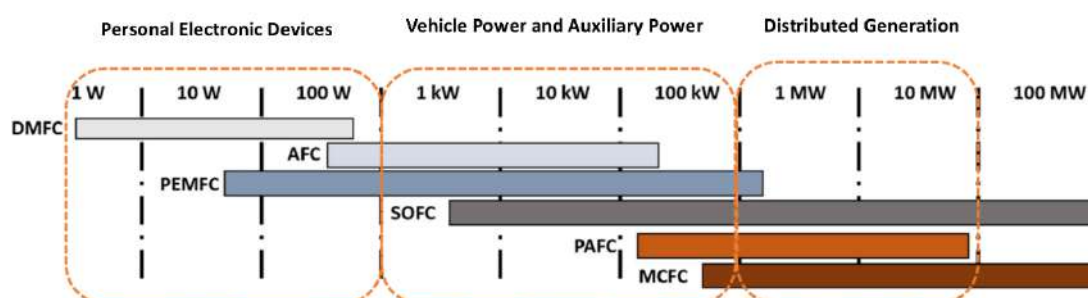


Figure 2.11.3 Power Range and Corresponding Applications of Various Fuel Cells³²³

From a technical perspective, the current power generation efficiency of hydrogen fuel cells is about 40% to 60% (lower heating value), but each has different technical challenges. For example, proton exchange membrane fuel cells face challenges related to the expensive catalysts and sensitivity to fuel impurities, while solid oxide fuel cells face technical challenges related to high-temperature corrosion of components, long startup times, and durability (see Table 2.11.2).

The global transportation sector aims to achieve net-zero emissions by 2050.

³²³ Cigolotti, V., Genovese, M. & Fragiaco, P. (2021). Comprehensive review on fuel cell technology for stationary applications as sustainable and efficient poly-generation energy systems, *Energies*, 14, 4963. <https://doi.org/10.3390/en14164963>

Based on this trend, by 2050, electricity will become the primary fuel for transportation, accounting for nearly 45% of final energy consumption, followed by hydrogen-based fuels (28%) and bioenergy (16%)³²⁴. Additionally, when estimating the sales share of different types of vehicles, light-duty vehicles are expected to be dominated by electric vehicles by 2030, with only a small number of fuel cell vehicles. The sales share of heavy-duty vehicles (such as freight trucks and buses) using fuel cells will remain low until 2030 but will significantly increase from 2030 to 2050. Two or three-wheeled vehicles (such as motorcycles) will be almost entirely electric vehicles in both 2030 and 2050 (see Figure 2.11.4).

Table 2.11.2 Technical Challenges Corresponding to Various Types of Hydrogen Fuel Cells³²⁵

Type of Hydrogen Fuel Cell	Technical Challenges
Solid Oxide Fuel Cell (SOFC)	• High-temperature corrosion of battery components • Long startup time • Durability
Molten Carbonate Fuel Cell (MCFC)	• High-temperature corrosion of battery components • Long startup time • Low energy density
Proton Exchange Membrane Fuel Cell (PEMFC)	• Expensive catalyst • Long startup time • Sensitivity to sulfur
Alkaline Fuel Cell (AFC)	• Sensitivity to carbon dioxide in fuel and air • Electrolyte management (liquid) • Conductivity of electrolyte (polymer)
Proton Exchange Membrane Fuel Cell (PEMFC)	• Expensive catalyst • Sensitivity to fuel impurities

³²⁴ *Ibid.*, 90.

³²⁵ US Department of Energy (2016). Comparison of fuel cell technologies. https://www.energy.gov/sites/default/files/2016/06/f32/fcto_fuel_cells_comparison_chart_apr2016.pdf

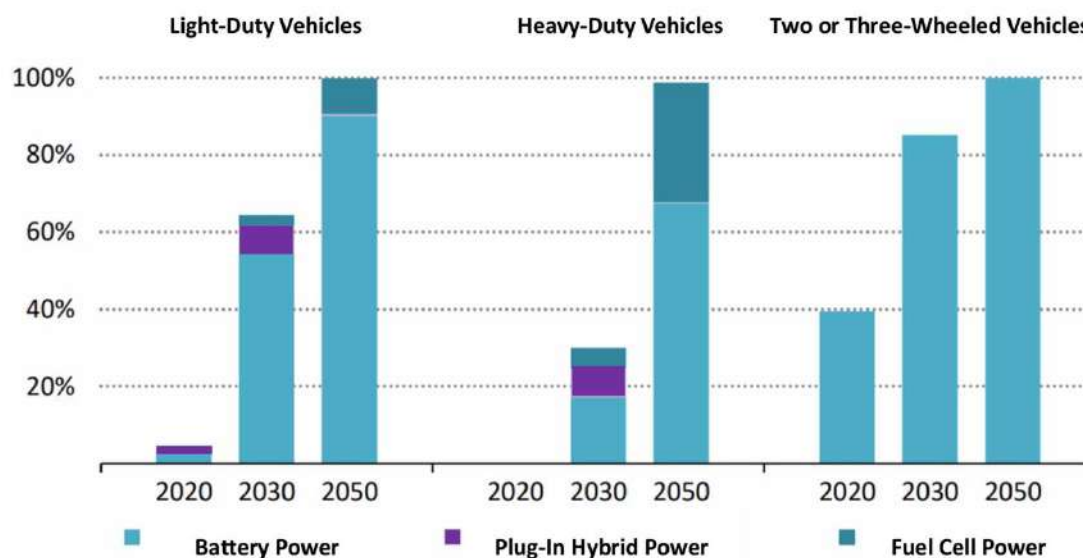


Figure 2.11.4 Sales Share of Different Types of Vehicles in 2020, 2030, and 2050 Under the 2050 Net Zero Scenario³²⁶

As for the use of hydrogen fuel cells in distributed generation, compared to other types of energy storage systems or devices, hydrogen energy has a lower power density (high-rate output for a short time) but a higher energy density, allowing for more sustained power output. Thus, it is more advantageous for long-term storage and power generation, especially for storage and power generation applications that span months to years. For short-term storage, batteries remain more competitive.

2.11.3 Analysis of Current Issues in Taiwan's Energy Storage Development

As Taiwan aims to achieve the 2050 net-zero emissions target, the primary task is to supply carbon-free electricity. This goal requires the development and deployment of energy storage technologies to ensure that the overall power system can flexibly and resiliently integrate renewable energy while maintaining grid stability and safety³²⁷. In addition to setting the policy goal for renewable energy to account for 20% of total electricity generation by 2025, Taiwanese government has also established policies to support the development and promotion of energy storage.

The 2016 New Energy Policy set forth initiatives to accelerate the deployment of

³²⁶ *Ibid.*, 90.

³²⁷ Yang, W.-J. (2020). Trends and opportunities of energy storage in renewable energy integration. https://km.twenergy.org.tw/Publication/thesis_down?id=267

energy storage and promote its development³²⁸. Subsequently, the Ministry of Economic Affairs (MOEA) outlined in its 2017 Guidelines on Energy Development the need to align energy storage system deployment with the commercialization timeline of storage technologies³²⁹. The Forward-Looking Infrastructure Development Program—Green Energy Construction launched the “Regional Energy Storage Equipment Technology Demonstration and Verification Program” in the same year. This program leverages the unique renewable energy strengths of various townships and Taiwan Power Company’s regional substations to establish regional energy storage systems. These systems aim to create distributed, regional energy supply centers while testing the storage systems’ capability of grid voltage stabilization³³⁰.

Regarding the plan for development and deployment of energy storage batteries, the Comprehensive Smart Grid Plan was amended in March 2020³³¹, with an initial target of achieving 590 MW of energy storage capacity for rapid ancillary services by 2025. These services include fast response reserve, regulation reserve, and spinning reserve³³². However, due to multiple unexpected power outages in 2021 and the March 3, 2022, blackout incident, Taiwan’s energy storage capacity goals were revised in the 2021 National Power Resource Supply and Demand Report. The 2025 target for energy storage battery capacity was increased to 1.5 GW, including 1 GW through Taiwan Power Company’s self-construction and procurement of ancillary services, and 0.5 GW (500 MW) from solar PV systems equipped with energy storage. The additional 0.5 GW is expected to be achieved through the “Guidelines for the Bidding and Capacity Allocation of Energy Storage Systems Combined with Solar PV Power Generation Equipment” announced by the Bureau of Energy, Ministry of Economic Affairs, on June 28, 2022, which aims to promote the installation of energy storage systems at solar PV

³²⁸ Executive Yuan (2016). Promoting new energy policies to achieve the 2025 nuclear-free homeland goal. <https://www.ey.gov.tw/Page/9277F759E41CCD91/c094fb4e-6c07-4a87-9435-fb97f11dde10>

³²⁹ Ministry of Economic Affairs (2017). Guidelines on energy development (authorized version). https://www.moeaboe.gov.tw/ECW/populace/content/wHandMenuFile.ashx?file_id=1206

³³⁰ Ministry of Economic Affairs (2017). Regional energy storage equipment technology demonstration and verification program. https://www.moea.gov.tw/MNS/CORD/content/wHandMenuFile.ashx?file_id=16037

³³¹ *Ibid.*, 278.

³³² Fast response reserve has a reaction time ranging from microseconds to seconds, with a duration of 3 to over 15 minutes; regulation reserve has a reaction time ranging from seconds to 3 minutes, with a duration of over 15 minutes; spinning reserve has a reaction time of 30 minutes, with a duration of over 1 hour.

plants, utilizing storage at the generation end^{333,334,335}.

With the implementation of the aforementioned policies, Taiwan's energy storage deployment has made some progress. For instance, the regional energy storage equipment technology demonstration and verification program directed by the Ministry of Economic Affairs has already planned demonstration sites on Taiwan main island. These efforts have, step by step, led to the establishment and operational maintenance of energy storage systems across the country. From 2018 to 2020, energy storage systems were installed at three sites: Taiwan Power Company's Yung'an salt flat lands, Longjing Solar PV and Wind Power Plant, and Changhua Coastal Solar PV Plant, achieving a capacity of 7 MW/7 MWh³³⁶.

With regard to Taiwan's new R&D directions, zinc-air batteries, flow batteries, and sodium-ion batteries are still in the R&D stage. Performance testing of 5 kW battery modules for flow batteries has been completed, while recent research on sodium-ion and zinc-air technologies has focused on battery materials, particularly electrode materials. Additionally, the Green Energy Technology Joint Research Program (2021) led by the Ministry of Science and Technology has set the development of all-solid-state lithium-ion secondary batteries (all-solid-state lithium-ion batteries wrapped in aluminum-foil/new lithium-ion secondary battery materials development) as the main focus for project proposals.

Based on the preceding discussion, it is clear that Taiwan's energy storage development, especially for grid applications, has entered the demonstration phase as renewable energy installations gradually scale up. However, large-scale deployment has not yet been achieved, and further experience at larger sites is needed to identify and address challenges related to practical operation and grid integration. This will facilitate the involvement of manufacturers in meeting Taiwan Power Company's ancillary

³³³ Chi, C.-F. (2022). Energy storage: A powerful ally, favored for its readiness for application and business opportunities, *TPC Journal*. <https://tpcjournal.taipower.com.tw/TPMM/2022/715/files/downloads/0801台電月刊7月號-電子書.pdf>

³³⁴ *Ibid.*, 212.

³³⁵ Bureau of Energy, Ministry of Economic Affairs (2022). Ministry of Economic Affairs promotes integration of energy storage systems with solar PV to enhance power supply flexibility and accelerate solar PV development. https://www.moeaboe.gov.tw/ecw/mobile/news/News.aspx?kind=1&menu_id=2136&news_id=26102

³³⁶ Green Energy & Environment Research Laboratories (GEL) ITRI (2020). Sharing experiences in energy storage system installation and operation: A case study of the forward-looking energy storage demonstration and verification sites. http://www.tp2e.org.tw/upload/fileList_file/356_1/03.工研院-儲能系統建置與運行經驗分享-以前瞻儲能示範驗證案場為例-v5-20201102-min.pdf

service needs of energy storage. Nonetheless, the most significant challenge in applying large-scale energy storage batteries for grid regulation is ensuring system safety and economic viability. Notably, recent incidents of energy storage system explosions and fires in countries such as the United States, Australia, and South Korea have significantly strained local firefighting resources. If Taiwan were to expand centralized large-scale grid-scale energy storage systems in conjunction with renewable energy expansion, it could raise public safety concerns and trigger the NIMBY (Not In My Backyard) effect^{337,338}.

Moreover, while the cost of energy storage systems has significantly decreased in recent years, the current price of Tesla's grid-scale Megapack system in California (comprising 10 battery units providing 7.7 MW/30.8 MWh, capable of supplying power for up to 4 hours) remains around \$10 million USD (excluding supporting equipment and taxes, approximately NT\$300 million). However, the price of energy storage systems is expected to continue declining. Taiwan can plan the corresponding expansion timeline according to the pace of renewable energy deployment to achieve better cost-effectiveness.

In assessing the current state of Taiwan's hydrogen energy fuel cell technology, the first and second phases of the National Energy Science and Technology Program focused on the R&D of proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC). The Industrial Technology Research Institute has primarily developed PEMFCs, while the Institute of Nuclear Energy Research has focused on SOFCs³³⁹. PEMFCs for stationary applications have been commercialized, with a per-kW cost of approximately NT\$200,000 to NT\$350,000. SOFCs remain in the prototype and demonstration stages³⁴⁰.

In terms of Taiwan's hydrogen energy fuel cell industry, there are around 20 to 30 domestic companies operating in the midstream and downstream sectors, primarily

³³⁷ In April 2019, a 2 MWh grid energy storage system explosion occurred in Arizona, USA, causing firefighters to be hospitalized after inhaling excessive chemical fumes produced by the fire. As cited in Wu, C.-C. (2021). Future challenges and application opportunities for energy storage development. <https://learnenergy.tw/index.php?inter=knowledge&caid=4&id=587>

³³⁸ At the end of July 2021, a Megapack system installed near Melbourne, Australia, through a collaboration between Tesla, Inc. and France's Neoen SA, exploded. It took the local fire department three days to declare the fire under control. As cited in Paul, S. (2021). Tesla Megapack fire in Australia blamed on undetected coolant leak, Reuters news. <https://www.reuters.com/technology/tesla-megapack-fire-australia-blamed-undetected-coolant-leak-2021-09-28/>

³³⁹ *Ibid.*, 104.

³⁴⁰ *Ibid.*, 117.

focusing on PEMFC and SOFC technologies. Most of these companies are PEMFC companies with a focus on developing small stationary systems, while SOFC component manufacturers in Taiwan have become key suppliers for medium and large-scale fuel cell manufacturers like Bloom Energy in the United States. Overall, Taiwan's hydrogen energy fuel cell industry chain is dominated by system integrators developing fuel cells, with some companies engaged in component material R&D³⁴¹.

The challenges and bottlenecks in Taiwan's hydrogen energy fuel cell development are summarized in Table 2.11.3. Technically, Taiwan's R&D efforts in hydrogen fuel cells began later than in advanced countries, and the R&D funding scale is smaller, resulting in relatively lagging technology. Additionally, core key materials and components (such as membrane electrode assemblies, gas diffusion layers/electrodes, and proton exchange membranes) are constrained by foreign patents and technological capabilities, necessitating reliance on imports.

On the market/industry side, the hydrogen energy fuel cell market is not yet fully mature, and initial setup costs and fuel expenses are high. Large-scale product promotion costs are also significant. The industry is dominated by small startups or small divisions within medium and large companies (companies with fewer than 30 employees and fewer than 10 R&D staff). The fuel cell industry remains largely unstandardized, with most products being custom-built. The components of SOFCs, which are suitable for centralized long-term power generation, are currently primarily supplied to international markets. Fuel cell vehicles are still in the demonstration and verification stage, lacking related infrastructure, and passenger vehicles face direct competition from electric vehicles. Therefore, Taiwan's strategy for developing fuel cells should prioritize resolving key technical issues from an R&D perspective to secure a competitive position in the global industry supply chain.

³⁴¹ *Ibid.*, 122.

Table 2.11.3 Bottlenecks and Challenges in the Development of Hydrogen Fuel Cells in Taiwan^{342,343,344}

Aspect	Bottlenecks and Challenges
Technical	• Taiwan's investment in hydrogen fuel cell R&D started later than in technologically advanced countries, and the scale of R&D funding is also smaller, resulting in relatively lagging technology. • Core key materials and components (membrane electrode assemblies, gas diffusion layers/electrodes, proton exchange membranes, etc.) are constrained by foreign patents and technological capabilities, necessitating reliance on imports. • Lack of domestic testing grounds to cultivate technical capabilities and accumulate practical experience.
Market/Industry	• The market is not yet fully mature, with high initial setup costs and fuel expenses. Additionally, the cost of large-scale product promotion is significant. • Companies are primarily small startups or small departments within medium and large companies (companies with fewer than 30 employees and fewer than 10 R&D personnel). • The fuel cell industry remains largely unstandardized, with most products being custom-built. • The components of SOFCs, which are suitable for centralized long-term power generation, are currently primarily supplied to international markets. The supply chain is still incomplete. • Fuel cell vehicles are still in the demonstration and verification stage, lacking related infrastructure.
Policy	• Taiwan's green energy policy mainly subsidizes renewable energy or lithium batteries, with hydrogen fuel cell R&D largely reliant on private companies. • Taiwan's relatively low electricity prices are not conducive to the development of new energy technologies. • Standards and regulations related to hydrogen energy and fuel cells are not yet fully developed. • There is a lack of a strategic blueprint for hydrogen fuel cell technology R&D, and resources are relatively scattered.
Social	• Public awareness of safety is insufficient.
Ecological/ Environmental	• Large-scale application of fuel cells still requires fossil fuels as the energy source in the short term.

³⁴² *Ibid.*, 122.³⁴³ *Ibid.*, 117.³⁴⁴ Wang, J.-G., Chen, C.-W., Hsu, C.-P., Hsu, Y.-S., Lai, Y.-W., Lu, C.-T., Kuo, P.-Y. & Chiu, P.-C. (2016). *Analysis of international and domestic hydrogen energy utilization, development, and promotion policies*, CTCI Foundation. https://www.ctci.org.tw/media/3001/2016-07_專題報告-國際與我國氫能運用發展與推動政策研析-全文.pdf

2.11.4 Policy Recommendations

Our policy recommendations primarily focus on five key directions:

1. Build Sufficient Grid-Scale Battery Energy Storage Systems to Support High Proportions of Renewable Energy

To achieve the 2050 net-zero emissions target, Taiwan will need to significantly expand its renewable energy capacity. As renewable energy generation is expected to continue growing under relevant policies, the instantaneous power connected to the grid is likely to fluctuate greatly. Due to Taiwan's isolated power system, which cannot connect to neighboring grids for cross-border power transmission regulation, it must rely entirely on its own generation and dispatch planning to maintain the balance between power supply and demand and to ensure system frequency stability. Failure to do so could easily lead to grid congestion and regional voltage instability, or even sudden frequency fluctuations that could severely impact the stability of the power system. Therefore, to achieve the goal of "Accelerating Power Decarbonization" and to accommodate the increasing share of high-proportion renewable energy, it is essential to build sufficient energy storage systems and integrate them with the grid to achieve peak load shifting.

Taiwan's energy storage system needs involve several factors (installation capacity, electricity demand, the share of renewable energy generation, etc.), which require further research to develop estimation methods. Appendix 2K provides the research methods used by Taiwan Power Company's Taiwan Power Research Institute and the potential demand for energy storage system capacity and storage under different proportions of variable renewable energy in various EU countries as a reference.

2. Develop Key Energy Storage Technologies Required for Transportation Electrification, Such as Battery Storage for Passenger Cars and Hydrogen/Fuel Cells for Large Vehicles and Distributed Generation

The transportation sector still heavily relies on fossil fuels for now, making electrification a key strategy to reduce carbon emissions in this sector. Battery storage, with its longer lifespan and relatively smaller size, is more advantageous for use in passenger cars, while hydrogen/fuel cells, due to their high energy density, are better suited for long-haul transportation such as heavy trucks. Therefore, it is necessary to develop key technologies for the corresponding energy storage systems, such as improving the quality and reducing the cost of battery storage, and investing in R&D

for core materials and components for fuel cell power generation.

3. Develop High-Energy-Density, High-Safety Grid-Scale Energy Storage Technologies, Such as All-Solid-State Lithium Batteries and Flow Batteries

In response to international targets set for 2030, which aim to significantly reduce the levelized cost of battery storage, increase battery energy density, and ensure battery safety, Taiwan must also focus on R&D that aligns with these important international development criteria. For example, all-solid-state lithium-ion batteries, which use solid electrolytes (with no separator), eliminate the risks of liquid leakage pollution, fire, and short-circuiting³⁴⁵, and have higher energy density compared to traditional liquid lithium-ion batteries. On the other hand, flow batteries use electrolytes that are resistant to degradation, have long energy storage durations and extended lifespans, and do not pose risks of overheating or combustion, making them highly safe. Both of these technologies are potential avenues for Taiwan to invest in and develop before 2030. Additionally, South Korea's forward-looking predictions suggest that from 2025 to 2027, it may be possible to achieve high-capacity, long-lifespan energy storage systems using low-cost metals. Taiwan should continue to monitor the progress of emerging energy storage technologies that do not rely on lithium or other rare earth and precious metals as battery materials and consider investing in R&D based on the development situation.

4. Develop Environmentally Friendly Battery Materials, Design, and Recycling Technologies

In response to the new battery regulations issued by the European Union at the end of 2020, which imposed requirements on battery sustainability, safety, carbon footprint, and the proportion of recycled raw materials, Taiwan must also focus on developing supporting technologies alongside high-energy-density, high-safety energy storage battery technologies. This includes developing environmentally friendly battery materials, design, and recycling technologies.

³⁴⁵ *Science Monthly* (2017). Free from the risk of explosion—All-solid-state lithium-ion batteries. <https://www.scimonth.com.tw/archives/2165>

5. Encourage Private Sector Investment in Energy Storage System R&D, Installation, and Expansion

Given the limited domestic market, private companies need to gradually build up products and technical strength through application in large-scale scenarios. The government should provide incentives for the operation of Taiwan's energy storage market to drive collaboration and integration across the battery industry supply chain. This would give companies opportunities for actual testing, application, and improvement in technology development to meet local energy storage needs and expand opportunities to enter the international market.

2.12 Conclusion

The goal to reach net-zero emissions by 2050 presents a difficult challenge, but it is also something that we must fully commit ourselves to for the well-being of Taiwan and for our future generations. With current technologies, it is almost impossible for us to achieve this goal. All the discussions so far have suggested directions for Taiwan's future efforts in scientific research. In this Section, we have chosen to use 2050 as the hypothetical year for us to reach our goals and flexible adjustments in the future may be needed.

Taiwan's electricity capacity in 2019 was 274.1 billion kilowatt-hours, and emissions from power generation accounted for 48.6% of total emissions. In addition to power generation, carbon emissions from the other energy sectors (direct combustion) account for 42.4% of total emissions. If we assume that the total energy demand remains unchanged and we change energy produced by direct combustion to electricity (50-90%), we will see an increased demand for power generation by approximately 393.7 to 489.3 billion kilowatt-hours, bear in mind that these numbers have not yet taken into account possible increasing electricity demands due to other socio-economic development factors.

Table 2.12.1 puts together the estimated supply of zero-carbon electricity mentioned in all the other sections. We can see that the annual supply of electricity in 2050 will reach about 490.404 to 679.236 billion kilowatt-hours, and the average power generation will be approximately 586.525 billion kilowatt-hours. Using the average scenario as a reference, we can see the share of electricity generated by low-carbon sources. In recent years, the number of solar energy systems and wind farms has increased significantly, but the challenge of intermittent power supply still needs to be overcome. At present, solar energy and wind energy account for about 39% of power supply. On the one hand, the increasing percentage of solar and wind energy can help stabilize the power grid, and on the other hand, it can also reduce the general public's resistance to developing solar and wind energy with the demand for land and environmental resources. We will argue that another feasible approach to developing carbon-free electricity in Taiwan is the Methane Pyrolysis To Power (MPTP) technology, a technology that can pyrolyze natural gas, remove its carbon, and burn only the hydrogen to create electricity. Electricity generated via this technology can contribute about 27% to Taiwan's power supply. This technology can further stabilize

Taiwan's supply of power and help Taiwan achieve the goal of energy security. However, this approach will require more import of natural gas. The remaining 34% will be supplied by traditional energy sources (biomass, hydropower), new energy (geothermal, ocean), and imported hydrogen energy. In sum, Taiwan's electricity will come from three main sources of energy: solar and wind energy, MPTP technology, and new energy. This approach will help stabilize the power grid and minimize social resistance. At the same time, it can distribute risks related to energy supply.

Table 2.12.1 Installed Electricity Capacity and Estimated Power Generation in 2050

Type of carbon-free electricity	Installed electricity capacity (GW)	Possible power generation (billion kilowatt-hours)	Possible power generation (average) Reference value (billion) kilowatt-hours	Proportion of reference value (%)
Solar energy	44.16-58.32	464.21-613.16	538.69	9.28
Wind energy (Onshore)	1.20-3.80	29.43-93.21	61.32	1.06
Wind energy (Offshore)	43.20-53.20	1,543.20-1,957.10	1,750.15	29.10
MPTP technology	20.80-24.00	1,456.00-1,685.00	1,570.50	27.06
Geothermal energy	8.13-12.88	468.29-741.89	605.09	10.43
Ocean energy	3.76-7.52	212.00-424.00	318.00	5.48
Biomass energy	2.50-3.00	122-194	158.00	2.72
Conventional hydro power and mini hydro power unit	2.26	33.91	34.00	0.59
Hydrogen energy (Imported)	8.20-15.50	575.00 -1,084.00	829.50	14.29
Subtotal		4,904.04-6,792.36	5,865.25	100

To predict future demands of electricity, we can look at the statistics provided in the Energy White Paper.³⁴⁶ Taiwan's gross domestic product (GDP) has continued to grow in recent years. Although energy use and electricity consumption have not grown as high as GDP, we can see a slight increase. Specifically, if we look at industrial sectors, we can see that their share of energy use and total electricity consumption has continued to grow. The main consumers are ICT sector industries (Computer, Communications, and Audio and Video Electronic Products Manufacturing). Even though a low birth rate could potentially affect the future demand for electricity consumption, digitization, electrification, and other key trends can continue to drive future demand for electricity.

Figure 2.12.1 provides estimates of electricity demand under various scenarios based on different average annual growth rates of electricity consumption. If the average annual growth rate of electricity consumption from 2020 to 2050 is zero, or only 1% to 2%, the estimated power needed is below 502.6 billion kilowatts. According to a recent report published by the Ministry of Economic Affairs, the average annual growth rate of electricity consumption is estimated to be about 2.5%. Using that number, it is estimated that by 2050, Taiwan's demand for electricity will be about 587.6 billion kilowatt-hours, which is roughly consistent with the estimated 586.5 billion kilowatt-hours of zero-carbon electricity suggested in the recommendations. If the annual growth rate of electricity consumption increases to over 3%, it would be necessary for Taiwan to actively increase the installed electricity capacity of wind energy and solar energy, as well as all supporting energy storage facilities; otherwise, Taiwan will need to suppress power demand.

³⁴⁶ Ministry of Economic Affairs (2020). *Energy White Paper* (Approved Version). https://energywhitepaper.tw/pdf/1091118_%E8%83%BD%E6%BA%90%E8%BD%89%E5%9E%8B%E7%99%BD%E7%9A%AE%E6%9B%B8%E6%A0%B8%E5%AE%9A%E6%9C%AC.pdf

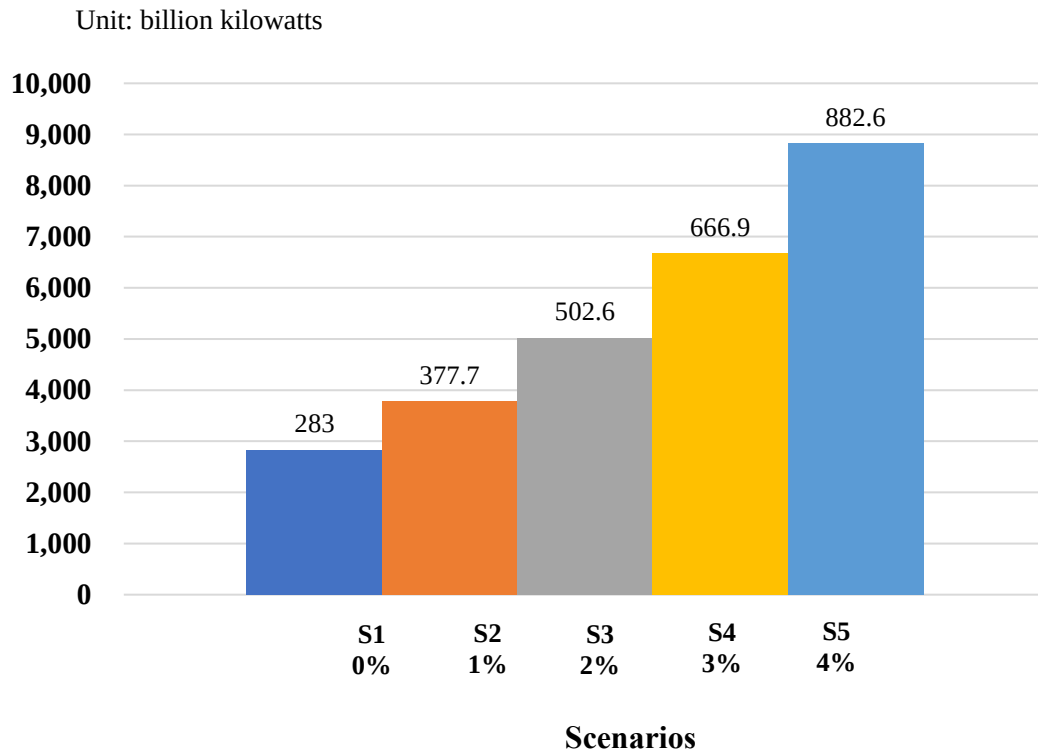


Figure 2.12.1 Estimates of Power Demand with Different Average Annual Growth Rates of Electricity Consumption from 2020 to 2050

Overall, we will recommend the government to start off by focusing on renewable energy with more mature technologies, such as solar energy and wind energy. Apart from promoting the development of relevant science and technology, such as solar cells with high conversion efficiency, wind turbines with high power generation efficiency, large onshore wind turbines, deep ocean floating wind turbines, and floating wind turbines, the government will also need to strengthen communication with the general public, provide incentives and supporting measures, and improve relevant policies and regulations to fully utilize renewable energy.

As for forward-looking carbon-free sources of electricity, such as geothermal energy, hydrogen energy, MPTP technology, biomass energy and ocean energy, it is necessary for the government to accelerate the overall investment in scientific research and technology now for Taiwan to lay a solid foundation before 2030 for gradual application and expansion of these new energy sources before 2050. For example, to promote Taiwan's geothermal energy, we will need to accelerate the exploration of shallow and deep geothermal energy to understand Taiwan's geothermal potential. At the same time, Taiwan also needs to pay close attention to the latest deep drilling and

heat extraction technology around the world. To develop hydrogen energy and the MPTP technology, Taiwan will need to invest in research and development of the MPTP technology to replace the burning of natural gas, develop technologies to use hydrogen enriched natural gas (HENG) for power generation, and explore ways to use solid carbon collected from methane pyrolysis. It is also recommended that Taiwan import hydrogen infrastructure technologies and invest in technologies and applications of locally produced green hydrogen. In the area of biomass, the government needs to (1) promote the research and development of pyrolysis technology to produce hydrogen via biomass gasification; (2) develop biotechnology to increase the photosynthetic efficiency of plants; (3) improve the yield of biomass crops and carbon-fixing microorganisms. At the same time, the government can also invest in research and development of bioconversion of single-carbon sources to valuable chemicals. Finally, in the area of ocean energy, we will need to (1) carry out precise hydrological, and geological surveys to identify suitable locations to explore ocean energy; (2) invest in ocean thermal energy conversion (OTEC) and secure access to a grid connection point; (3) and launch plans to set up experimental power plants and introduce international technology, etc. In addition to investment in science and technology, supporting laws and regulations, infrastructure, and business models are required to develop these forward-looking carbon-free energy. For instance, the government will need to draft a special act for geothermal energy and build port facilities to support ocean energy research and construction vessels. In addition, it is recommended to import ethanol fuel to be mixed with gasoline. Such ethanol blended fuel can fuel automobiles and locomotives during the transitional period before all automobiles and locomotives in Taiwan become e-vehicles.

As the share of renewable energy in power generation continues to increase, it will be necessary to have a smarter power grid with real-time adjustment, accurate prediction and comprehensive control of the load to ensure safe and stable power supply. In other words, we will need to optimize the safety and stability of the power supply from various aspects, including power generation, power grid management (transmission, distribution, and storage), and demand (sale of electricity). Hence, it would be necessary to promote various key strategies, including the weather forecast models supported by AI, prediction of real-time power generation, installation of low-voltage smart meters, GW-level battery storage facilities, end-user participation in demand response programs, and gradual transformation of the power supply system to a decentralized system.

Chapter 3 Carbon Sinks, Zero Carbon, and Negative Emission Technologies

Sections

3.1 Introduction

3.2 Natural Carbon Sinks

3.3 Traditional CCUS (Carbon Capture, Utilization, and Storage)

3.4 Application of Carbon Biosequestration and Bio-based Processing

3.5 Conclusion

3.1 Introduction

Even if Taiwan generates substantial zero-carbon electricity and uses electrification strategies to reduce greenhouse gas (GHG) emissions, zero-carbon electricity cannot replace some emission sources (for example, industries that have to use boilers during the manufacturing processes). For Taiwan to reach the goal of net zero emissions by 2050, it is necessary to use carbon capture, utilization, and storage (CCUS) technologies to minimize the impact of flue gas emissions from large emission sources like power generation facilities and factories that burn fossil fuel. Carbon dioxide (CO₂) accumulated in the atmosphere from past emissions will need to be removed through “Negative Emission Technologies” (NETs) (also known as carbon-negative technologies). NETs can remove CO₂ from the atmosphere and store it underground and under the ocean to offset carbon emissions³⁴⁷ and help Taiwan achieve net-zero emissions or even negative emissions by 2050.

NETs can be roughly divided into three categories: nature-based solutions (natural carbon sinks, including terrestrial and aquatic photosynthetic carbon sinks), technical solutions (such as traditional CCUS technologies), and hybrid solutions (using artificial technologies to enhance natural processes such as accelerated weathering). Each has its advantages, disadvantages, and challenges. Nature-based solutions, such as natural carbon sinks, are more advantageous with a lower cost of carbon storage. However, active management and investment in research is needed to assess any new potential of carbon storage. When adapting technical solutions, it is unavoidable that the operation of relevant systems will result in energy consumption, so it would be necessary to assess these solutions with other options for carbon reduction to ensure that these solutions can actually help achieve carbon reduction.

Hybrid solutions combine natural processes with human intervention to go carbon negative. For instance, spreading crushed silicate minerals and water onto surfaces can speed up chemical reactions and accelerate weathering (grinding) to achieve negative emissions. Although it is a nature-based method, long-term verification and monitoring are required to ensure negative emissions are achieved. At present, we do not know enough about the potential impact of hybrid solutions on the natural environment and

³⁴⁷ Haszeldine, R. S., Flude, S., Johnson, G. & Scott, V. (2018). Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. <https://royalsocietypublishing.org/doi/10.1098/rsta.2016.0447>

ecosystems. Therefore, hybrid solutions still face many issues and challenges, including an environmental impact assessment, costs, and regulations. This chapter will focus on the possibility of using nature-based solutions, technical solutions, and hybrid solutions. At the same time, emerging technologies with potential will be reviewed and assessed.

3.2 Natural Carbon Sinks

Summary

Natural carbon sinks are nature-based solutions that can mitigate climate change with multiple potential environmental and socioeconomic benefits. Compared with existing CCUS technologies or other NETs, the cost of carbon storage is much lower. Hence, it is necessary to consider expanding natural carbon sinks to help Taiwan achieve net-zero emissions by 2050 and reduce the pressure to rely on carbon-free energy during the transition period. Considering Taiwan's situation, our recommendations are as follows:

1. Expanding forest carbon sinks by increasing forest area (coastal forests, lowland forests, reforestation of farmland), improving the management of artificial forests (state-owned forests and private forests), and increasing Taiwan's production of timber (for carbon sequestration in wood).
2. Active management of Taiwan's replanted forests: The primary approach aims to increase the biomass per unit area with planned thinning (for carbon sequestration in wood), reforestation, and cultivation.
3. Initiating research on quantitative methods to assess emerging natural carbon sinks (such as crop carbon sinks, soil carbon sequestration, and blue carbon sinks) and their potential of carbon removal. Once these methods are mature, they can be used to estimate the capacity of various emerging natural carbon sinks.

3.2.1 Introduction

Natural carbon sinks refer to forests or other ecosystems that can absorb carbon from the atmosphere to offset CO₂ emissions³⁴⁸, as shown in Figure 3.2.1. Natural carbon sinks include oceans (blue carbon, wetlands, and seagrass), forests (crops, soils, trees), and geological formations. According to the United Nations Environment Programme (UNEP), carbon sinks are part of nature-based solutions used to mitigate climate change³⁴⁹. Apart from absorbing atmospheric CO₂ and storing it, carbon sinks have potential environmental and socioeconomic benefits, including protecting biodiversity, maintaining climate stability, soil health and water quality, reducing the risks of extreme climate events, providing food, energy and cultural services, as well as maintaining health and safety. In addition, compared with existing CCUS technologies or other carbon-negative technologies, the costs of carbon storage using these nature-based solutions are much lower. Take forest carbon sinks as an example, the cost is under US\$100/tCO₂eq³⁵⁰. Therefore, from a cost-benefit perspective, Taiwan should prioritize the expansion of carbon sinks to achieve net-zero emissions.

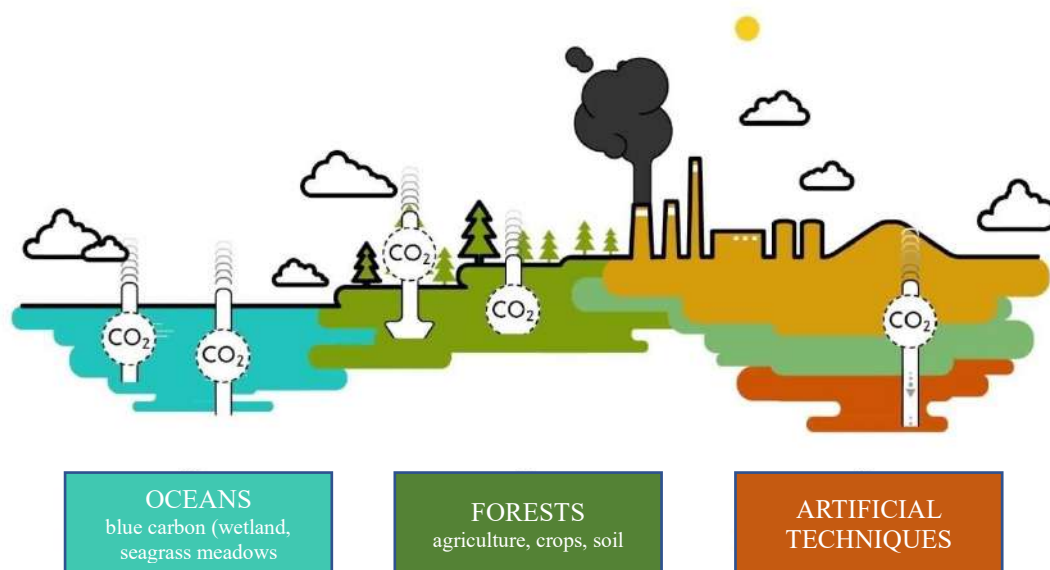


Figure 3.2.1 Carbon Sinks (Oceans, Forests, and Artificial Techniques)³⁵¹

³⁴⁸ European Environment Agency (2022). Term-carbon sink. <https://www.eea.europa.eu/help/glossary/eea-glossary/carbon-sink>

³⁴⁹ UNEP (2021). *Nature-based solutions for climate change mitigation*. UN Environment Programme. <https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/37318/NBSCCM.pdf>

³⁵⁰ UNECE (2021). UNECE technology brief - Carbon capture, use and storage. https://unece.org/sites/default/files/2021-03/CCUS%20brochure_EN_final.pdf

³⁵¹ ACCIONA (2021). What are carbon sinks? https://www.activesustainability.com/climate-change/carbon-sinks-what-are/?_adin=02021864894

Taiwan already includes some quantitative statistics on forest carbon sinks and statistics on agriculture, forestry, and other land uses (AFOLU) in the National Greenhouse Gas Inventory Report. Other carbon sinks have not been included because the survey data doesn't meet methodology requirements or the methodology is still being evaluated. In 2019, the total forest land in Taiwan was 2.1 million hectares, and carbon sinks from land use, land use change, and forestry (LULUCF) removed 21.4 million tonnes of CO₂ equivalent (Mt CO₂e)³⁵² in one year, as shown in Figure 3.2.2, offsetting approximately 7.5% of Taiwan's total GHG emissions. These numbers have not changed drastically since 1990. Most carbon sinks are original forest land. Only a tiny amount of new carbon removals come from new afforestation.

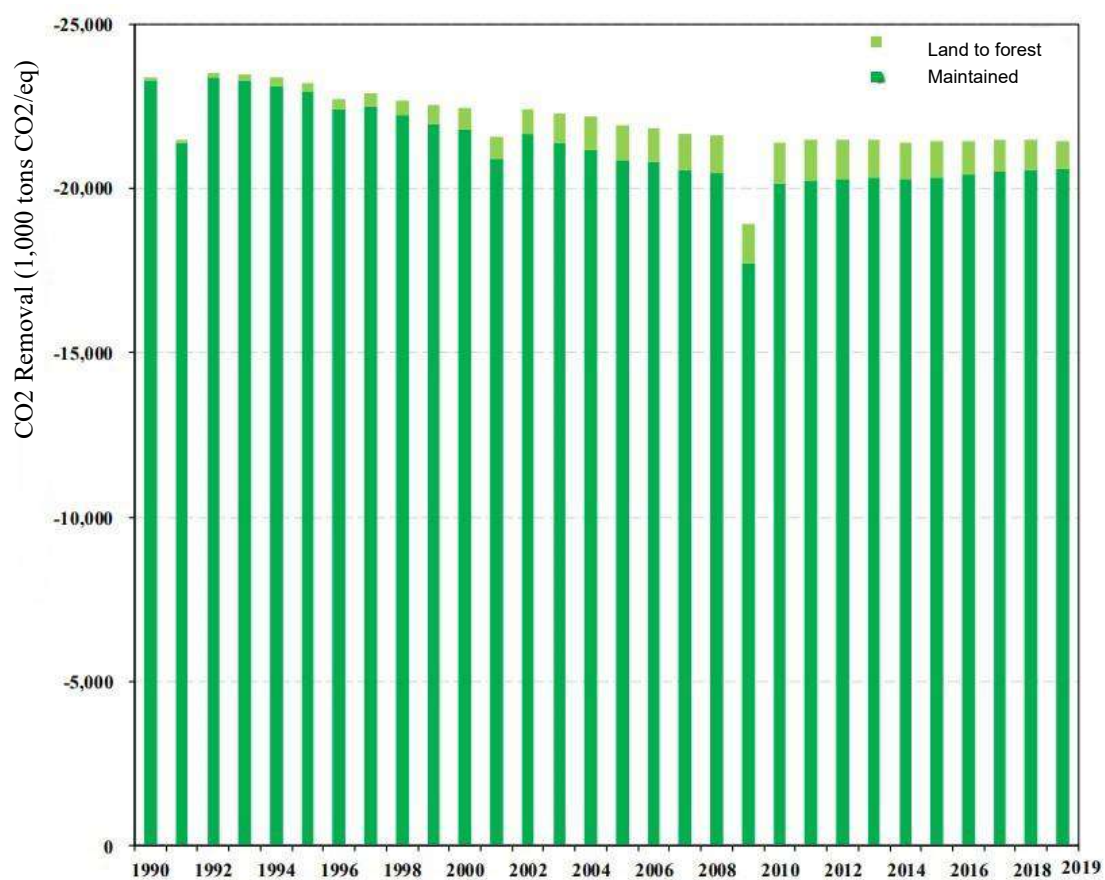


Figure 3.2.2 GHG Removal by Taiwan's Natural Carbon Sinks (Forests)³⁵³

³⁵² Environmental Protection Administration, Executive Yuan (2021). 2021 national greenhouse gas inventory.

³⁵³ *Ibid.*, note 錯誤! 尚未定義書籤。.

3.2.2 International Trends

Natural carbon sinks include forests, land, agriculture, wetlands and oceans. However, at present, when measuring the removal of GHGs, the international community is focusing mainly on terrestrial carbon sinks³⁵⁴. Annex I - Greenhouse Gas Inventory Data of the United Nations Framework Convention on Climate Change (UNFCCC) shows data from 43 countries^{355,356}. From 2010 to 2018, the LULUCF sector removed 1.8-2.0 Gt CO₂eq, which was about 10% of the total annual GHG emissions from the 43 countries (Figure 3.2.3). If the ocean is also counted as a carbon sink, using biogeochemical models and dynamic global vegetation models, the Global Carbon Budget Project estimated that between 2010 and 2019, global land and ocean sinks absorbed 19 to 23 GtCO₂³⁵⁷.

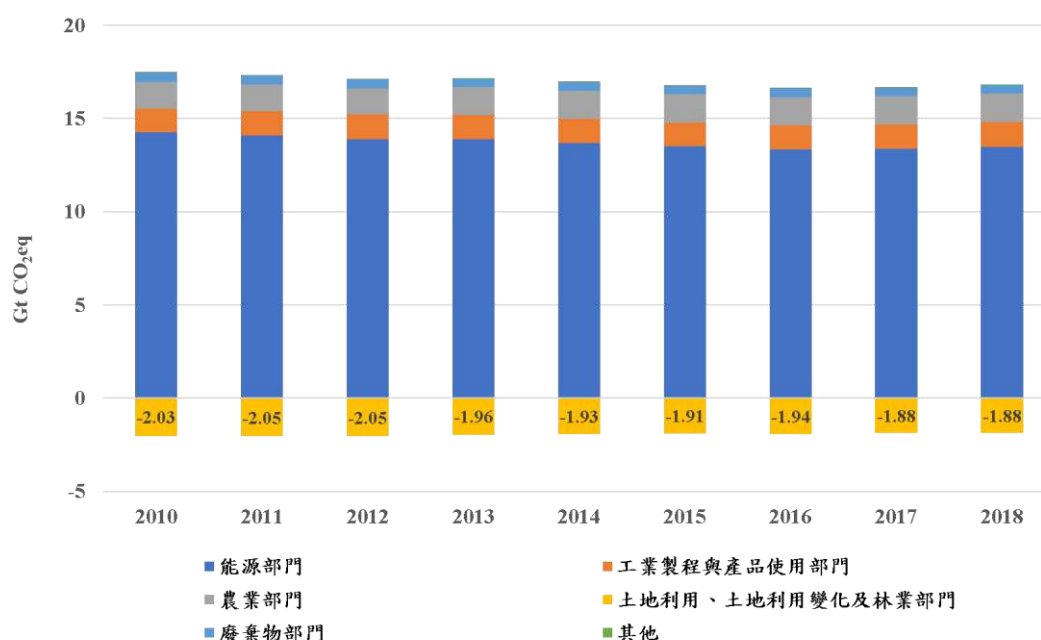


Figure 3.2.3 2010-2018 GHG Emissions and Removals in Annex I of the UNFCCC Convention³⁵⁸

³⁵⁴ The 2006 IPCC Guidelines for National Greenhouse Gas Inventories drafted by the United Nations Intergovernmental Panel on Climate Change (IPCC) states that Agriculture, Forestry and Other Land Use (AFOLU) includes forests, croplands, grasslands, wetlands, settlements and other land use.

³⁵⁵ UNFCCC (2020). Greenhouse gas inventory data - Detailed data by party. https://di.unfccc.int/detailed_data_by_party

³⁵⁶ Annex 1 of UNFCCC Convention: The 43 Parties to the UNFCCC listed include OECD members, as well as industrialized (developed) countries and "economies in transition" (EITs). <https://unfccc.int/parties-observers>

³⁵⁷ Pierre Friedlingstein et al. (2020). Global carbon budget 2020. *Earth Syst. Sci. Data*, 12, 3269–3340. <https://doi.org/10.5194/essd-12-3269-2020>

³⁵⁸ *Ibid.*, note 356.

1. Terrestrial Carbon Sinks: Forests, Soil, Agriculture, Wetlands

With the increasing need to reduce carbon emissions and reach net-zero emissions in recent years, the international community has begun to pay attention to the expansion and management of terrestrial carbon sinks and relevant systems. At the 26th United Nations Climate Change Conference (COP26) in November 2021, 141 countries signed the Glasgow Leaders' Declaration on Forest and Land Use, committing to reverse forest loss and land degradation. In the same year, both the EU and the United States drew up draft regulations or action plans^{359,360} on land use and forest carbon sinks. In the area of finance and carbon rights, Singapore established Climate Impact X (CIX) in 2021, allowing businesses to invest in nature-based solution carbon credits.³⁶¹ According to a report by VERRA, the organization that maintains the Verified Carbon Standard, verified carbon units (VCUs) of Agriculture, Forestry and Other Land Use (AFOLU) are on the rise. As of October 2021, more than half of VCUs were related to AFOLU³⁶², showing that the international community has been paying more attention to terrestrial carbon sinks.

2. Marine and Coastal Carbon Sinks (Mangroves, Salt Marshes, and Seagrass Meadows)

Marine and coastal carbon sinks are usually referred to as “blue carbon.” More studies on blue carbon are needed as the international community has not come up with a consistent assessment method to assess the potential of blue carbon.³⁶³ The Blue Carbon Initiative co-organized by the Conservation International (CI), the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific, and Cultural Organization, IOC-UNESCO and the International Union for

³⁵⁹ European Commission (2021). Land use and forestry regulation for 2021-2030.

³⁶⁰ U.S. Department of State (2021). Plan to conserve global forests: Critical carbon sinks.

³⁶¹ Environmental Information Center (2021). Singapore will establish a carbon rights trading market focused on nature conservation projects in Southeast Asia. <https://e-info.org.tw/node/231675>

³⁶² DATA AND INSIGHTS-VCS Quarterly Update (2021). <https://verra.org/datainsights/data-and-insights-october-2021/>

³⁶³ The Blue Carbon Initiative published guidelines to provide standardized recommendations for assessing and measuring coastal blue carbon on a global scale. The guidelines attempt to provide standardized measurements on blue carbon flux and storage. However, due to the lack of data in certain regions, insufficient assessment of human activities and coastal erosion, the accuracy still needs to be improved. See Howard, J. et al. (2019). Coastal blue carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrass meadows. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature. Arlington, Virginia, USA.

Conservation of Nature (IUCN) pointed out³⁶⁴ that for blue carbon to be included in international or national policy frameworks, quantification of CO₂ removal is necessary to show blue carbon can affect the climate and can be effectively managed, so the international community can recognize the value of blue carbon to mitigate climate. Apart from standardized assessment and measurement, the international community's current discussions and research on blue carbon concentrate on potential GHG emissions resulting from the loss of marine ecosystems, especially coastal ecosystems, and how to effectively mitigate and restore blue carbon ecosystems.^{365,366}

3.2.3 Taiwan's Carbon Sink Potential

1. Forest Carbon Sinks

Forests are the main ecosystem in terrestrial ecosystems. Plants in the forests absorb CO₂ in the air, convert it into organic carbon, and store it in their biomass. Therefore, afforestation and forest management are the most cost-effective approaches to mitigate climate change.³⁶⁷ "Forest carbon sinks" refer to the capacity of forests to absorb CO₂ via the process, activities, and mechanisms of removing carbon dioxide from the air. Generally speaking, a forest carbon sink refers to the total amount of CO₂ absorbed by forests per unit of time (e.g., within one year). Taiwan's estimation of forest carbon sinks mainly follows the calculation suggested in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories published by the United Nations Intergovernmental Panel on Climate Change (IPCC). The calculation considers all forest areas, including original forest land, new forest area established through planting, and reduced forest cover due to disasters. Data on the annual growth of forest stock and increase in forest cover, thus, can be obtained from the statistics in the Results of the Third and Fourth National Forest Resources Surveys published by the Forestry Bureau of the Council of Agriculture, Executive Yuan. Once multiplied by the activity coefficient, we can obtain the data on forest carbon sinks. Moreover, the above-mentioned estimation of forest

³⁶⁴ Isensee, K. et al. (2019). Blue carbon: Science developments of relevance to the UNFCCC.

³⁶⁵ L, Donato DC, Murray BC, Crooks S, Jenkins WA, et al. (2012). Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLOS ONE* 7(9): e43542. <https://doi.org/10.1371/journal.pone.0043542>

³⁶⁶ Murray, B. C., Pendleton, L., Jenkins, W. A., Sifleet, S. (2011). Green payments for blue carbon: Economic incentives for protecting threatened coastal habitats. Nicholas Institute Report. NI R 11-04.

³⁶⁷ Chung-I Chen, Heng-Hsun Lin, Ching-Wen Wang, Ya-Nan Wang (2017). What is carbon sequestration in forests? *Nature Conservation Quarterly* No. 99. https://www.tesri.gov.tw/A15_1/download1/30141/3

carbon sinks shows that the removal of GHG calculated by the forestry department focuses mainly on CO₂.

According to Chapter 6—Land Use, Land Use Change and Forestry (LULUCF)—of the 2021 Republic of China National Greenhouse Gas Inventory Report mentioned in the introduction, the estimated annual carbon removal of Taiwan’s LULUCF sector in 2019 was approximately 21.4 MtCO₂eq/year. The carbon removal of “maintained forest land” accounted for 96.1%, and the carbon removal of “land converting to forest land” accounted for 3.9% (see Table 3.2.1). According to the estimation of inventory reports over the years, the average carbon removal from Taiwan’s forestry sector from 1990 to 2019 was between 18.9 to 23.5 MtCO₂eq/year. The numbers have seen slight increases or decreases, but they are quite stable³⁶⁸. This was mainly due to Taiwan’s Regional Planning Act and Forestry Act, which regulate changes in forest land and forest logging. Also, since 1992, the government has banned logging in natural forests. Hence, it has been rare to see forests being converted to other uses (see Figure 3.2.2 Current Status of Greenhouse Gas Removal by Taiwan’s Natural Carbon Sinks). In addition, in 2019, Taiwan’s area of “maintained forest land” was 2,119,110 hectares. The land use map included in the “Results of the Fourth National Forest Resources Survey” in 2015 (including both state-owned and other forests) can be used as the baseline to calculate the forest area, while the area of damaged forest land can be deducted and not included in the forest growth area (see Table 3.2.2). The area of “land converted to forest land” in 2019 was 508 hectares (see Table 3.2.3). However, after a 20-year transition period, this area will be included in the area of maintained forest land, so an afforestation area in 1990 will be added to the area of maintained forest land in 2011.

Table 3.2.1 Taiwan’s Carbon Removal by Forestry in 1990 and 2019³⁶⁹

Unit: Thousand tonnes of carbon dioxide equivalent

Year	Maintained forest land		Land converting to forest land	Total carbon dioxide removed ΔCO ₂	Uncertainty (%)
	Biomass carbon removal (ΔCO _{2G})	Biomass carbon emissions (ΔCO _{2L})	Biomass carbon removal (ΔCO _{2G})		
1990	-23,902.42	607.25	-90.75	-23,385.92	7.57

³⁶⁸ Ya-Hui Shih, Ming-Chieh Lin, Chilng Chen (2021). Developing Low Carbon Agriculture and Carbon Trade mechanism in Taiwan Symposium on eco-friendly crop management for sustainable environment (2021) p 74-87.

³⁶⁹ Environmental Protection Administration, Executive Yuan (2021). Taiwan’s national greenhouse gas emission inventory report for 2021.

2019	-20,710.34	115.73	-845.17	-21,439.78	8.84

Table 3.2.2 Area of Maintained Forest Land in 1990 and 2019³⁷⁰

Unit: Hectare

Forest type	Natural coniferous forest	Natural coniferous and broad-leaved mixed forest	Natural broad-leaved forest	Artificial coniferous forest	Artificial coniferous and broad-leaved mixed forest	Artificial broad-leaved forest	Bamboo and broad-leaved mixed forests	Bamboo grove	Total
Year									
1990	220,100	286,376	975,800	218,400	37,287	144,600	67,537	152,300	2,102,400
2019	202,647	116,131	1,312,722	93,232	52,335	115,442	114,127	112,474	2,119,110

Table 3.2.3 Area of Land Converted to Forest Land in 1990 and 2019³⁷¹

Unit: Hectare

Year	Coniferous forest		Coniferous and broad-leaved mixed forest		Broad-leaved forest		Bamboo grove	Total
	Area of forestry	Total area	Area of forestry	Total area	Area of forestry	Total area	Area of forestry	
1990	959	959	67	67	2,696	2,696	161	3,883
2019	102	102	0	0	406	406	0	508

³⁷⁰ *Ibid.*, note 369.

³⁷¹ *Ibid.*, note 369.

To achieve net-zero emissions by 2050, a research team from National Taiwan University proposed pathways to expand Taiwan's potential forest carbon sink³⁷². The pathways cover forest carbon sinks that have been included and not included in Taiwan's National Greenhouse Gas Inventory. The carbon sink potential of Taiwan's forestry sector is estimated below. For "forest carbon sink potential included in the National Greenhouse Gas Inventory," it is necessary to improve forest management, carry out planned thinning (for carbon sequestration in wood), and plant trees to absorb carbon to significantly expand the carbon sink in the future. Another approach is the reforestation of farmland. Hence, there are three pathways:

- (1) Pathway 1: Strengthening the management of the carbon sink potential of state-owned forests (including bamboo groves)
- (2) Pathway 2: Strengthening the management of the carbon sink potential of private forests (including bamboo groves)
- (3) Pathway 3: The carbon sink potential of reforestation of farmland

On the other hand, for "forest carbon sink potential NOT included in the National Greenhouse Gas Inventory," the plan is to include potential carbon sinks of new afforestation, national street trees, campus and park trees, and trees in private properties. At the same time, we should try to fully recycle imported wood products to ensure that CO₂ can be stored in wood products for a long time to expand the carbon sink. Such an approach is divided into Pathways 4 through 6 as follows:

- (4) Pathway 4: The carbon sink potential of new afforestation (700 hectares of new trees every year), such as coastal forests
- (5) Pathway 5: The carbon sink potential of urban forests (street trees, campus trees, park trees, etc.)
- (6) Pathway 6: The carbon sink potential of fully recycling and reusing imported wood products (6 million m³ of wood products are imported every year)

The above-mentioned six pathways could reach 5.1 to 8.2 MtCO₂eq/year. Compared with the current estimate of the carbon sink potential of the forestry sector in the National Greenhouse Gas Inventory Report, we can expand the carbon sinks by 23.7~38.1% (Figure 3.2.4).

³⁷² Chyi-Rong Chiou (2021). Pathway analysis of forest carbon sinks for net-zero by 2050.

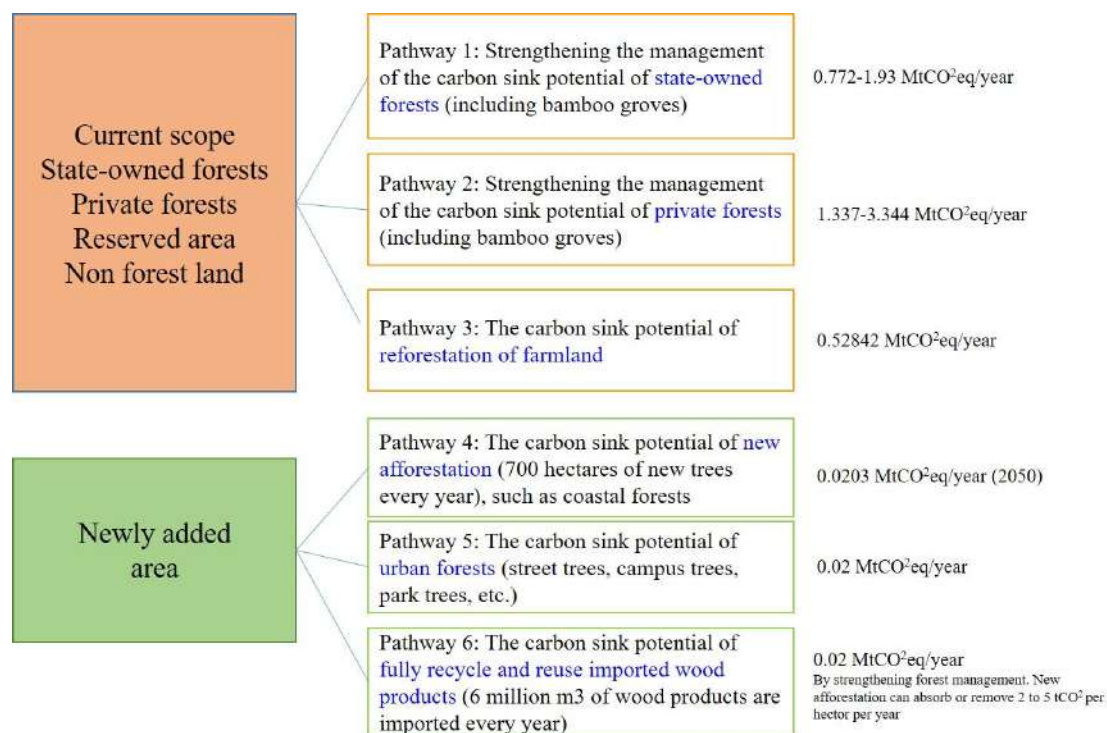


Figure 3.2.4 Pathways to Expand the Carbon Sink Potential of Forests for Net-Zero Emissions by 2050³⁷³

2. Carbon Sinks of Agriculture, Crops, and Soil

In 2020, Taiwan had 790,000 hectares of agricultural land³⁷⁴. Compared with data extracted from the 2004 moderate resolution imaging spectroradiometer (MODIS)³⁷⁵, excluding forest land, the land area with carbon sink potential includes 300,200 hectares of farmland, 361,500 hectares of land with mixed farmland and natural vegetation, 13,400 hectares of grassland, and 36,600 hectares of steppe. The total is 711,700 hectares. Hence, it is reasonable to use the 790,000 hectares in 2020 to estimate the area of non-forest land with carbon sink potential. The average net primary productivity³⁷⁶ of farmland or grassland is about 3 metric tons of carbon per hectare per year³⁷⁷. Extrapolating, the annual carbon sink of 790,000 hectares of Taiwan's agricultural land is about 2.37 million tons of carbon (8.685 million tons of CO₂). However, it should be

³⁷³ *Ibid.*, note 372.

³⁷⁴ Executive Yuan (2022). Current status of agriculture in Taiwan

³⁷⁵ Ching-Yu Hu (2010). Using MODIS image data to estimate the terrestrial primary production of Taiwan. <https://hdl.handle.net/11296/tby776>

³⁷⁶ A plant's ability to absorb CO₂ within a specific area and time.

³⁷⁷ National Library of Medicine (2010). Spatial and seasonal characterization of net primary productivity and climate variables in southeastern Taiwan using MODIS data. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2852544>

noted that most of the net primary productivity of crops is consumed³⁷⁸, while farmland does emit carbon. The issue of carbon emissions will be discussed in Section 5.4. Agriculture and Waste. Therefore, more research is needed to determine if farmland can be considered a carbon sink or a carbon source. In addition, in recent years, the international “4 per 1000” Initiative has started discussing the possibility of soil carbon storage. If the level of carbon stored in the top 40 centimeters of soil increased by 0.4% (or 4‰) per year, the annual increase of carbon dioxide (CO₂) in the atmosphere due to human activity would be significantly reduced. However, this initiative requires further research to evaluate its feasibility and net carbon storage.

3. Blue Carbon Sinks (Seagrass Meadows, Wetlands)

(1) Estimating Taiwan’s Blue Carbon Sink Potential Based on Global Potential

Taiwan’s blue carbon sink potential is estimated using Taiwan’s share in the global annual carbon emissions and global blue carbon sink potential. According to the IPCC’s (2019) “Special Report on the Ocean and Cryosphere in a Changing Climate,” it is argued that restoration of coastal ecosystems such as mangroves, tidal marshes, and seagrass meadows (i.e., coastal blue carbon ecosystems) can mitigate climate change by increasing carbon sequestration and storage. This would account for about 0.5% of current global annual emissions (medium confidence)³⁷⁹. In 2020, global CO₂ emissions reached 34 Gt (34 billion tons)³⁸⁰, so the global blue carbon sink potential can be benchmarked at 0.17 Gt (170 million tons) per year. Taiwan’s annual carbon emissions (0.3 Gt)³⁸¹ account for 0.88% of the global emissions (34 Gt). If we use this percentage to calculate Taiwan’s blue carbon sink potential, the initial estimation would be up to 1.5 MtCO₂eq/year (1.5 million tons/year).

(2) Relevant Research on Blue Carbon Sink Potential in Taiwan

Over the years, the Urban and Rural Development Branch of the National Land Management Agency of the Ministry of the Interior has subsidized research in wetland

³⁷⁸ Naser, H.M. et al. (2019). Carbon sequestration and contribution of CO₂, CH₄ and N₂O fluxes to global warming potential from paddy-fallow fields on mineral soil beneath peat in central Hokkaido, Japan. <https://www.mdpi.com/2077-0472/10/1/6/htm>

³⁷⁹ IPCC (2019). Summary for policymakers. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H. -THEIR. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

³⁸⁰ Environmental Protection Administration, Executive Yuan (2020). Global carbon emissions was down by record 7% in 2020 due to the pandemic. https://ghgregistry.epa.gov.tw/ghg_rwd/Main/Information/Information_3_detail?r_id=3058

³⁸¹ Please refer to 1.2.1 to see the data on zero-carbon electricity and Taiwan’s challenges to reduce greenhouse gas emission.

carbon sinks^{382,383}. Through these research projects, standard operating procedures (SOP) to investigate wetland carbon sinks have been updated. At the same time, important natural wetlands have been selected to conduct on-site measurement of carbon sinks. Studies on Taiwan's wetland carbon sinks have also been collected for mapping of wetland carbon sink distribution, which can be used as important scientific references when the government works to maintain and manage wetlands in the future. However, due to the fact that quantitative assessment methods are not mature and there is limited manpower and resources to carrying out relevant research, complete data on carbon removal potential is not yet available. Additional studies are needed to improve the assessment methods and data. Moreover, it is possible that wetlands can emit another greenhouse gas, i.e., methane, and this possibility must be taken into account.

Our recommendations provide comprehensive information on the potential area of blue carbon sinks in Taiwan and the carbon sequestered per unit area of different types of carbon sinks. The research data is shown in Appendix 3A and Appendix 3B.

(3) Potential Ancillary Benefits of Coral Reef Ecosystems to Blue Carbon Sinks

Coral reefs are important coastal ecosystems in Taiwan's waters³⁸⁴. Coral reefs cannot absorb a lot of CO₂, and they release CO₂ during the calcification process. Hence, scientific debates are still ongoing in the international community as to whether or not coral reefs can be included in blue carbon sinks. For example, Ware et al.³⁸⁵ estimate that during the calcification process, coral reefs release 0.02 to 0.08 Gt of carbon as CO₂ annually. However, we should pay attention to the diverse ecosystems supported by coral reefs, as well as coral reefs' indirect benefits in helping to store carbon. A paper on the island of San Andrés in the southwestern Caribbean³⁸⁶ shows that in tropical

³⁸² Hsing-Juh Lin, Chi-Ling Chen, Tien-Shui Chen, Shi-Bo Li, Ming-Ru Song, Wei-Jen Lin, Wei-Chung Chen, Chia-Yi Chen, Yan-Kwang Chen, En-Tse Chang (2018). *Research outcomes of "2017-2018 Annual Investigation of Carbon Sinks of Important Wetlands"* carried out by National Chung Hsing University. Urban and Rural Development Branch, Construction and Planning Agency, Ministry of the Interior. <https://wetland-tw.tcd.gov.tw/upload/file/20190521161653265.pdf>

³⁸³ The Urban and Rural Development Branch, Construction and Planning Agency, Ministry of the Interior (2011). Summary report on the investigation of carbon sinks of important wetlands in Taiwan. Carried out by Kao Yuan University and Chia Nan University of Pharmacy and Science. <https://wetland-tw.tcd.gov.tw/upload/file/20190522110235955.pdf>

³⁸⁴ Hsing-Juh Lin (2020). Blue carbon strategy under climate change. *Sci-Tech Vista*. <https://scitec.hvista.nat.gov.tw/Article/c000009/detail?ID=6cb9c91e-8b10-4830-8683-7ad15cdc57a7>

³⁸⁵ Ware, J. R., Smith, S. V. & Reaka-Kudla, M. L. (1992). Coral reefs: Sources or sinks of atmospheric CO₂? *Coral Reefs II*, 127-130. <https://doi.org/10.1007/BF00255465>

³⁸⁶ Guerra-Vargas, L. A., Gillis, L. G., Mancera-Pineda, J. E. (2020). Stronger together: Do coral reefs enhance seagrass meadows "blue carbon" potential? *Frontiers in Marine Science*. <https://www.frontiersin.org/articles/10.3389/fmars.2020.00628/full>

climates, seagrass meadows are often connected to coral reefs. Coral reefs act as barriers to dissipate waves, facilitate sediment accumulation and prevent erosion, so seagrass meadows can grow and expand their blue carbon sinks. The loss of coral reefs due to coral bleaching and other stressors may result in smaller seagrass meadows and reduction of blue carbon sinks. Researchers carrying out the study tested their hypothesis by assessing blue carbon across a gradient of connected seagrass meadows and coral reef sites and found that sites with reduced wave disturbance (protected by coral reefs), compared with sites with higher disturbance (no protection from coral reefs), have higher carbon accumulation in seagrass meadow sediment. Hence, when we study the carbon removal potential of blue carbon sinks, we should examine the role played by Taiwan's coral reefs in supporting blue carbon sinks.

3.2.4 Policy Recommendations

Negative emission technologies and maximizing carbon sinks are a tool for Taiwan to achieve its net-zero goal. These approaches can help reduce some of the pressure as Taiwan makes the transition to carbon-free energy. Our recommendations are:

1. Measures should be taken to expand forest carbon sinks, including increasing the area of forest land (coastal forests, lowland forests, reforestation of farmland); improve the active management of Taiwan's man-made forests (state-owned forests and private forests); and increase Taiwan's wood production (for carbon sequestration in wood), so as to meet the goals of carbon sinks by 2050. A detailed description of each measure is provided below:

A. Increasing forest land: We need to increase the total area of forest cover by planting coastal forests, afforestation of state-owned forests, and planting trees on plains and slope land. At the same time, we need to consider gradual reforestation of farmland. On Taiwan's plains, the carbon sink potential of trees along streets, in campuses and parks as well as in private residential areas need to be taken into account.

B. Improving the active management of man-made forests in Taiwan: To increase biomass per unit area, approaches include reforestation, cultivation and thinning. We can also consider approaches for timber stand conversion. We can identify species or genotypes with a higher likelihood to adapt to future challenges based on future climate patterns and environmental conditions and carry out a long-term projection of forest structure and species composition with the goal of

significantly expanding Taiwan's carbon sinks.

C. Increasing Taiwan's wood production: The carbon sequestration capacity of forests gradually slows down after a period of rapid growth; hence, timely thinning should be carried out to ensure that our forests can continue to absorb carbon. At the same time, trees cut down during thinning should be put to good use. The timber can be used to make furniture and ensure that carbon can be sequestered in the wood for a long time, or it can be used as biomass fuel. At present, lumber mills in Taiwan mainly use imported lumber, so their use of lumber cannot help increase Taiwan's forest carbon sink and, in fact, will increase the carbon footprint generated during transportation. Hence, it is necessary to strategically increase Taiwan's wood production and exports to promote the renewal of forests, thereby maintaining the carbon sink capacity of Taiwan's forest lands. Moreover, imported wood products should be fully recycled and reused to extend the time of carbon sequestration and reduce subsequent imports.

2. Research quantitative methods for assessing newer natural carbon sinks (crops, soil, and blue carbon), as well as carbon removal potential (accelerate investment before 2030). Once such methods are mature, they can be used to estimate the carbon sink capacity of various natural carbon sinks (and the methods can be gradually applied after 2030).

Apart from forest carbon sinks, which have become quite mature, crops and soil, as well as blue carbon, are areas that can be considered in the future. For example, we should invest in projects like high-efficiency fertilizers, biofertilizers, farming methods that can reduce soil exposure time, and low-carbon emitting crops. If high-efficiency fertilizers can be used, we can reduce the use of nitrogen fertilizers and increase the use of biochar. Compost can also be used to produce biogas before it is used as fertilizer. These approaches can all expand the carbon sink of farmland. Reduced or minimized plowing using roller crimpers can reduce the loss of biochar from the soil. As for carbon emissions and the carbon sinks of crops, if we take rice paddies as an example, its carbon sink is often offset by the emission of methane from microorganisms in the water. Hence, water level management and changing crops to drought-tolerant rice can improve the capacity of the carbon sink.

As for methods to assess soil carbon sinks, we face challenges posed by the complexity of plant ecosystems. If we take rice paddies as an example again, even though the plants can store carbon through photosynthesis, different varieties of rice

will have different capacities, while water levels, microbial community respiration, and methane emissions, as well as the carbon sequestration of different soils all need to be taken into consideration. Since wetlands can also emit methane, researchers are still debating whether wetlands can be considered net carbon sinks or net carbon emitters. Without accurate assessment methods, it is difficult to know the real situation. Without information on the real situation, it will be difficult to convince farmers to change their farming habits. The government can encourage consumers to eat low-carbon food and use the results of reliable experiments to allow farmers to experience and compare different farming methods and promote farming methods that could expand carbon sinks.

As for blue carbon sinks, the international community has not yet come up with a consistent assessment method, so it would be necessary to carry out studies on quantitative assessment methods and carbon removal potential while encouraging relevant investigators and researchers. At the same time, such studies can help examine the role of Taiwan's coral reefs in supporting blue carbon sinks. The research outcomes can help Taiwan evaluate the possibility of applying blue carbon to expand Taiwan's natural carbon sinks.

3.3 Traditional CCUS (Carbon Capture, Utilization, and Storage)

Summary

Carbon capture, utilization, and storage (CCUS) technologies currently available can recover carbon dioxide (CO₂) from flue gas. If mature, it can reduce the direct emissions from the power sector and most industrial sectors. Carbon capture technologies have been developed for many years, but the utilization technology is still in its infancy. The only storage technology that has been in use for years is injection into oil wells, but there are no confirmed large-scale sites domestically for storage, so the problem remains to be solved by exploration technology. The technology of direct air capture (DAC) of carbon dioxide from the atmosphere is even more challenging. In addition to biological methods (microalgae cultivation), there are only a few foreign pilot plants conducting tests at present. In addition, the operation of related equipment systems still has a certain energy consumption. Aside from cost factors, the carbon emissions from the power sources required for operation (green energy or fossil fuels) should be taken into account to ensure that the carbon capture of the system in operation is higher than the carbon emissions from the equipment energy consumption, so that it can achieve net zero/net negative emissions overall. Hence, based on the various situations in Taiwan, actions are recommended as follows:

1. Strengthen the competitiveness and collaborative assessment of CCUS technologies with other green energy options on carbon reduction applications, ensuring that the technologies can deliver benefits of net-zero/net-negative emissions in operation;
2. Promote the development of Direct Air Capture (DAC) technologies, including both biological and chemical methods for carbon dioxide capture.

3.3.1 Preface

CCUS refers to Carbon Capture, Utilization, and Storage. In terms of the value chain of the technologies, it can be divided into different stages: Capture, Transport, Storage, and Use. Traditional CCUS technologies mainly capture carbon dioxide from large emission sources (flue gas), such as power generation or industrial facilities using fossil fuels or biomass as fuel. In addition, DAC technologies capable of capturing carbon dioxide from the atmosphere directly has also been developed in recent years³⁸⁷. If the captured carbon dioxide is not used directly, it can be further compressed and transported via pipeline, ship, rail, or truck for a series of applications, or injected into deep geological formations (including depleted oil and gas reservoirs or saline aquifers) for permanent storage of the captured carbon dioxide (Figure 3.3.1).

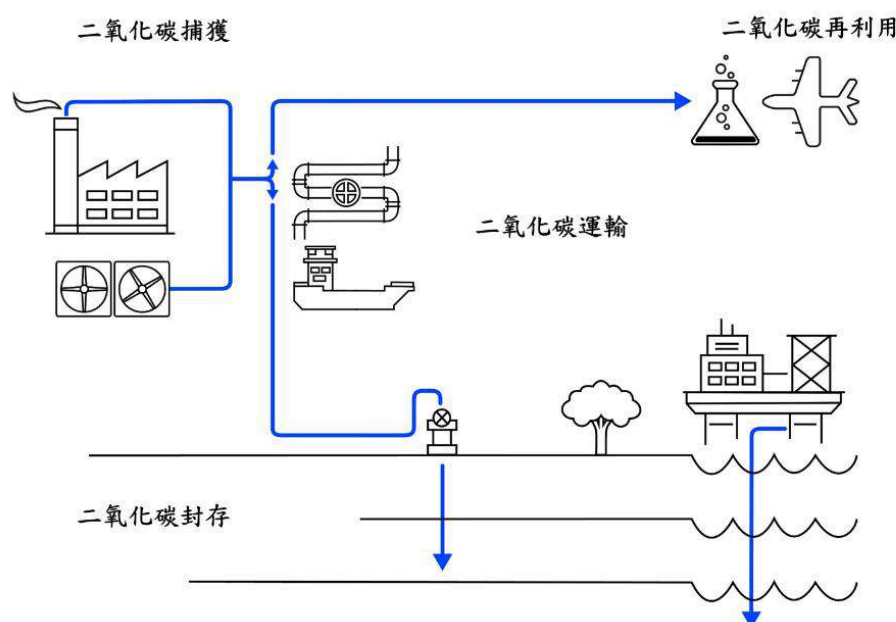


Figure 3.3.1 The Technical Scope of CCUS³⁸⁸

CCUS has been in development for several decades and has been applied in certain fields. Early applications were mainly in natural gas processing or fertilizer production, where costs were relatively low (approximately 15 USD/tCO₂eq). In 2000, the production of synthetic fuels for long-haul transportation (especially in aviation) began, but it remained in the early experimental stage. Currently, the progresses in key areas

³⁸⁷ IEA (2021). About CCUS. <https://www.iea.org/reports/about-ccus>

³⁸⁸ *Ibid.*, note 387.

remain sluggish (e.g., the high-carbon emission industries with limited options of carbon reduction technologies, such as cement, steel, and petrochemicals, etc.), merely in their early stages of development (Figure 3.3.2).

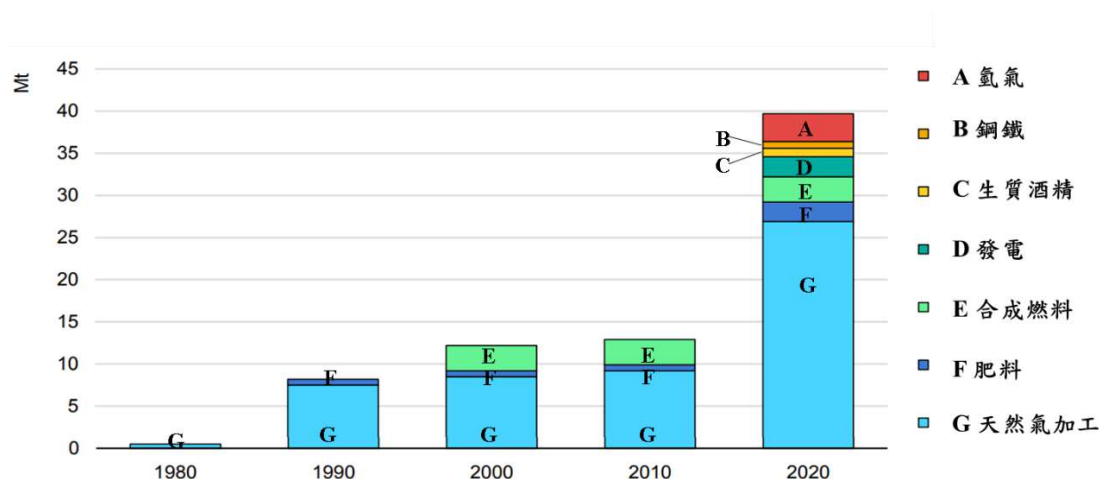


Figure 3.3.2 Current Sources of CO₂ Captured by CCUS Facilities Worldwide³⁸⁹

CCUS is a crucial technology in the global effort to achieve net-zero emissions by 2050. The technology can reduce direct emissions from most industrial sectors, either through retrofitting of existing industrial and energy facilities or incorporation into the development of new facilities. Non-traditional CCUS technologies that capture carbon from sources other than fossil fuels and industrial processes (see Section 3.4 Application of Carbon Biosequestration and Bio-based Processing and Section 6.2 Direct Air Capture Technologies) can also remove CO₂ from the atmosphere directly (e.g., achieving carbon capture and storage using bioenergy, and directly capturing carbon dioxide from the air), offering the possibilities of large-scale, deep CO₂ removal from the climate system³⁹⁰. The International Energy Agency (IEA) report estimated the contributions of various CCUS technologies to 2050 Net Zero, with the potential to capture 1.67 GtCO₂eq by 2030 and up to 7.6 GtCO₂eq by 2050, accounting for 25% of total emissions in 2050 (30.2 GtCO₂eq). In particular, 5.25 GtCO₂eq will be captured from fossil fuels and industrial processes, 1.38 GtCO₂eq from bioenergy, and 0.99

³⁸⁹ IEA (2020). Energy technology perspectives, CCUS in clean energy transitions. https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf

³⁹⁰ IEA (2020). Energy technology perspectives 2020: Special report on carbon capture utilisation and storage. <https://webstore.iea.org/download/direct/4191>

GtCO₂eq through DAC³⁹¹.

3.3.2 International Trends and Current Technology Development Statutes

1. CO₂ Capture Technologies

The development of existing carbon dioxide capture technologies is quite diversified, including chemical absorption, physical adsorption, oxy-fuel separation, membrane separation, calcium looping, and chemical looping³⁹². For the emerging DAC technologies, please refer to Section 6.2 Direct Air Capture Technologies. The principles, current statuses, and readiness levels of respective technology are summarized in Figure 3.3.3. We can see that many technologies, such as chemical absorption and physical adsorption, have reached the stage of commercial operation, while oxy-fuel separation, membrane separation, calcium looping, chemical looping, and direct separation are in pilot program or demonstration/pre-commercial stage (approximately TRL 4-7). The gap in DAC technologies is relatively large, with huge differences across regions or technology readiness levels, ranging from TRL3 to 9. However, even though many technologies have reached the stage of commercial operation, all of these technologies require energy to operate, nevertheless. Therefore, in selecting suitable technologies, it is still necessary to consider the carbon emissions of the energy sources when incorporated into the overall system for operation, so that the system operation can achieve the goal of net zero/net negative emissions.

³⁹¹ IEA (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroBy2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

³⁹² *Ibid.*, note 387.

CO ₂ Capture Technologies	Principle	Technology Status and Readiness Level
Chemical Absorption	Chemical absorbents (such as ethanolamine compounds) react with CO₂.	Commercially operational (TRL 9-11)
Physical Absorption	Utilize the attractive force between CO₂ and adsorbents.	Commercially operational (TRL 9-11)
Oxy-fuel Separation	Combustion is carried out with near-pure oxygen, followed by carbon capture.	Large-scale prototype/pre-demonstration stage (TRL 5-7)
Membrane Separation	Polymeric or inorganic membranes selectively allow CO₂ to pass through.	- Only natural gas processing applications have reached the demonstration stage (TRL 6-7) - Pilot projects/pre-commercialization stage (TRL 5-6)
Calcium Looping	Calcium oxide (regenerable) combines with CO₂ to form calcium carbonate.	Pilot projects (TRL 4-6)
Chemical Looping	Metal oxide particles (reducible and regenerable) react with fuel to produce high-concentration CO₂.	Pilot projects (TRL 6)
Direct Separation	Use a special calciner to indirectly heat limestone to capture carbon emissions from cement production.	Pilot projects or commercialized (TRL 3-9) (TRL varies by region)
Direct Air Capture	Directly captures CO₂ from the air rather than from specific emission sources.	

Figure 3.3.3 Existing Carbon Dioxide Capture Technology Categories, Principles, and Technology Development Statuses^{393,394}

Note: The technology readiness levels are primarily based on the IEA categories.

³⁹³ *Ibid.*, note 387.

³⁹⁴ *Ibid.*, note 錯誤! 尚未定義書籤。.

In addition to the technology readiness, the capture cost in CCUS also varies depending on the CO₂ concentration. Generally speaking, if a plant's exhaust gas has a high CO₂ concentration, such as in the natural gas processing, the carbon capture cost is lower (25 USD/tCO₂eq). However, if the CO₂ concentration is low, the capture cost is higher. For example, carbon capture in the power and cement sectors costs 50 USD/tCO₂eq or more, and DAC can cost up to 300 USD/tCO₂eq or more (Figure 3.3.4).

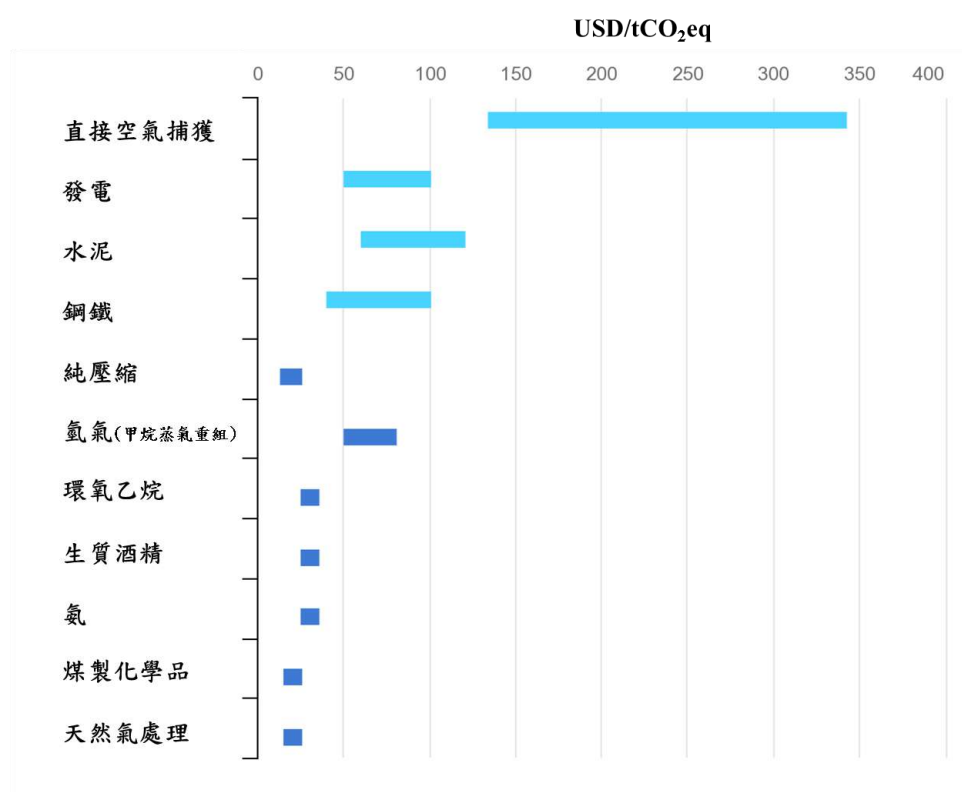


Figure 3.3.4 CO₂ Capture Costs for Different Technologies and Applications³⁹⁵

2. CO₂ Transport Technologies

CO₂ transport technologies can be generally divided into pipeline transport, ship transport, and truck/rail transport. Pipeline transport is the cheapest and can transport larger volumes, yet subject to distance and volume. The cost of CO₂ transport can be reduced by economies of scale through aggregating transportation and storage demand development, such as developing shared infrastructure industrial clusters. Or, reusing existing oil and gas pipeline infrastructure can help reduce costs as well³⁹⁶.

³⁹⁵ IEA (2021). Is carbon capture too expensive? <https://www.iea.org/commentaries/is-carbon-capture-too-expensive>

³⁹⁶ *Ibid.*, note 錯誤! 尚未定義書籤。.

3. CO₂ Utilization Technologies

CO₂ utilization can mainly fall into two categories: direct use and conversion. The amount of direct use is rather small, including for greenhouse application, industrial dry ice, and electronic-grade CO₂. Conversion involves reacting CO₂ with hydrogen or hydrogen-containing substances to convert it into chemicals or energy products. Chemicals such as fertilizers (urea), (poly)carbonates, acetic acid, cement substitutes, as well as energy products like methanol, dimethyl ether, dimethyl carbonate, etc^{397,398}.

From the perspective of the global potential for conversion and use of chemical products, urea and cement substitutes have a scale of hundreds of millions of tons; methanol has tens of millions of tons; dimethyl ether (DME) and polycarbonate have millions of tons; dimethyl carbonate (DMC) has hundreds of thousands of tons³⁹⁹. Recently, China Steel Corporation (CSC) and petrochemical plants have promoted the steel and chemicals co-production, in an attempt to capture carbon monoxide (CO) or carbon dioxide (CO₂) from converter gas or blast furnace gas of CSC, and with the assistance of petrochemical plants, react them with hydrogen or hydrogen-containing substances to produce products such as methanol, acetic acid, and methane, with the hope to scaling up to the “commercial application” level ultimately⁴⁰⁰. Although the volume of these products is large, it is not enough to solve the problem of carbon emissions in Taiwan, nevertheless, requiring still the combination with storage technologies.

4. CO₂ Storage Technologies

The existing CO₂ storage technologies can be broadly classified into geological storage, mineral storage, and bioenergy with carbon capture and storage (BECCS). Domestic research has previously assessed that Taiwan’s potential for geological storage could reach 95.3 billion tons (95.3 Gt) (Table 3.3.1). Although the preliminary estimated storage potential is huge, the uncertainty of the value is also high, and the costs and risks of implementing sequestration would need to be taken into consideration. Taiwan is not a continental country, so the land-based storage capacity is relatively limited. It is most likely to start with the depleted oil and gas reservoirs that have been

³⁹⁷ Srivastav, P., Schenkel, M., Rehman Mir, G. U., Berg, T. & Staats, M. (2021). Carbon capture, storage, and utilisation: Decarbonisation pathways for Singapore’s Energy and Chemicals Sectors. Navigant Netherlands B.V. <https://www.nccs.gov.sg/singapores-climate-action/low-carbon-tech/>

³⁹⁸ National Science Council, Executive Yuan (2013). Master plan for the national energy program phase II (approved version).

³⁹⁹ *Ibid.*, note 錯誤! 尚未定義書籤。

⁴⁰⁰ China Steel Corporation (2021). Special report: Striving for carbon reduction, CSC promotes steel and chemicals co-production. https://www.csc.com.tw/CSC/hr/csr/env/env_fea.htm

exploited for the past four or five decades on Taiwan Island itself, since there is abundant research data on the geological structure and physical and chemical properties of the formation fluids, which can be directly applied in CO₂ storage without exploration or research especially⁴⁰¹. Although the potential for storage is difficult compared with that of offshore storage, the development cost is low and presents advantages, and it can be used to facilitate the energy sector in accelerating emission reduction in the short and medium term. If we are to find another suitable site for storage in the coastal or nearshore areas, it is necessary to set up a plant for directional drilling⁴⁰², but the challenge lies in the necessity to resolve the public concerns over the environmental impacts. If the option of offshore storage (such as saline aquifer storage) is adopted, there will be a need for offshore exploration, and the development risks will be further increased. On one hand, Taiwan lacks relevant offshore exploration experience; on the other, the exploration cost will soar as well.

In addition, there is a certain distance between the storage sites and the scattered emission sources. If Taiwan decides to develop carbon capture and storage, we may need to consider how to smoothly transport the captured CO₂ from various emission sources to the storage sites. If we plan to transport it by truck, it may generate more transportation emissions and be costly. If we use pipelines, we need to take into account the deployment costs of land/sea pipelines, land ownership negotiation, and public acceptance. As for mineral storage, assessment of the possible sites and their potential in Taiwan is to be conducted. We may refer to the innovative practices of the case studies described in the later chapters. Regarding BECCS, improvement to the reaction efficiency is desired.

⁴⁰¹ Li, Y. H. (2017). Geological storage of carbon dioxide (Part 1): Geological storage. <https://scitechvista.nat.gov.tw/Article/C000003/detail?ID=0bba508f-329c-4788-951a-f17a793f4d3b>

⁴⁰² According to the article in *Scientific Development* (2017), oil and gas drilling projects can be broadly classified into three types based on well trajectory: vertical wells, horizontal wells, and directional wells. Directional or horizontal wells are primarily employed when there are limitations due to surface environmental conditions or underground geological conditions, in which directional wells are wells inclined at a specific angle.

Table 3.3.1 Preliminary Assessment of (Total) Domestic Geological Storage Capacity⁴⁰³

Unit under Assessment	Taiwan Power Company	CPC Corporation, Taiwan	National Central University	Industrial Technology Research Institute
Scope of Assessment	Taixi Basin	14 oil and gas structures onshore	1. Taipei-Taoyuan Area 2. Hsinchu-Miaoli Area 3. Taichung-Changhua Area 4. Yunlin-Chiayi Area 5. Open saltwater aquifers along the coasts of Kaohsiung-Tainan Area	The foreland basins in Western Taiwan, ranging from Taoyuan County to Changhua County's coastal areas.
\ (Gt) Estimated Storage Capacity (Gt)	3.70	2.83	13.60~95.30 13.60-95.30	9.00~68.00 9.00-68.00

Furthermore, geological carbon storage, like geothermal exploration, requires surveying suitable geological structures. When comparing the benefits of investing in geothermal exploration and applying carbon capture and storage to power generation with fossil fuels, the biggest difference is that geothermal energy is a baseload green energy and is recognized as a renewable energy category by the internationally renowned renewable energy initiative RE100⁴⁰⁴, which can directly contribute to maintaining the supply chain competitiveness of our core industries, such as the semiconductor industry. This is the first benefit. In addition, conducting geothermal power exploration on land, compared to offshore storage exploration, can significantly reduce risks and costs. Aided by carbon pricing in the future, geothermal exploration will inevitably become more cost-competitive. This is the second benefit.

⁴⁰³ *Ibid.*, note 12.

⁴⁰⁴ RE100 Climate Group (2021). RE100 technical criteria. <https://www.there100.org/sites/re100/files/2021-08/RE100%20Technical%20Criteria%20Aug%202021.pdf>

5. Innovative Case - Mineral Storage

In terms of innovative cases in CO₂ storage, the CarbFix project in Iceland, which has been assisting the Hellisheidi geothermal power plant since 2007 in utilizing basalt for carbon storage, is a worth noting case. The project involves injecting a mixture of CO₂ and geothermal water into the ground, where it comes into contact with the basalt minerals at a depth of 400-500 meters. The slightly acidic geothermal water dissolves the calcium and magnesium ions from the basalt, allowing them to react with the CO₂ and convert it into stable, white limestone solids for a safe storage within the basalt formations. This technology is characterized by its rapid sequestration rate, with 95% solidification achieved in less than two years. The challenge, however, lies in its high water consumption, requiring approximately 25 tons of water to sequester 1 ton of CO₂^{405,406,407,408}.

3.3.3 Policy Recommendations

1. Strengthen the competitiveness and collaborative assessment of CCUS technologies with other green energy options on carbon reduction applications, ensuring that the technologies can deliver benefits of net-zero/net-negative emissions in operation

The operation, transportation, and storage of CCUS devices still consume certain energy. Apart from cost factors, the carbon emissions from the power sources required for CCUS operation (green energy or fossil fuels) should also be taken into account considered to ensure that the amount of carbon captured is higher than the carbon emissions from the energy consumption of CCUS devices. Even if the energy consumed in CCUS operation comes from green energy, it is still necessary to consider if the same green energy is applied to other approaches will offer better benefits in carbon reduction.

⁴⁰⁵ Lin, L. H. (2016). The ultimate choice for carbon dioxide storage—Basalt? https://www.gst.org.tw/cht/fridgeo_detail.php?serial=11

⁴⁰⁶ Matter, J.M., Stute, M., Snæbjörnsdóttir, S. Ó., Oelkers, E.H., Gislason, S.R., Aradóttir, E.S., Sigfusson, B., Gunnarsson, I., Sigurdardóttir, H., Gunnlaugsson, E., Axelsson, G., Alfredsson, H.A., Wolff-Boenisch, D., Mesfin, K., Fernandez de la Reguera Taya, D., Hall, J., Dideriksen, K. & Broecker, W.S. (2016). Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science*, 352(6291):1312-4. doi: 10.1126/science.aad8132. PMID: 27284192.

⁴⁰⁷ Zalzal, K. S. (2017). Burying the sky: Turning carbon dioxide into rock. <https://www.earthmagazine.org/article/burying-sky-turning-carbon-dioxide-rock/>

⁴⁰⁸ Hsiao, K. H. (2016). Basalt formations can rapidly fix carbon dioxide, offering the world with a solution for carbon capture and storage technology. https://km.twenergy.org.tw/Data/db_more?id=1255

For example, with the same power, directly replacing coal-fired power with green energy may provide better emission reduction benefits than installing additional CCUS devices for coal-fired power. However, if there is too much intermittent green power that cannot be consumed immediately, in order to avoid wind and solar curtailment, the application in CCUS operation, or regulation through energy storage systems, may be considered.

2. Promote the development of Direct Air Capture (DAC) technologies, including both biological and chemical methods for carbon dioxide capture

At present, some international DAC projects (using chemical methods) are gradually reaching profitability even without government subsidies or carbon tax credits. Additionally, some methods can effectively capture CO₂ without the use of energy-intensive air intake systems. Thus, they can contribute to a significantly reduction of the CO₂ levels in the atmosphere. Nonetheless, the relevant research capacity Taiwan regarding this area remains in short supply. Therefore, we need to promote the development of DAC technologies through international cooperation and technical exchanges. For further details, please refer to Section 6.2 Direct Air Capture Technologies.

Meanwhile, utilizing biological photosynthesis to reduce CO₂ using light energy, such as through natural carbon sinks and blue carbon, offers a cost advantage in carbon storage compared to the traditional CCUS technologies or other negative emissions technologies. Therefore, it is also recommended to adopt biological methods for CO₂ capture to support Taiwan in achieving the goal of net-zero emissions. For more information, please see Section 3.2. Furthermore, the CO₂ captured through biological methods can be further converted into various metabolic products or a variety of chemical materials or plastic monomers through emerging metabolic engineering and synthetic biology technologies, to bring about economic benefits. For more information, please refer to Section 3.4 Application of Carbon Biosequestration and Bio-based Processing, as well as Section 6.3 Analysis of Biological and Chemical CO₂ Utilization Technologies.

3.4 Application of Carbon Biosequestration and Bio-based Processing

Summary

Photosynthesis is currently the only means to capture carbon from the air on a large scale. Bio-based materials are materials derived from atmospheric carbon fixation through photosynthesis and can be considered an effective product of DAC. With that, we can utilize spaces of idle lands and waters to generate bio-based carbon sinks through terrestrial and aquatic photosynthesis, before conversion thereof into hydrogen and solid biochar by means of pyrolysis. Hydrogen can be used to generate power, contributing to baseload power, while solid biochar can be stored, contributing to carbon sinks, achieving bioenergy with carbon capture and storage (BECCS). In addition to traditional chemical conversion processes, bio-based materials can also be converted into energy products and chemical materials through bio-based processing to replace petrochemical products. Hence, the policy recommendations in this section are as follows:

1. Invest in research on terrestrial/aquatic photosynthetic carbon biosequestration (pyrolysis technologies for hydrogen production and carbon fixation) and utilize idle spaces of lands and waters effectively for application of bioenergy with carbon capture and storage (BECCS) to achieve net-zero/net-negative emissions.
2. Shift to use of bio-based materials and development of bio-based processing to promote the development of bio-economy in place of high-carbon-emitting petroleum and traditional chemical processes to produce chemicals and energy products. At present, such technologies cannot compete with petrochemical products and require carbon pricing to reflect the true cost in order to be profitable.

3.4.1 Preface

Bio-based materials are materials derived from atmospheric carbon fixation through photosynthesis. Utilizing natural photosynthesis to capture carbon from the air on a large scale can be considered an effective method of direct air capture. Even if these materials are eventually burned to produce CO₂, it remains a carbon-neutral cycle. Traditionally, bio-based materials were directly burned for thermal energy, yet prone to air pollution. Recently, they have been made into bioethanol and blended with gasoline as fuel for cars and motorcycles, capable of reducing the use of petroleum. In the future, spaces of idle lands and waters can be leveraged to generate bio-based carbon sinks through terrestrial or aquatic photosynthesis, before conversion thereof into hydrogen and solid biochar by means of pyrolysis. Hydrogen can be used to generate power, contributing to baseload power, while solid biochar can be stored, contributing to carbon sinks. This is an example of bioenergy with carbon capture and storage, also known as carbon negative technology. In addition to traditional chemical conversion processes, bio-based materials can also be converted into alternative petrochemicals (such as aviation and marine fuels) and chemical materials through bio-based processing to replace petroleum products. This section shall conduct a detailed analysis of relevant biomass production, process conversion, and end-use applications.



Figure 3.4.1 The Value Chain of the Application of Carbon Biosequestration and Bio-based Processing⁴⁰⁹

⁴⁰⁹ A self-drawn figure of the Policy Proposal.

3.4.2 Terrestrial Photosynthetic Biosequestration (Pennisetum + Pyrolysis)

In terms of the terrestrial carbon cycle on Earth, terrestrial plants absorb 123 Gt C (123 billion tons of carbon equivalent) from the atmosphere through photosynthesis each year. However, 60 Gt C is quickly released back into the atmosphere due to plant respiration. Also, about 60 Gt C is released into the atmosphere through soil microbial respiration and decomposition each year, resulting in a near dynamic equilibrium in the terrestrial carbon cycle. However, due to impacts of human activities (mainly fossil fuel consumption, industrial emissions, and land use changes), an additional 9 Gt C (equivalent to 33 Gt CO₂) of emissions is seen each year, disrupting such dynamic equilibrium. Therefore, to restore the balance of the carbon cycle, one approach is to reduce emissions from human activities (e.g., through zero-carbon electricity and industrial decarbonization). In addition, the pathway of carbon biosequestration can be used as well^{410,411}. For the types of biomass that can be utilized on land for atmospheric carbon fixation, please refer to the sources mentioned in Section 2.7 Bioenergy. In particular, the planting of short-rotation biomass crops (such as Pennisetum) on the lands unsuitable for cultivation is a promising direction. Furthermore, thanks to advancements in synthetic biology, scientists have recently demonstrated that biotechnology can be used to enhance photosynthetic efficiency and stress resistance to increase the annual yield of plants per unit area and reduce the use of water, chemical fertilizers, and pesticides. If such technologies are applied to energy crops (like Pennisetum), the annual yield of bio-based materials can be increased.

In terms of utilizing Pennisetum, if traditional solid biomass utilization methods are employed, such as for incinerators to generate power, the power generation potential is 4.65 billion kWh, and the power generation equipment capacity required to intake it is about 1.0 GW (estimated based on a power generation efficiency of 30%)⁴¹² (see

⁴¹⁰ Jansson, C., Wulfschleger, S. D., Kalluri, U. C. & Tuskan, G. A. (2010). Phytosequestration: Carbon biosequestration by plants and the prospects of genetic engineering, *BioScience*, 60(9):685–696, <https://doi.org/10.1525/bio.2010.60.9.6>

⁴¹¹ Yang, C. C. (2021). [Letter to the Editor] Soil carbon storage: The world is focusing on climate issues, and it is the elixir for Earth's carbon neutrality! Independent Comment @CommonWealth. <https://opinion.cw.com.tw/blog/profile/52/article/11587>

⁴¹² Assuming a gross calorific value of 9000 MJ/t and a power generation efficiency of 30%, the conversion is as follows: $1.2409 \times 10^9 \text{ t} \times 9000 \text{ MJ/t} \times 0.2778 \text{ kWh/MJ} \times 30\% = 9.31 \times 10^9 \text{ kWh}$. Assuming the power plant operates 200 days a year, the conversion is: $9.31 \times 10^9 \text{ kWh} / 200 \text{ days} / (24 \text{ h/day}) = 1.94 \text{ GW}$.

Section 2.7 Bioenergy for details). However, if the grown *Pennisetum* is processed through the pyrolysis technology, the traditional solid biomass utilization method can be further elevated from carbon neutral to carbon negative. However, the detailed technologies such as conversion rate, hydrogen utilization, energy efficiency, and biochar separation are not mature enough yet, so a long-term government support and investment in research and development are required (see Box 2.7.2 in Section 2.7 Bioenergy for details). In addition, Section 2.7 Bioenergy mentions that the energy that can be generated per square meter by grown biomass is much smaller than that of solar PV system, but it can effectively maintain the cultivability of the soil. Therefore, the government also needs to pay attention to improving the land use efficiency on which energy crops are grown through biotechnology. In the future, the international community will restrict the exploitation of petrochemical raw materials. In order to ensure that our country's materials are not in short supply and for strategic considerations, the production of chemical materials from bio-based materials through biotechnology is also a necessary direction for special attention in the national science and technology development.

3.4.3 Aquatic Photosynthetic Carbon Biosequestration (Blue Carbon/Algae + Pyrolysis)

In addition to terrestrial photosynthetic carbon biosequestration, aquatic photosynthetic carbon biosequestration is also a potential option for carbon negative technologies. For example, algae, as one of the aquatic bio-based materials, is considered one of the most promising biofuel sources due to its unique characteristics. It accumulates lipids that can be converted into biofuels, proliferates rapidly, has the ability to sequester CO₂ from the atmosphere, and does not require farmland or freshwater for growth, thus avoiding high water consumption issues. Compared to terrestrial photosynthetic carbon biosequestration, it does not present competition for farmland, and the entire organism can be used in biofuel conversion. Algae cultivation along with wastewater treatment processes is also a means to provide sustainable renewable biomass, saving water by not requiring large amounts of freshwater for algae cultivation, and is an environmentally friendly process⁴¹³. If livestock wastewater is

⁴¹³ e Silva, F. V. & Monteggia, L. O. (2015). Pyrolysis of algal biomass obtained from high-rate algae ponds applied to wastewater treatment. *Front. Energy Res.* <https://doi.org/10.3389/fenrg.2015.00031>

used for cultivation, it can effectively reduce the chemical oxygen demand (COD) in the wastewater and achieve water purification purposes as well⁴¹⁴.

However, the carbon sink potential of marine and coastal ecosystems (blue carbon), including wetlands (such as salt marshes and mangroves) and seagrass beds, is still under research. It is expected that they can capture CO₂ from the atmosphere and store it in their leaves, stems, and soil, thus storing it in coastal or marine ecosystems. As mentioned in Section 3.2 Natural Carbon Sinks, there is not yet a method agreed internationally for assessing the potential⁴¹⁵. Therefore, for blue carbon to be incorporated into international or national policy frameworks, it must be clearly demonstrated that its carbon removal capacity can be quantified and is sufficient to have a climate impact, and that it can be effectively managed. Only then can the climate regulation value of blue carbon be further recognized.

The current research assessing the potential of marine-related negative emissions technologies suggests that if the area, water, and nutrient requirements are taken into consideration, preliminary conclusions indicate that the BECCS with large algae (seaweed) may be a better long-term option than terrestrial wood-based bioenergy crops, as it can achieve a higher productivity, does not require the use of freshwater, and may have lower nutrient requirements if a nutrient recovery system of high efficiency is developed. Nevertheless, the short-term feasibility is low, mainly because this method has not been verified on a large scale yet, and it may take a decade or more of research to demonstrate its potential, cost-effectiveness, and safety. Its cost-effectiveness (based on a single study estimate) is initially estimated to be high, with the removal cost of BECCS using marine biomass as fuel at 26 USD/t CO₂eq.

Furthermore, the use of these algae to manufacture long-lasting products like plastics can serve as a replacement for the carbon emissions associated with traditional petrochemical production processes. Besides, if aquatic photosynthetic carbon biosequestration is processed through methods such as pyrolysis, the hydrogen produced can be used for power generation by combustion, and the generated solid biocarbon can also be used as biochar to promote carbon fixation, while simultaneously

⁴¹⁴ Chen, T. Y., & Lin, C. S. (2013). Using livestock wastewater to cultivate microalga *chlorella* sp. For biomass and lipid production. <https://ir.nctu.edu.tw/handle/11536/75288>

⁴¹⁵ *Ibid.*, note 369.

improving soil fertility⁴¹⁶.

3.4.4 Bio-Based Processing for Energy and Chemicals (Bioenergy and Biochemicals)

The existing petrochemical production processes mainly rely on crude oil as raw material, which is then processed downstream into light oil, bulk petrochemical raw materials, and finally plastic products. Although carbon is retained in the products, the manufacturing processes often require high-temperature and high-pressure reaction conditions, and a large amount of carbon emissions will still be released into the air when the products are incinerated after consumption. Therefore, low-carbon or carbon-free raw materials are needed to replace traditional petrochemical raw materials in order to reduce carbon emissions⁴¹⁷.

To address the aforementioned issues, the international trend is to utilize biological photosynthesis to reduce CO₂ using light energy, converting it into bio-based materials for bio-based processing to replace high-carbon-emitting petroleum and traditional chemical processes for the production of bulk chemicals and aviation fuels. Although this field has been researched in academia for years, continued investment is required, nevertheless, for several more years, and the industry in Taiwan is yet to take off. Successful cases abroad include 1,3-PDO, 1,4-BDO, lactic acid, ethylene, PLA, 1-Butanol, isobutanol, and succinic acid. In recent years, there has been further development of terephthalic acid, ethylene glycol, diacids, diamines, and other plastic monomers, which are then used to produce bio-based plastics^{418,419,420,421,422}.

Initially, the primary bio-based material was sugar for research and development

⁴¹⁶ Gattuso, J. P., Williamson, P., Duarte, C. M. & Magnan, A. K. (2021). The potential for ocean-based climate action: Negative emissions technologies and beyond. <https://www.frontiersin.org/articles/10.3389/fclim.2020.575716/full>

⁴¹⁷ Please refer to the text of Section 4.4 Petrochemical Industry.

⁴¹⁸ Atsumi, S., Hanai, T. & Liao, J.C. (2008). Non-fermentative pathways for synthesis of branched-chain higher alcohols as biofuels. *Nature*, 451:86-89

⁴¹⁹ Atsumi, S., Higashide, W. & Liao, J.C. (2009). Direct recycling of carbon dioxide to isobutyraldehyde using photosynthesis. *Nature Biotechnol*, 27, 1177-1180. <https://doi.org/10.1038/nbt.1586>

⁴²⁰ Lan, E.I. & Liao, J.C. (2011). Metabolic engineering of cyanobacteria for 1-butanol production from carbon dioxide. *Metab Eng.*, 13(4):353-63.

⁴²¹ Felnagle, E.A.; Chaubey, A., Noey, E. L., Houk, K. N. & Liao J.C. (2012). Engineering synthetic recursive pathways to generate non-natural small molecules. *Nature Chem Biol.*, 8(6):518-26.

⁴²² Yu, H., Li, X., Duchoud, F., Chuang, D. S. & Liao J.C. (2018). Augmenting the Calvin–Benson–Bassham cycle by a synthetic malyl-CoA-glycerate carbon fixation pathway. *Nat Commun.*, 9, 2008. <https://doi.org/10.1038/s41467-018-04417-z>

centering around bio-based processing with sugar as the raw material to produce various chemicals. Later, the technologies to replace sugar with cellulose as the raw materials were developed. In the future, bio-based materials can be imported, and bio-based processing can be exported. Furthermore, it is also a worthwhile direction to utilize methane (the main component of natural gas and landfill gas) or methanol as raw materials and develop bio-based processing to convert methane or methanol into other chemical raw materials⁴²³.

In the past, bio-based processing was mainly used to produce food additives (such as MSG), feed (such as amino acids), and antibiotics. In recent years, thanks to advancements in metabolic engineering and synthetic biology, microorganisms can already be converted into cell factories via gene editing technology to produce various chemicals. Domestically, there is already a good foundation for such technologies, and we are leading the world in several areas, but the research and development is still limited to academia. The domestic chemical industry generally lacks a foundation in biotechnology, and most domestic biotech talents are also engaged in pharmaceutical research and development. If we aim to solve the problem of high carbon emissions in the petrochemical industry, all sectors of domestic industry, government, academia, and research have to work together to develop bio-based processing for specific chemicals, using metabolic engineering and synthetic biology technologies to replace traditional chemical processes and petrochemical raw materials. Overall, in the short term, Taiwan can still focus on high-value food additives, dyes, spices, among others, as R&D targets. Although the quantity is small and not enough to reduce carbon emissions to net zero, it can nurture industrial biotechnology in relay to achieve the goal of Net Zero by 2050.

3.4.5 Policy Recommendations

1. Invest in the research on terrestrial/aquatic photosynthetic carbon biosequestration (pyrolysis technologies for hydrogen production and carbon fixation) and utilize idle spaces of lands and waters effectively for application of bioenergy with carbon capture and storage (BECCS) to achieve net-zero/net-negative emissions

Photosynthesis is currently the only means to capture carbon from the air on a large scale. We ought to make good use of idle lands and waters to produce biomass

⁴²³ Chen, F.Y.-H., Jung, H. W., Tsuei, C.Y. & Liao, J.C. (2020). Converting *Escherichia coli* to a synthetic methylotroph growing solely on methanol. *Cell*, 182, 933-946. doi: 10.1016/j.cell.2020.07.010

through terrestrial/aquatic photosynthesis, before conversion thereof into hydrogen and solid biochar through pyrolysis gasification. Hydrogen can be used to generate power and contribute to baseload power, while solid biochar can be stored and contribute to carbon sinks. Therefore, carbon capture and storage can be achieved while producing bioenergy. This method can also help achieve net-zero/net-negative emissions through the ongoing growth and carbon fixation of biomass, coupled with subsequent carbon reduction applications in a circular process.

2. Shift to use of bio-based materials and development of bio-based processing to promote the development of bio-economy in place of high-carbon-emitting petroleum and traditional chemical processes to produce chemicals and energy products. At present, such technologies cannot compete with petrochemical products and require carbon pricing to reflect the true cost in order to be profitable

The existing production processes in the petrochemical industry and product consumption still result in substantial carbon emissions into the atmosphere. Hence, to effectively reduce carbon emissions, it is necessary to have low-carbon or carbon-free raw materials in place of traditional petrochemical raw materials. By shifting to bio-based materials and advanced bio-based processing, such as emerging metabolic engineering and synthetic biology technologies, to replace high-carbon petroleum and conventional chemical processes for producing chemicals and energy, the goal of significant carbon reduction may be achieved.

3.5 Conclusion

It will take considerable time for Taiwan to substantially increase the deployment of zero-carbon power, and some industrial processes find it difficult to reduce carbon emissions by relying on zero-carbon power. To achieve the goal of Net Zero by 2050 of Taiwan, it is necessary to apply carbon capture, utilization, and storage (CCUS) technologies to the flue gas of large emission sources such as fossil fuel power generation facilities and factory facilities to minimize existing emissions, and to use “negative emissions technologies” (also known as carbon negative technologies) capable of a direct removal of CO₂ from the air to remove CO₂ from the atmosphere, so as to help deliver Taiwan’s Net Zero by 2050 or even achieve net-negative emissions benefits.

This chapter explores the potential technological facets for investment from three strategic perspectives: nature-based solutions, tech-based solutions, and the combination of nature-based solutions with new technologies. For other carbon negative technologies, please refer to Appendix 3C.

In terms of **nature-based solutions**, natural carbon sinks play a role as nature-based solutions in climate change mitigation. They have lower costs and potentially multiple environmental and socioeconomic benefits. Therefore, it is recommended to focus on increasing forest carbon sinks, actively managing our forest plantations, and initiating research on quantification and assessment methods for emerging natural carbon sinks (such as crop carbon sinks, soil carbon sinks, and blue carbon sinks), carbon removal potential, and estimation of the capacity of various natural carbon sinks as the main directions for promotion.

In terms of **tech-based solutions** [e.g., carbon capture, utilization, and storage (CCUS)], it is recommended in the Policy Proposal to strengthen the competitiveness and collaborative assessment of CCUS technologies with other green energy options on carbon reduction applications, ensuring that the technologies can deliver benefits of net-zero/net-negative emissions in operation. In addition, it is also necessary to promote the development of Direct Air Capture (DAC) technologies (see Section 6.2), including the capture of carbon dioxide by biological and chemical methods.

In terms of **composite solutions**, it is recommended to invest in the research on terrestrial/aquatic photosynthetic carbon biosequestration (pyrolysis technologies for hydrogen production and carbon fixation) and utilize idle spaces of lands and waters

effectively for application of bioenergy with carbon capture and storage (BECCS) to achieve negative emissions. It can be combined with the shift to the utilization of bio-based materials and the development of bio-based processing to promote the development of the bio-economy in place of high-carbon-emitting petroleum and traditional chemical processes to produce chemicals and energy products.

Chapter 4: Carbon Reduction in Manufacturing

Sections

4.1 Introduction

4.2 Steel Industry

4.3 Cement Industry

4.4 Petrochemical Industry

4.5 Electronics industry

4.6 Conclusion

4.1 Introduction

In terms of domestic greenhouse gas emissions⁴²⁴, Taiwan's manufacturing sector produced approximately 149.6 Mt CO₂eq in 2019, accounting for about 52.1% of the country's total emissions of 287.1 Mt CO₂eq in that year. The emission sources can be categorized into three types: process emissions, electricity consumption, and fuel combustion, with electricity making up the largest portion at 63% (refer to the left side of Figure 4.1.1). Taiwan's manufacturing sector consists of four major industries: petrochemicals, electronics, steel, and cement. Together, these industries emitted a total of 112.2 Mt CO₂eq, accounting for 75% of the manufacturing sector's emissions and 39.1% of the nation's total emissions.

To reduce carbon emissions within the manufacturing sector, companies have continuously improved energy efficiency across the board. Some industries have even adopted artificial intelligence to optimize processes or energy management systems, enhancing efficiency and reducing energy consumption. In line with the global trend of carbon reduction, the demand for green electricity in Taiwan's manufacturing industry is expected to rise steadily. Additionally, industries like petrochemicals, steel, and cement have considerable carbon emissions from fuel combustion. In the short term, natural gas can replace coal to reduce emissions, while in the long term, the use of imported green hydrogen or integration with CCUS (Carbon Capture, Utilization, and Storage) technologies will be necessary to achieve decarbonization. Major companies should collaborate with domestic academic and research institutions to actively develop and adopt relevant technologies.

⁴²⁴ Ministry of Economic Affairs (2021). Assessment report on the direction of the manufacturing sector's 2050 net zero emissions pathway. Presentation at the Executive Yuan's Net Zero Emissions Project Task Force meeting on April 1 (unpublished data).

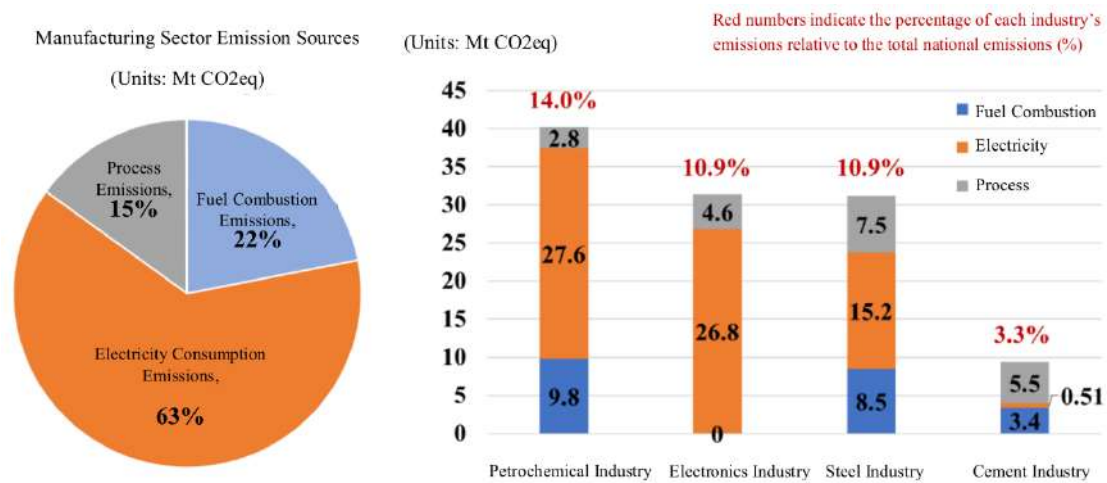


Figure 4.1.1 Emissions of Taiwan's Manufacturing Sector, Breakdown of Four Major Industries

4.2 Steel Industry

Summary

The steel industry has long supported Taiwan's industrial development. Due to the energy-intensive nature of steel production and its high carbon emissions, it is a key sector for Taiwan to target in achieving the 2050 net-zero emissions goal. The following strategies are recommended for the future development of Taiwan's steel industry:

1. Actively accelerate the introduction and development of zero-carbon processes by increasing the share of natural gas in fuel usage, or by replacing natural gas with carbon-neutral natural gas or hydrogen. When replacing equipment, it is essential to consider the impact of zero-carbon requirements and carbon pricing, setting the stage for a long-term low-carbon transition in the steel industry.
2. Hydrogen steelmaking and direct-reduced iron (DRI) technologies can significantly reduce carbon emissions in steel production. It is recommended that domestic industries closely monitor the development of these technologies and conduct small-scale testing. Consideration should also be given to importing reduced iron or semi-finished steel products, while keeping a close eye on the development of syngas utilization and CCUS technologies to enable timely adoption.
3. Promoting material recycling to enhance steel regeneration not only helps reduce carbon emissions during the mining stage but also lowers the consumption of natural resources. It is recommended to increase the proportion of recycled scrap steel and properly manage the waste generated from electric arc furnace steelmaking processes. This approach ensures carbon reduction, improves resource efficiency, and contributes to environmental protection.

4.2.1 Introduction

Steel is often referred to as the “mother of industry” due to its longstanding role in supporting industrial and technological development, as well as driving the growth of related industries. Although steel products have long life cycles and are 100% recyclable, steel production is energy-intensive and emits significant amounts of carbon. Therefore, reducing carbon emissions from the production process has become a critical task for countries addressing climate change. On July 14, 2021, the European Union officially announced its Carbon Border Adjustment Mechanism (CBAM), which includes steel among its regulated sectors. Countries with more carbon-efficient steel production processes will gain a competitive edge in the global market in the future. For Taiwan, the steel industry is a key element in supporting industrial development, making it essential to continually strengthen carbon reduction measures within this industry. Doing so not only responds to the evolving trends in environmental protection and economic development but also contributes to Taiwan’s goal of achieving net-zero emissions by 2050.

According to statistics from Taiwan’s Ministry of Economic Affairs^{425, 426}, Taiwan’s steel production in 2020 reached 56.95 Mt, including iron and steel smelting, iron and steel casting, iron and steel rolling and extrusion, and drawing of iron and steel. In the same year, domestic consumption amounted to 56.64 Mt, indicating that the majority of steel production is used to meet domestic demand. With respect to trade, Taiwan imported 12.26 Mt of steel (including re-imports) and exported 12.57 Mt (including re-exports) in 2020. The top three export destinations were China (2.22 Mt), Vietnam (1.62 Mt), and the United States (1.35 Mt). In 2019, Taiwan’s steel industry emitted approximately 31.2 Mt CO₂eq⁴²⁷, with 24% of these emissions coming from industrial processes, 49% from electricity consumption, and 27% from fuel combustion (refer to Figure 4.2.1), accounting for 10.9% of the country’s total emissions and 20.9% of the manufacturing sector’s emissions.

⁴²⁵ Department of Statistics, Ministry of Economic Affairs (2021). Product statistics, industrial production, shipment & inventory activity survey. <https://dmz26.moea.gov.tw/GMWeb/investigate/InvestigateDA.aspx>

⁴²⁶ Customs Administration, Ministry of Finance (2021). Total imports/total exports, statistics database query, customs-port-trade (CPT) single window. <https://portal.sw.nat.gov.tw/APGA/GA30>

⁴²⁷ *Ibid.*, 430.

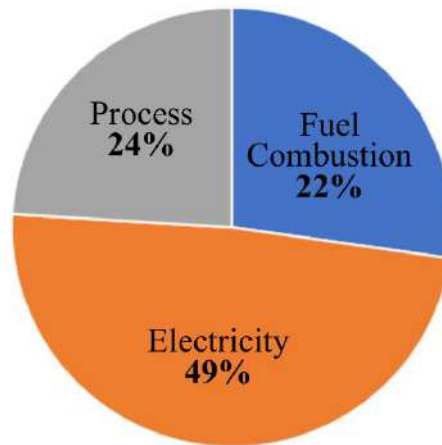


Figure 4.2.1 Emission Sources in Taiwan's Steel Industry⁴²⁸

Research on the relationship between steel production and carbon emissions shows that from 1900 to 2015, global steel production reached approximately 45 Gt⁴²⁹, resulting in the emission of 140 Gt CO₂eq, which accounts for roughly 9% of global greenhouse gas emissions during the period. Although production efficiency improved significantly by around 67%, the increase in annual steel production by 44 times offset these gains, leading to a 17-fold increase in annual emissions. Studies also show that emissions are distributed across four main stages of steel production: mining (13.3%), ironmaking (42.2%), steelmaking and casting (28.4%), and rolling (16.1%)⁴³⁰ (refer to Appendix 4A). The steelmaking process is not only energy-intensive but also has high carbon emissions. According to estimates by the International Energy Agency (IEA), each ton of crude steel produced generates about 2 tons of CO₂⁴³¹. However, steel materials and products are essential for industrial development. As a result, in the pursuit of the 2050 net-zero emissions target, the steel industry faces the following significant challenges^{432,433,434}:

1. Use of Fossil Fuels in the Steelmaking Process: Blast furnaces, a critical piece of equipment in steel production, primarily use fossil fuels like iron ore, coking

⁴²⁸ *Ibid.*, note 430.

⁴²⁹ Wang, P., Ryberg, M., Yang, Y. et al. (2021). Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. *Nat Commun*, 12, 2066. <https://doi.org/10.1038/s41467-021-22245-6>

⁴³⁰ *Ibid.*, 435.

⁴³¹ IEA (2020). Iron and steel technology roadmap.

⁴³² CTCI Foundation (2014). *Value chain and competitiveness of the steel industry*. https://www.ctci.org.tw/media/3012/專題報告_2014-08_鋼鐵產業的價值鏈與競爭力-全文.pdf

⁴³³ IEA (2020). *Energy technology perspectives 2020*. <https://www.iea.org/reports/energy-technology-perspectives-2020>

⁴³⁴ *Ibid.*, 437.

coal, and limestone, all of which contribute significantly to CO₂ emissions. While electric arc furnace steelmaking can reduce carbon emissions by using green electricity, the costs are relatively higher, and some high-quality steel materials cannot be produced through this method.

2. **High Complexity of the Steelmaking Process:** The steelmaking process is continuous and highly integrated, limiting the flexibility to adjust individual equipment or stages. Any changes made at one stage of the process will impact the technical parameters of other stages. While reducing carbon emissions through process improvements is a fundamental approach, it requires comprehensive coordination from upstream to downstream, which is costly.

3. **High Capital Costs and Long Equipment Lifecycles:** The steel industry is capital-intensive, with equipment lifecycles reaching up to 40 years. Transitioning to low-carbon technologies or replacing equipment would result in sunk costs for steelmakers, meaning that short-term efforts will likely focus on modifying or upgrading existing equipment to gradually reduce carbon intensity.

4. **Market Competition and Low Profit Margins:** The steel market is highly commoditized and competitive, with raw material costs—such as iron ore, scrap steel, and energy—heavily influencing production costs, accounting for 60-80% of total production costs. While emerging production technologies can reduce carbon emissions, if the increased production costs exceed the profits, it will weaken competitiveness and reduce the willingness of companies to adopt these technologies.

In summary, reducing carbon emissions in the steel industry requires not only a focus on technological improvements, such as enhancing process efficiency and upgrading equipment, but also a consideration of raw material input. The following sections will explore carbon reduction options and innovative case studies, providing an initial assessment of the potential methods and opportunities for decarbonizing the steel industry.

4.2.2 Global Carbon Reduction Trends in the Steel Industry

Based on research reports from the International Energy Agency (IEA), global carbon reduction efforts in the steel industry up to 2030 will primarily focus on traditional processes combined with CCUS (Carbon Capture, Utilization, and Storage) technologies⁴³⁵. Other key strategies include green processes and improvements in energy efficiency, while some countries and regions are switching to alternative fuels such as bioenergy and hydrogen (refer to Figure 4.2.2). After 2030, the introduction of innovative technologies to enhance processes will become the primary path for achieving carbon reduction. Examples of these technologies include hydrogen reduction ironmaking and electrolytic iron production technologies.

In comparing the various emission reduction technologies employed globally in the steel industry⁴³⁶, the greatest contribution to cumulative reductions in direct CO₂ emissions from 2020 to 2050 comes from improving material efficiency, such as recycling scrap steel. This is followed by improvements in technology performance (refer to Figure 4.2.3).

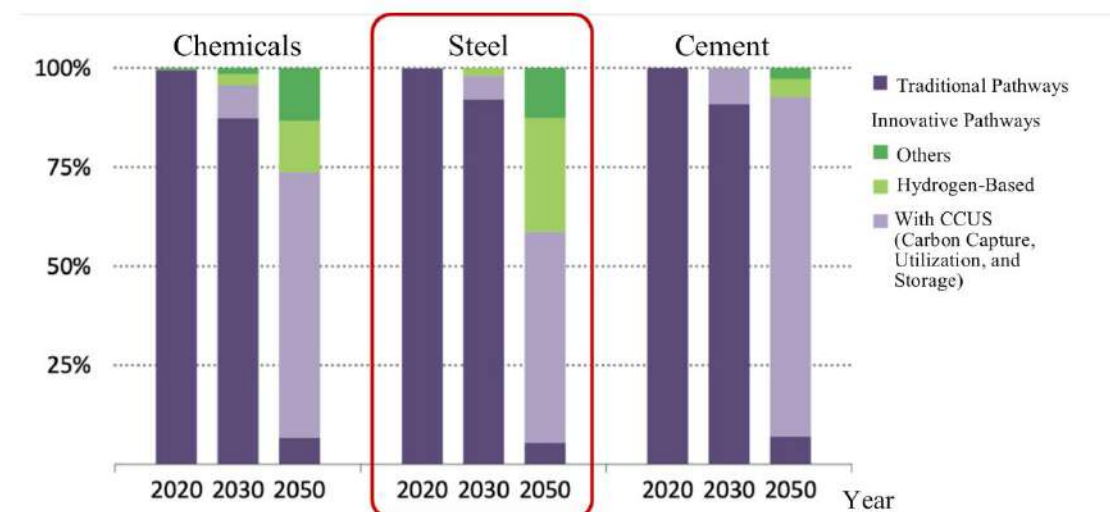
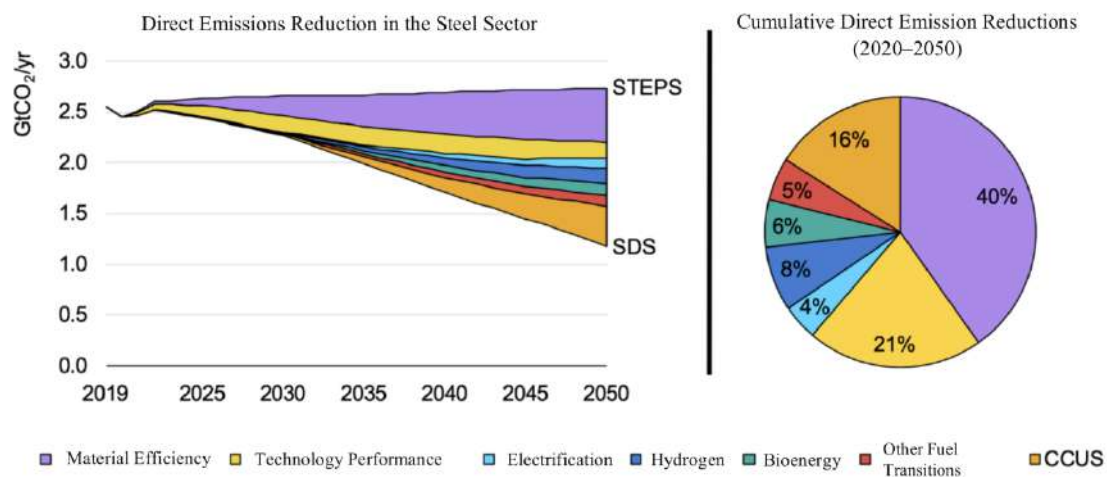


Figure 4.2.2 Global Carbon Reduction Trends in Steel Production Technologies⁴³⁷

⁴³⁵ IEA (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroBy2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

⁴³⁶ *Ibid.*, 437.

⁴³⁷ *Ibid.*, 441.



Note: STEPS = Stated Policies

SDS = Sustainable Development Scenario

Figure 4.2.3 Proportions of Cumulative Reductions in Direct CO₂ Emissions in the Global Steel Industry (2020 to 2050, by Emission Reduction Technology)⁴³⁸

Looking further into the situation, due to the varying levels of development in steel industries across different countries, it is necessary to tailor carbon reduction measures based on the age and type of infrastructure in each region. In countries or regions where industrial equipment is generally outdated, increasing the rate of equipment replacement to improve efficiency and reduce carbon emissions may be a viable option. On the other hand, in countries with more modern industrial equipment, adopting more energy-efficient and lower-carbon intensity technologies is likely the most cost-effective approach.

4.2.3 Carbon Reduction Options and Innovative Case Studies in the Steel Industry

1. Analysis of Carbon Reduction Options

Based on the aforementioned analysis of the steel industry's production processes and the sector's contribution to the manufacturing sector's carbon emissions, if Taiwan aims to achieve its 2050 net-zero emissions target, it is advisable to analyze the available carbon reduction options for the three main sources of emissions in the steel industry^{439,440} (refer to Figure 4.2.4).

⁴³⁸ *Ibid.*, 437.

⁴³⁹ *Ibid.*, 439.

⁴⁴⁰ *Ibid.*, 437.



Figure 4.2.4 Innovative Technologies for Steel Industry Carbon Reduction

(1) Combustion emissions primarily arise from blast furnaces using coal, coal gas, heavy oil, and other fossil fuels for iron smelting, followed by steelmaking in converters. This process also contributes to carbon emissions. Adopting alternative fuels such as natural gas and green hydrogen can effectively reduce carbon emissions. However, this option involves challenges like updating and adjusting the main process equipment, representing a relatively high-cost investment for the industry and a primary reason why changes cannot be rapidly implemented.

(2) Process emissions mainly occur during blast furnace ironmaking, where coal generates coke oven gas (mostly CO and H₂), which also serves as a reductant to facilitate the reduction of iron oxide to pig iron (reaction formula: $\text{Fe}_2\text{O}_3 + 3\text{CO} \rightarrow 2\text{Fe} + 3\text{CO}_2$; at higher temperatures: $\text{FeO} + \text{C} \rightarrow \text{Fe} + \text{CO}$). Therefore, developing reduction technologies to drive process innovation and replace the carbon emissions from coke oven gas is a focal point for technological advancements. Technologies like blast furnace steelmaking with hydrogen as a heat source, or producing direct-reduced iron through hydrogen steelmaking or electrolytic steelmaking, are currently under development internationally by major steelmakers as potential carbon reduction strategies. Additionally, common methods to reduce process carbon emissions include implementing the best available techniques (BAT) for performance enhancements, such as heat recovery in ironmaking processes, energy efficiency improvements in blast furnaces, and preheating of scrap feed for electric arc furnaces.

(3) Emissions from electricity consumption are significant, particularly for

electric arc furnaces and rolling mills. Therefore, embracing a circular materials approach to enhance material efficiency, promoting scrap steel recycling, and increasing the output of electric arc furnaces is crucial. Additionally, carbon emissions from various in-plant processes or combustion can be managed using CCUS technologies to capture carbon, with plans for subsequent carbon storage or reuse.

2. Innovative Technologies and Case Studies

The above-mentioned analysis of carbon reduction options for the steel industry indicates that technological innovation in smelting processes is essential for the industry to actively pursue carbon reduction. From a broader industry perspective, collaboration between the steel and petrochemical sectors, alongside leveraging domestic natural resources to produce carbon-free steel for the global market, will be crucial for Taiwan to achieve its 2050 net-zero target with partner countries. The following outlines the two main areas of focus: technological innovation and collaborative innovation.

In terms of technological innovation, a synthesis of research reports from the International Energy Agency and the International Renewable Energy Agency (IRENA) summarizes the key emerging technological developments as follows:

(1) Hydrogen Reduction Ironmaking: This technology aims to replace carbon with hydrogen as the reducing agent for iron oxide reduction. Given that H_2 molecules are smaller and diffuse into iron ore five times faster than CO , the reduction rate is improved. Furthermore, the reaction product of hydrogen with oxygen is water (H_2O), significantly reducing carbon emissions. However, the hydrogen-based iron ore reduction is an endothermic process, and meeting the heat demand of this process remains a central focus of research⁴⁴¹.

(2) Hydrogen Plasma Smelting Reduction (HPSR): This process involves generating discharges between two or more electrodes using either direct current or alternating current, which causes electrons to accelerate in the electric field and gain extremely high kinetic energy. These high-energy electrons collide with gas molecules or atoms, resulting in ionization reactions. In the HPSR process, an electric arc plasma reactor facilitates collisions between electrons and hydrogen molecules, producing excited-state hydrogen (H , H^+ , H_2^+ , H_3^+), which are then

⁴⁴¹ CTCI Foundation (2013). *Challenges and opportunities in Taiwan's steel industry*. https://www.ctci.org.tw/media/3033/專題報告_2013-08_臺灣鋼鐵業的挑戰與機會.pdf

used to reduce iron ore during smelting. The ionization level of hydrogen in the arc zone is a critical factor influencing the reduction rate of iron ore. Compared to the traditional carbothermic reduction of iron ores, HPSR offers thermodynamic and kinetic advantages, while significantly reducing carbon emissions⁴⁴².

(3) Electrolytic Ironmaking: Electrolytic Ironmaking involves the electrolytic reduction of iron ore, where iron is directly reduced from iron oxide (Fe_2O_3 or Fe_3O_4) through electrolysis, producing pure iron and oxygen. If powered by green electricity, this emerging technology could greatly contribute to reducing carbon emissions. The process can be developed under different temperature settings. In high-temperature electrolytic ironmaking, iron ore is loaded into an electrolytic cell and heated to a molten state (around $1,600^\circ\text{C}$), followed by the use of different carbon-free inert anodes for electrolysis. During the process, negatively charged oxygen ions migrate to the positively charged anode, generating oxygen gas, while positively charged iron ions move to the negatively charged cathode and are reduced to elemental iron. Alternatively, low-temperature electrolytic ironmaking involves adding iron oxide particles to a specially formulated low-temperature (110°C) NaOH alkaline electrolyte, followed by electrolysis, during which positively charged iron ions precipitate at the cathode^{443,444}.

In terms of collaborative industrial innovation, the Carbon2Chem project led by German steel giant Thyssenkrupp serves as a reference for analyzing how joint production between the steel and petrochemical industries can achieve significant carbon reduction results. Additionally, the Australian Green Steel initiative will be examined to understand how producing green steel for global trade not only supports the country's economic growth but also contributes to carbon reduction efforts in the global steel industry.

(1) Carbon2Chem Project: Germany, the European Union's largest steel producer and the world's seventh-largest, plays a crucial role in the automotive and machinery supply chains. The chemical industry is also indispensable for everyday consumer products, with chemical products being ubiquitous in daily life.

⁴⁴² Naseri Seftejani, M.; Schenk, J. (2018). Fundamentals of hydrogen plasma smelting reduction (hpsr) of iron oxides, a new generation of steelmaking processes. In Proceedings of the 7th Asia Steel International Conference 2018, Odisha, India, 6–9 February 2018.

⁴⁴³ Worldsteel (2021). Fact sheet: Electrolysis in ironmaking. World Steel Association AISBL. <https://www.worldsteel.org/publications/position-papers/climate-change-policy-paper.html>

⁴⁴⁴ *Ibid.*, 447.

As a result, Thyssenkrupp in Germany launched the Carbon2Chem project from the perspective of joint production between the steel and petrochemical industries. The project aims to reuse the waste gases generated during the steelmaking process, known as metallurgical gases, which contain nitrogen, hydrogen, and carbon dioxide. These gases are processed into synthesis gases, which serve as precursors for methanol, ammonia, or polymers, as well as basic components for fuels, fertilizers, and plastics⁴⁴⁵.

The Carbon2Chem project is the first to utilize gases produced during the steelmaking process as raw materials for chemical production. While this technology has been under development for some time, scaling it up to become an industrial solution is estimated to require around 15 more years of research and the right market incentives. This technology not only reduces overall carbon emissions but also has the potential to achieve nearly carbon-free steel production. According to Thyssenkrupp's estimates, about 50 steel plants worldwide meet the conditions to implement the Carbon2Chem project, and the company is already exploring collaboration possibilities with these plants.

Although the hydrogen present in metallurgical gases is sufficient to synthesize ammonia, additional hydrogen is needed to produce methanol. To meet this need, the Carbon2Chem project also plans to use water electrolysis to generate hydrogen for chemical production. Considering the large power demands of industrial facilities like steel and chemical plants, the future goal is to switch to green electricity from renewable sources to meet carbon reduction targets.

On the other hand, large industrial facilities can also act as energy buffers. When there is excess power from wind or solar energy, the chemical production process can be activated to fully utilize the surplus green electricity. In practice, the gas streams from steel production can be divided into two parts: one used for steel manufacturing and the other for chemical production. By implementing load management strategies, this approach not only maximizes the use of green electricity but also helps stabilize the power grid⁴⁴⁶. From the perspective of its broader application, this technology can be transferred beyond the steel industry

⁴⁴⁵ Thyssenkrupp (2021). Carbon2Chem: When emissions become valuable substances. thyssenkrupp AG. <https://www.thyssenkrupp.com/en/stories/carbon2chem-when-emissions-become-valuable-substances>

⁴⁴⁶ Thyssenkrupp (2021). The Carbon2Chem® project. thyssenkrupp AG. <https://www.thyssenkrupp.com/en/newsroom/content-page-162.html>

to other carbon-intensive sectors, enhancing overall carbon reduction efforts. However, it is still uncertain whether Taiwan has the necessary conditions to generate surplus green electricity.

(2) Green Steel Initiative⁴⁴⁷: Australia produces 38% of the world's iron ore and 18% of world's metallurgical coal, making it a key exporter of the two primary raw materials needed for steel production. However, Australia itself only accounts for 0.3% of global steel production. According to 2020 statistics, global crude steel production reached 1,878 million tons, with Australia contributing 5.5 million tons, ranking 29th globally.

At present, Australia benefits from low raw material export costs, and the cost of shipping key raw materials to the Asian market is even lower. For instance, the total cost of exporting Australian metallurgical coal increases by less than 10%, resulting in higher profits compared to selling steel products. Furthermore, if Australia were to retain these raw materials for domestic steel production, high local wages and other factors would significantly drive up the cost of smelting.

Although Australia has abundant renewable energy resources that can be used to produce green hydrogen, the cost of transporting hydrogen is much higher than shipping metallurgical coal. In fact, the cost of transporting hydrogen to Asian markets nearly doubles compared to using hydrogen domestically. As a result, while Australia can produce green hydrogen using renewable energy, the high cost of exporting hydrogen presents a challenge for advancing carbon reduction efforts. This has led Australia to consider the best use of hydrogen produced domestically.

To address these challenges and meet smelting needs, Australia is exploring the use of green hydrogen in steelmaking to produce "Green Steel" for export, establishing "Green Steel Export Pathways". This approach not only costs significantly less than directly transporting hydrogen abroad but also helps partner countries reduce carbon emissions in their steel industries. The Green Steel Export Pathways utilizes three distinct routes to export green steel and hydrogen, aimed at supporting the steelmaking needs of its trade partners. The three routes are as follows:

- Pathway 1: Primarily focuses on exporting semi-finished steel products. Iron ore is heated in a shaft furnace without reaching the melting point,

⁴⁴⁷ Wood, T., Dundas, G., and Ha, J. (2020). Start with steel. Grattan Institute.

where reductant gases ($H_2 + CO$) are injected to produce direct-reduced iron (DRI). The DRI is then refined and cast into semi-finished steel products for export.

- Pathway 2: Focuses on exporting direct-reduced iron (DRI), which is further refined into steel by the importing countries.
- Pathway 3: Primarily focuses on exporting hydrogen. Hydrogen produced in Australia is shipped to steel-importing countries, where it can be used for steelmaking.

The economic benefits of these three pathways depend on factors such as local wages and the cost of producing hydrogen in the countries that require steel and related resources. For example, in Pathway 1, importing steel from Australia offers both economic and carbon reduction advantages for countries like Japan or South Korea, where wages are relatively high. Taiwan is also likely to face similar challenges in the future, with rising wages and labor shortages. Therefore, both of the first two pathways are viable options for Taiwan. As for importing hydrogen, it will remain an important option for power generation.

4.2.4 Policy Recommendations

The development of various innovative technologies has created new opportunities for reducing carbon emissions in the steel industry. Building on the previous discussion and evaluation of carbon reduction measures, the following summarizes the key areas Taiwan's steel industry can actively invest in by 2050, along with the potential challenges it may encounter:

In terms of fuel use, increasing the share of natural gas or replacing it with carbon-neutral natural gas or hydrogen is a primary measure for steelmakers to achieve net-zero emissions. Using green hydrogen as a substitute would further enhance the effectiveness of carbon reduction efforts. Although hydrogen combustion turbine technology will not mature until after 2030, steelmakers are already exploring and testing hydrogen injection into existing blast furnaces. This ongoing research will provide critical data for future full hydrogen combustion operations and potential blast furnace rebuilds. Given the high cost of rebuilding blast furnaces, early-stage research and on-site testing should begin to minimize the impact of the low-carbon transition.

With respect to innovative production processes, since blast furnace ironmaking involves both heat generation and reduction reactions, hydrogen can be considered a

reducing agent. Leading steel-producing countries are already investing in technologies such as hydrogen-based blast furnace steelmaking and direct-reduced iron. Taiwan's steel industry is closely monitoring these developments and conducting small-scale testing. Additionally, the industry should consider importing reduced iron or semi-finished steel products and remain attentive to the development of syngas utilization and CCUS technologies to enable timely adoption.

Lastly, increasing the recycling and reuse of scrap steel is another promising carbon reduction measure. Although electric arc furnace steelmaking requires careful disposal of pollutants such as electric furnace slag and collection dust (containing dioxins and heavy metals like zinc and lead), promoting steel regeneration through material recycling not only reduces carbon emissions from the mining stage but also lowers the consumption of natural resources.

In response to climate change, achieving net-zero emissions in the steel industry is imperative. By innovating process technologies, the industry can mitigate the impacts of carbon reduction while enhancing production efficiency. Zero-carbon steel products can drive the circular economy and shape the future of energy transition.

4.3 Cement Industry

Summary

Cement production is a high-carbon, energy-intensive industry. Cement, the primary material for concrete, is used mainly in the construction of residential buildings, schools, hospitals, and other infrastructure. The production of cement and concrete contributes approximately 7% of global carbon emissions. As the global population grows and urban development accelerates, the demand for concrete in infrastructure construction continues to rise. It is estimated that global cement production will increase by 12% to 23% by 2050. Reducing carbon emissions in cement production is challenging due to the chemical reactions and high-temperature calcination processes that continuously release carbon dioxide, making the industry's high energy consumption incompatible with environmental sustainability. However, achieving net-zero emissions by 2050 has become a global consensus, and local cement producers have joined global cement associations, collectively committing to the goal of carbon neutrality for cement and concrete by 2050. The following policy recommendations are for the cement industry meeting carbon-emission targets:

1. Encouraging cement manufacturers to upgrade outdated equipment with advanced energy-saving technologies through plant renovations, or construct new plants with modern process technologies to improve energy efficiency.
2. Engaging in public communication and amend fuel restriction regulations to allow for the partial replacement of coal with biomass energy and waste incineration, which can reduce the use of coal and natural resource consumption, while simultaneously improving air quality.
3. Introducing and developing alternative raw materials and new types of cement.
4. Encouraging the cement industry to actively invest in carbon capture, storage, and utilization technologies, and provide relevant infrastructure to assist plants in obtaining low-carbon power sources, such as natural gas, hydrogen energy, and renewable energy.

4.3.1 Introduction

The cement industry's primary production process can be divided into four stages: mining of raw materials, raw material grinding, clinker calcination, and cement grinding. The main source of carbon emissions in cement production occurs during the clinker calcination stage, which includes both combustion-related emissions and process emissions.⁴⁴⁸ According to 2019 greenhouse gas emission data, the cement industry emitted approximately 9.4 million metric tons of carbon dioxide. In terms of combustion-related emissions, coal is primarily used as fuel in kilns and rotary furnaces to provide heat, generating 3.356 million metric tons of carbon dioxide (accounting for 36% of total emissions). In the clinker calcination process, raw cement materials are heated at high temperatures, producing calcium oxide and carbon dioxide, with process emissions amounting to 5.508 million metric tons of carbon dioxide (accounting for 59% of total emissions). More than 90% of these emissions occur during clinker production, as shown in Figure 4.3.1⁴⁴⁹.

Through the analysis of the cement industry's production processes and carbon emission sources, it is clear that the cement industry is one of the major contributors to greenhouse gas emissions. To achieve the 2050 net-zero emission goal, the industry should focus on transitioning in several areas, including alternative fuels, alternative raw materials and circular materials, energy-saving technologies for equipment, and innovative technologies⁴⁵⁰.

⁴⁴⁸ Industrial Development Bureau, Ministry of Economic Affairs (2017). Compilation of low-carbon green process technology selection evaluations.

⁴⁴⁹ Bureau of Energy, Ministry of Economic Affairs (2018). 2019 greenhouse gas inventory report of the Republic of China.

⁴⁵⁰ National Development Council (2022). *Taiwan's 2050 Net-Zero Emissions Pathway and Strategy Overview*.

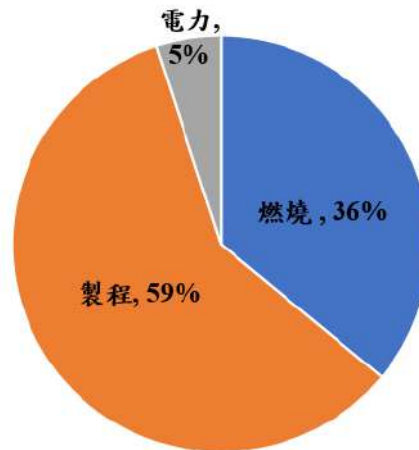


Figure 4.3.1 Proportion of Emission Sources in the Cement Industry

According to a research report by the International Energy Agency (IEA), the cement industry accounts for approximately 7% of global carbon dioxide emissions.⁴⁵¹ Each stage of cement production, from mining, transportation, calcination, to the use of fuel, generates carbon dioxide. Around 60% of these emissions stem from the decomposition of raw materials used in cement production, while the remaining 40% comes from the high-temperature energy required for chemical reactions.⁴⁵² Cement is one of the essential materials for construction and infrastructure development. It is anticipated that the demand for cement will significantly increase each year, driven by ongoing construction needs and large-scale infrastructure projects in developing countries.⁴⁵³

Cement producers worldwide acknowledge that the industry's substantial carbon emissions are a critical factor contributing to the worsening of climate change. To meet the goal of net-zero emissions by 2050, the cement industry can focus on several areas for carbon reduction assessment. Firstly, from a manufacturing perspective, improving energy efficiency is key. This can be achieved by optimizing the clinker production process, developing low-carbon fuels, or introducing green hydrogen to generate the high temperatures required for production. On the environmental front, it is essential to actively develop carbon capture and utilization technologies, research cutting-edge negative carbon technologies, and explore bio-carbon sequestration techniques.

⁴⁵¹ IEA (2018). *Technology Roadmap-Low-Carbon Transition in the Cement Industry*. <https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry>

⁴⁵² Yi-Hsiung Chou & Li-Fang Chou (2019). *Understanding Cement and Sustainable Cement Manufacturing*.

⁴⁵³ *Ibid.*, note 457.

Additionally, through the concept of a circular economy, waste materials can be incorporated into the cement kiln process.

On the economic and regulatory front, as countries begin to impose carbon tariffs, governments should assess the market impacts of carbon reduction on cement trade. It is crucial to introduce domestic regulatory revisions and provide guidance for future international trade negotiations concerning carbon reduction policies.

4.3.2 Global Carbon Reduction Trends in the Cement Industry

As one of the most widely used construction materials globally, cement demand has increased 2.4 times over the past 20 years alongside economic growth. Currently, the cement industry produces over 4 billion tons of cement annually. However, the chemical reactions and thermal combustion processes required for cement production consume significant amount of energy, making it one of the top three global industrial sources of carbon dioxide emissions⁴⁵⁴. China is the largest cement producer, accounting for 55% of global production and emitting 1.2 billion tons of carbon dioxide per year, followed by India with an 8% share⁴⁵⁵.

According to the International Energy Agency's (IEA) 2021 report, *Net Zero by 2050 - A Roadmap for the Global Energy Sector*, while cement demand will continue to rise due to economic development, global economic growth is expected to slow by 2050. As a result, the overall global demand for cement is expected to remain similar to current levels⁴⁵⁶. However, since the cement industry still represents a significant portion of global carbon emissions, the industry is under immense pressure to reduce emissions to meet the Paris Agreement's goal of limiting global warming to 2°C, or even the more ambitious target of 1.5°C set by the Intergovernmental Panel on Climate Change (IPCC) in 2018⁴⁵⁷.

In June 2021, the European Council passed the European Climate Law, establishing carbon reduction targets for the next decade. According to the Carbon Border Adjustment Mechanism (CBAM), cement is classified as a carbon-intensive product. Cement imported into the EU market will be subject to the purchase of carbon certificates, requiring the declaration of the carbon emissions associated with the

⁴⁵⁴ CDP (2018). Cement companies must more than double efforts to meet Paris climate goals.

⁴⁵⁵ US Geological Survey, Cement statistics and information.

⁴⁵⁶ *Ibid.*, note 441.

⁴⁵⁷ IPCC (2018). Global warming of 1.5°C.

imported product⁴⁵⁸. The European Parliament approved CBAM in June 2022, with implementation expected to begin in 2027⁴⁵⁹.

Many international organizations and businesses have proposed strategies to achieve the 2050 net-zero emissions target. The World Business Council for Sustainable Development (WBCSD) introduced a low-carbon transition pathway focused on improving thermal and electrical energy efficiency, fuel substitution, clinker substitution, and innovative technologies.⁴⁶⁰ The Global Cement and Concrete Association (GCCA) outlined six strategies: reducing fossil fuel use, increasing renewable energy use, developing carbon capture and utilization technologies, reducing clinker content in concrete, recycling concrete, and accounting for the carbon absorbed by recycled concrete⁴⁶¹.

The UK's Mineral Products Association (MPA) went even further, proposing to surpass net-zero carbon and achieve negative emissions through decarbonizing electricity, advanced manufacturing processes, low-carbon cement and concrete, biofuels and hydrogen, and carbon capture and storage (CCS) technologies⁴⁶². Similarly, the European Cement Association (CEMBUREAU) set out its plan, which includes reducing production emissions, replacing clinker, incorporating hydrogen and electrification, achieving carbon-neutral transportation, improving thermal efficiency, deploying CCS technologies, and promoting the recarbonation of concrete⁴⁶³.

Currently, the cement industry's carbon reduction strategies are not only focused on improving energy efficiency, replacing fossil fuels, increasing the share of alternative fuels, substituting clinker, and advancing CCS technologies and low-carbon cement production processes, but also on expanding carbon reduction efforts across the entire product lifecycle. This includes considerations for production, use, demolition, and recycling. The industry is even looking to achieve net-zero emissions through innovations like concrete recarbonation and building energy efficiency technologies.

⁴⁵⁸ European Commission (2021). *European Climate Law*.

⁴⁵⁹ Climate Leadership Council (2022). European parliament passes CBAM. <https://clcouncil.org/bl-og/european-parliament-passes-cbam/>

⁴⁶⁰ IEA(2018). Cement technology roadmap plots path to cutting CO₂ emissions 24%.

⁴⁶¹ GCCA (2019). Concrete future Roadmap to netzero.

⁴⁶² MPA (2019). *MPA Cement Sustainable Development Report 2019*.

⁴⁶³ CEMBUREAU (2020). Recarbonation - How concrete locks up and stores carbon dioxide – permanently.

4.3.3 Carbon Reduction Options and Innovative Case Studies in the Cement Industry

In the cement production process, producing 1 ton of clinker requires 3,140 MJ of thermal energy and 92 kWh of electricity (using Taiwan Cement Corporation as an example), both of which are directly related to carbon dioxide emissions.⁴⁶⁴ According to the International Energy Agency's (IEA) cement technology roadmap, which aims to achieve a 50% reduction in global carbon dioxide emissions by 2050⁴⁶⁵, the following strategies are recommended for the cement industry to reduce carbon emissions:

(1) improving thermal and energy efficiency, (2) using alternative fuels and waste, (3) utilizing alternative raw materials and developing new types of cement, and (4) implementing large-scale carbon capture, utilization, and storage (CCUS).

1. Analysis of Carbon Reduction Options

(1) Improving Thermal and Electrical Energy Efficiency

For newly built cement plants, adoption of the latest industrial process technologies is recommended to optimize overall energy consumption and to improve equipment maintenance. For older cement plants, energy-saving retrofits can be carried out after comprehensive feasibility evaluations, such as waste heat power generation systems, variable frequency control devices, and intelligent power management systems. Researching fluidized bed technology to achieve higher thermal energy efficiency, developing new grinding equipment, and using grinding aids to reduce the energy consumption of mills, as well as improving rotary kiln energy efficiency, are all feasible pathways to significantly lower carbon dioxide emissions in the cement production process.

(2) Using Alternative Fuels and Waste

For newly built cement plants, adoption of the latest industrial process technologies is recommended to optimize overall energy consumption and to improve equipment maintenance. For older cement plants, energy-saving retrofits can be carried out after comprehensive feasibility evaluations, such as waste heat power generation systems, variable frequency control devices, and intelligent power management systems. Researching fluidized bed technology to achieve

⁴⁶⁴ Yi-Hung Liu & Tzu-Chin Pan (2021). Analysis of energy use per unit of product in Taiwan's cement industry. *Combustion Quarterly*, 114, 61-74.

⁴⁶⁵ *Ibid.*, note 441.

higher thermal energy efficiency, developing new grinding equipment, and using grinding aids to reduce the energy consumption of mills, as well as improving rotary kiln energy efficiency, are all feasible pathways to significantly lower carbon dioxide emissions in the cement production process.

(3) **Alternative Raw Materials and New Types of Cement**

Conventional cement is mainly composed of calcium oxide, silicon dioxide, aluminum oxide, and iron oxide, which are derived from raw materials such as marble, clay, silica, and iron ore. As a result, any waste material containing calcium, silicon, aluminum, or iron can be used as an alternative raw material for cement. This opens the door to implementing circular economy principles, by actively seeking alternative materials to reduce the consumption of natural resources during cement production. For instance, calcium-rich waste materials, such as blast furnace slag, desulfurization slag, reduction slag, and stone-cutting sludge, can be used. Silicon-containing waste, such as foundry sand, water treatment sludge, and semiconductor grinding sludge, as well as aluminum-containing waste from chemical plant exhaust filters and power plant bottom ash, can also be utilized. Additionally, iron-containing waste like rust scrap and iron slag may serve as substitutes.

Clinker is the main component of cement, and when mixed with gypsum and ground, it reacts with water to harden gradually. However, some mineral compositions resemble clinker, such as blast furnace slag from the steel industry, coal ash from thermal power plants, and natural pozzolans. New binder materials with lower carbon intensity can be developed by adding various minerals (e.g., slag and fly ash) to reduce clinker content. For example, limestone calcined clay cement (LC3) contains only 50% clinker, significantly reducing the need for clinker production. These materials can partially replace clinker in cement⁴⁶⁶, thus reducing the associated processes, fuel, electricity, and carbon dioxide emissions.

Precasting methods can be employed to complete components in the factory, increasing cement use efficiency. Additionally, the recarbonation of pre-cast concrete can naturally absorb approximately 20% of the total carbon dioxide emitted during the process. However, chloride ions accelerate the corrosion of steel

⁴⁶⁶ Fennell, P.S, Davis, S.J., & Mohammed, A. (2021). Decarbonizing cement production. *Joule*, 5, 1305-1311.

reinforcement within concrete, leading to expansion or spalling, which increases exposure and jeopardizes the durability and safety of structures. As a result, the chloride ion content standards for cement under the CNS 61 Portland Cement Specification were revised in 2022, raising the limit from 200 ppm to 240 ppm, still stricter than Japan's (350 ppm) and Europe's (600–1,000 ppm) standards.⁴⁶⁷ Furthermore, according to CNS 3090 standards for ready-mixed concrete, the water-soluble chloride ion content in fresh concrete must not exceed 0.15 kg/m³.⁴⁶⁸ However, it is expected that more industrial waste will be used to produce alternative cement and new types of concrete through circular reuse, and the chloride ion standard may need further relaxation in the future.

(4) Large-Scale Carbon Capture, Utilization, and Storage (CCUS)

Carbon capture, utilization, and storage (CCUS) is considered an emerging technology that can help reduce the amount of greenhouse gases released into the atmosphere. For the cement industry, suitable carbon capture technologies include post-combustion capture, a process that captures carbon dioxide at the end of the cement production process without significantly altering clinker production. This method is particularly suitable for retrofitting or building new cement kilns. Relevant technologies include chemical absorption, membrane technology, calcium looping (carbonate looping), and mineral adsorption.

After capture, carbon dioxide can be reutilized through innovative technologies to convert it into valuable chemical materials. Examples include direct use of carbon dioxide in the food and beverage industry or converting carbon dioxide into chemicals and biofuels⁴⁶⁹.

2. Innovative Case Studies

(1) Cemex in Mexico developed the world's first carbon-neutral ready-mixed concrete, which can reduce the carbon footprint by up to 70%, with the remaining 30% offset through carbon credits⁴⁷⁰. Geopolymer, an inorganic polymer material, can dissolve silicon and aluminum ions from minerals or waste at room

⁴⁶⁷ Bureau of Standards, Metrology and Inspection, Ministry of Economic Affairs (2022). Introduction to National Standard CNS 61 "Portland Cement".

⁴⁶⁸ Construction and Planning Agency, Ministry of the Interior (2016). Guidelines for chloride ion content testing in concrete of buildings under construction.

⁴⁶⁹ Hai-Jen Lin (2019). International industry and policy trends in carbon capture, storage, and utilization. *Science & Technology Policy Perspectives*, National Applied Research Laboratories Science & Technology Policy Research and Information Center.

⁴⁷⁰ CEMEX (2021). Integrated report, Mexico.

temperature using an alkaline solution. After polymerization, dehydration, and hardening, it forms a three-dimensional Si-O-Al structure primarily bonded by covalent bonds⁴⁷¹. The polymerization process does not emit carbon dioxide, thus offering carbon reduction benefits.

(2) Carboncure Technologies from Canada developed an innovative carbon dioxide sequestration technology. Captured carbon dioxide is injected into concrete, where it reacts with calcium ions in the cement to form nano-sized calcium carbonate, which is embedded in the concrete. This process strengthens the concrete while also sequestering carbon dioxide. This technology is already applicable in pre-mixed concrete, precast concrete, and masonry products⁴⁷².

(3) Mitsubishi in Japan invested in the development of CO₂-SUICOM⁴⁷³, a type of concrete that absorbs carbon dioxide. By using additives and carbon dioxide curing methods, it can be applied in industrial processes such as those in steel plants, power plants, and cement plants (e.g., coal ash and blast furnace slag) to absorb carbon dioxide.

(4) A Carbon Built research team at the University of California, Los Angeles (UCLA), developed a new cement formula that introduces silicates, significantly reducing the need for Portland cement and increasing the use of waste materials like fly ash. During the curing process, carbon dioxide is directly injected into the concrete mix from flue gas streams (e.g., from power plants or cement plants), where it undergoes chemical transformation and permanently stores greenhouse gases. Research shows that embedding carbon dioxide into concrete through this curing technology can reduce its carbon footprint by over 50%, while producing concrete as strong as traditionally manufactured materials⁴⁷⁴. The Carbon Built team won the NRG COSIA Carbon XPRIZE competition in April 2021.

(5) Solidia's concrete production technology can reduce carbon emissions from

⁴⁷¹ Da-Wei Cheng (2020). What is the difference between geopolymer and alkali-activated materials? *Civil and Hydraulic Engineering*, 47, 10-12.

⁴⁷² CarbonCure Technologies (2021, December 2). Carbon removal with CarbonCure concrete: A permanent storage solution. <https://www.carboncure.com/carbon-removal/carbon-removal-with-carboncure-concrete-a-permanent-solution/>

⁴⁷³ Higuchi, T., Morioka, M., Yoshioka, I., & Yokozeki, K. (2014). Development of a new ecological concrete with CO₂ emissions below zero. *Construction and Building Materials*, 67, 338-343. <https://doi.org/10.1016/j.conbuildmat.2014.01.029>

⁴⁷⁴ Prentice, D., Mehdipour, I., Falzone, G., Raab, S., Simonetti, D. & Sant, G. (2022, February 2). Field demonstration of the Reversa™ mineral carbonation process using coal and natural gas flue gas streams. *REWAS 2022: Developing tomorrow's technical cycles*.

cement production by 30-40%, and an additional 240 kg of carbon dioxide is captured during the concrete curing process, equivalent to 24% of the cement mass. As a result, Solidia's system can reduce the carbon footprint of cement and concrete by up to 70%.⁴⁷⁵ The process involves: (A) using less limestone and lower kiln combustion temperatures during cement production to effectively reduce carbon emissions; (B) during Solidia's concrete curing process, cement, polymer, sand, and water are mixed and react with carbon dioxide to form a durable matrix. Each ton of cement can capture 300kg of carbon dioxide, permanently transforming it into calcium carbonate.

(6) The EU Horizon 2020 program supports the Low Emissions Intensity Lime and Cement (LEILAC) project. Heidelberg Cement and Australian technology supplier Calix developed a breakthrough calciner that can directly separate and capture carbon dioxide released during the conversion of limestone into clinker⁴⁷⁶. This calciner requires no chemicals and does not require any retrofitting of existing cement plants. The equipment replaces the preheater tower in cement plants or the lime kiln in lime plants. The new calciner uses a direct separation reactor concept for indirect heating, where the calcination heat does not directly contact the limestone but is introduced through a high-strength steel thermal surface at temperatures of 1,050°C or higher. Since the captured carbon dioxide does not mix with other combustion gases, its concentration can reach up to 95%. In the future, the calciner's heating system can use any form of fuel or heat source, such as biofuels, electricity, or hydrogen.

4.3.4 Policy Recommendations

The primary sources of carbon dioxide emissions in the cement industry come from fuel, production processes, and transportation. Most carbon reduction measures focus on improving energy efficiency and developing low-carbon alternative fuels. Since the chemical reactions involved in clinker production during cement manufacturing also generate carbon dioxide as a byproduct, developing new types of cement with alternative clinker and carbon capture technologies are crucial strategies

⁴⁷⁵ Meyer, V., Sahu, S., & Dunster, A. (2019, June 24-26). Properties of Solidia Cement and Concrete, ILCCC, London, UK.

⁴⁷⁶ Hills, T.P., Sceats, M., Rennie, D., & Fennell, P. (2017). LEILAC: Low cost CO₂ capture for the cement and lime industries. *Energy Procedia*, 114, 6166-6170.

for reducing emissions.

In terms of improving energy efficiency, many countries, including Taiwan, are reducing carbon emissions by building new plants, adopting new production technologies, or retrofitting energy-saving equipment (see Appendix 4B). For fuel substitution, international cement producers often use alternatives such as natural gas, waste-derived fuels, or direct solar heating, and some are even exploring the use of green hydrogen. However, given that most of Taiwan's cement plants are located in the eastern region, adopting these alternatives will require overcoming specific challenges. For example, when using natural gas as a fuel, the shortage of natural gas infrastructure in the east must be addressed. Additionally, the use of waste-derived fuels raises concerns about air pollution and the transportation of waste to eastern Taiwan.

With the large-scale deployment of renewable energy systems in the future, some fuel substitution solutions could involve converting equipment to electrical systems. At the same time, it is important to engage in social communication and amend relevant regulations to allow for the replacement of coal with biomass energy or waste incineration, while simultaneously improving local air quality.

For clinker substitution, slag or alternative raw materials can be developed into new cement products to help reduce carbon emissions. Currently, Taiwan has strict standards on the chloride ion content in cement and concrete. Using slag as a substitute raw material may increase chloride and metal content, making it difficult to meet these standards. Furthermore, the process of treating slag with excessive impurities may result in additional carbon emissions, which requires further research.

Internationally, carbon capture and storage (CCS) technologies are considered key to significant carbon reductions, but Taiwan has made limited investments in the research and development of these technologies. Current carbon capture technologies can use adsorption and solidification methods to increase capture rates from 20% to over 90%. It is expected that by 2050, technologies such as direct separation and low-temperature processes will improve carbon capture efficiency (see section 3.3 of this report for details). While carbon capture technologies already have demonstration sites, carbon storage is limited by storage locations and costs, making it difficult for individual companies to pursue on their own. National investment and collaboration with the private sector will be necessary for any successful implementation.

4.4 Petrochemical Industry

Summary

The petrochemical industry is the largest emitter of total carbon emissions in the manufacturing sector in Taiwan, with chemical raw materials and chemical product manufacturing and oil and gas refining and processing the major emission sources. This is mainly due to the reliance on fossil fuel combustion for heat to carry out high-temperature, energy-intensive processes, and the use of crude oil as a raw material to produce light oil, bulk petrochemical materials, and plastic products downstream. In addition, most of the electricity used is still generated from fossil fuels. Therefore, the petrochemical industry will be a key industry for Taiwan to reduce emissions to achieve its goal of Net Zero by 2050. Relevant recommendations are as follows:

1. Accelerate investment and development of alternative fuels (e.g., bioenergy or green hydrogen) and alternative material technologies (bio-based plastics, material recycling technologies, etc.), as well as electrification of steam crackers, and acquire technologies related to electrification of steam crackers and green hydrogen in the petrochemical industry through international collaborations, with the goal of widespread adoption between 2030 and 2050.
2. Develop innovative process technologies to raise production yield and achieve carbon reduction (e.g., catalytic cracking of crude oils and catalyst conversion rate enhancement technologies by 2030, and light olefin production technologies between 2030 and 2050).
3. Continuously promote the transformation of the petrochemical industry and provide investment incentives for transformation equipment, such as offering tax credits, subsidies, grants, rewards, or assistance through green finance-related investment and financing tools.
4. Expedite the initiation of research and development on carbon-free hydrogen production technologies (including pyrolysis for decarbonization and carbon reuse) and continue to develop such technologies between 2030 and 2050 to achieve maturity and cost reduction, as detailed in Section 2.6 Carbon-free Hydrogen Production.

4.4.1 Preface

The petrochemical industry is the largest emitter of greenhouse gases in the manufacturing sector of Taiwan. In 2019, 7 out of our top 20 emitting enterprises (the power industry excluded) were in the petrochemical industry⁴⁷⁷. In the same year, the petrochemical industry emitted 40.2 Mt CO₂eq^{478,479}, accounting for approximately 26.9% of total emissions from the manufacturing sector, of which electricity use accounted for about 70%, fuel use for about 24%⁴⁸⁰, and industrial processes for the remaining less than 10% (Figure 4.4.1). An examination of the main sources of emissions from fuel combustion revealed that fuels for boilers are the primary contributor⁴⁸¹.

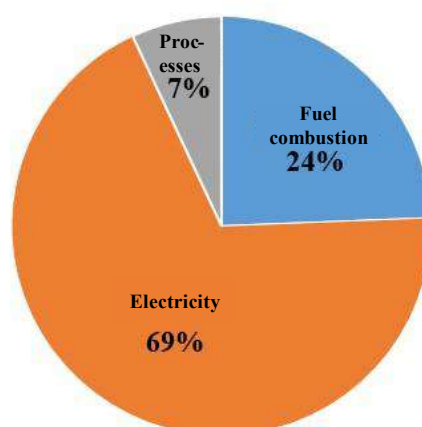


Figure 4.4.1 Proportion of Emission Sources in the Petrochemical Industry⁴⁸²

A further examination of the proportion of GHG emissions in the petrochemical industry chain (Appendix 4C) based on international analytical data indicates that oil and gas extraction accounts for 9.61%, oil and gas refining and processing for 19.99%, chemical raw materials and chemical products manufacturing for 59.02%, and chemical

⁴⁷⁷ Environmental Protection Administration, Executive Yuan (2021). *National Greenhouse Gas Registration Platform: Greenhouse gas emission reporting and inventory registration data*. https://ghgregistry.epa.gov.tw/ghg_rwd/Main/Examine/Examine_2

⁴⁷⁸ *Ibid.*, note 錯誤! 尚未定義書籤。

⁴⁷⁹ Industrial Development Bureau, Ministry of Economic Affairs (2021). Strategies and pathways for net-zero emissions in the cement industry, presentation at the Seminar of Low-Carbon Industry Working Group (Cement Industry), Executive Yuan (May 2021) (Unpublished data).

⁴⁸⁰ Since the emissions scope does not include oil refining in the upstream currently, the carbon emissions from fuel combustion are underestimated.

⁴⁸¹ Foundation of Taiwan Industry Service (2020). Industrial green technology upgrading program (3/4). <https://www.moeaidb.gov.tw/ctrl?PRO=filepath.DownloadFile&f=executive&t=f&id=15530>

⁴⁸² *Ibid.*, note 錯誤! 尚未定義書籤。

products manufacturing for 11.38%⁴⁸³. The main sources of carbon emissions are the chemical raw materials and chemical products manufacturing as well as the oil and gas refining and processing industries. The main emission sources from the oil and gas refining and processing industry are power generation from Combined Heat and Power Plant (CHP), Fluid Catalytic Cracker (FCC), Steam Methane Reformer (SMR), Crude Distillation Unit (CDU), Vacuum Distillation Unit (VDU), and Heat pyrolysis furnaces⁴⁸⁴ (as shown in Table 4.4.1).

Table 4.4.1 Main Emission Sources in Oil and Gas Refining and Processing⁴⁸⁵

Main processes of emissions	Purpose
Combined Heat and Power Plant, CHP	Cogeneration
Fluid Catalytic Cracker, FCC	Further conversion of high molecular weight hydrocarbons into gasoline, etc.
Steam Methane Reformer, SMR	Hydrogen production
Crude Distillation Unit, CDU	Extraction of oil products with different boiling points
Vacuum Distillation Unit, VDU	Extraction of oil products with different boiling points
Heat pyrolysis furnaces	Fuel combustion generates high-temperature steam, and cracking produces ethylene, along with hydrogen and methane (but can be sent back to the cracking furnace for heating).

In the chemical raw materials and chemical products manufacturing industry, due to the complex production relationships involved in generating a wide variety of chemicals or raw materials from petrochemical feedstock, it is difficult to isolate the main sources of carbon emissions. Moreover, the sources of these emissions vary depending on the type of chemical produced. The European Union (EU) has examined carbon emissions across the entire life cycle of the industry through the major plastic raw materials, finding that the vast majority of emissions occur during the manufacturing stage (from oil refining to the chemicals production stage), followed by

⁴⁸³ World Resources Institute (2015). Study on the key technologies of greenhouse gas emissions data management and verification techniques of the petrochemical industry. <https://wri.org.cn/research/study-key-technologies-greenhouse-gas-emissions-data-management-and-verification>

⁴⁸⁴ Concawe (2018). Concawe review. https://www.concawe.eu/wp-content/uploads/Concawe-Review-27-1_webfile.pdf

⁴⁸⁵ *Ibid.*, note 484.

the conversion stage (from chemicals to plastic products), and lastly, the disposal or recycling stage⁴⁸⁶.

As for further converting plastics into final products, various moulding technologies are used, including injection mould processing, blow mould processing, stretch blow moulding, calendering (for rigid sheets), extrusion of plastic film, extrusion of plastic pipes, polymer foaming processing, and thermoforming with calendering (Table 4.4.2). According to the analysis of EU data, the emissions from these moulding technologies primarily stem from electricity consumption.

Table 4.4.2 Plastic Conversion and Moulding Techniques and Greenhouse Gas Emission Sources⁴⁸⁷

Conversion technology and key contributing processes	Greenhouse gas emissions (kg CO₂eq/kg product)
Injection mould processing (Europe)	0.962
Electricity, medium voltage (Europe)	0.620 (64%)
Heat, district or industrial, natural gas (Europe excluding Switzerland)	0.220 (23%)
Blow mould processing (Europe)	0.917
Electricity, medium voltage (Europe)	0.720 (78%)
Solid bleached board	0.120 (13%)
Stretch blow moulding (Europe)	1.140
Electricity, medium voltage (Europe)	1.060 (93%)
Calendering, rigid sheets (Europe)	0.322
Electricity, medium voltage (Europe)	0.210 (66%)
Steam, in chemical industry (Europe)	0.070 (21%)
Extrusion of plastic film (Europe)	0.416
Electricity, medium voltage (Europe)	0.280 (67%)
Heat, district or industrial, natural gas (Europe excluding Switzerland)	0.030 (8%)
Waste plastic, mixture (Europe)	0.030 (8%)
Extrusion of plastic pipes (Europe)	0.294
Electricity, medium voltage (Europe)	0.210
Heat, district or industrial, other than natural gas (Europe)	0.050

⁴⁸⁶ Dils, E. (2021). Greenhouse gas emissions and natural capital implications of plastics (including biobased plastics). ETC/WMGE Report 3/2021, European Topic Centre Waste and Materials in a Green Economy. <https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/greenhouse-gas-emissions-and-natural-capital-implications-of-plastics-including-biobased-plastics>

⁴⁸⁷ *Ibid.*, note 486.

Polymer foaming processing (RER)	0.513
Electricity, medium voltage (RER)	0.330 (64%)
Heat, district or industrial, other than natural gas (Europe)	0.180(36%)
Thermoforming with calendering (Europe)	0.642
Electricity, medium voltage (Europe)	0.420 (66%)

In a nutshell for the aforementioned analysis, the petrochemical industry faces several challenges in its transition to net-zero emissions:

1. Heavily Reliance of Petrochemical Processes on Fossil Fuels and Fossil Fuel-Based Electricity

At present, the upstream refining and chemical industries in the petrochemical industry largely depends on combustion for heat to carry out high-temperature, energy-intensive processes. For example, the steam crackers used in oil refining (for producing ethylene, propylene, and BTX aromatics, which comprise most chemicals) and other large-scale equipment operate at temperatures close to 1,000°C. Hence, they consume a significant amount of fossil fuels and generate substantial carbon emissions. With suitable and sufficient supply of carbon-free fuels available, or if the existing energy-intensive thermochemical pathways and processes could be replaced or improved, it would be greatly beneficial for a smooth transition to net-zero emissions. However, fuel conversion adjustments require corresponding production process equipment to be replaced as well. Since the upstream equipment in the petrochemical industry is mostly large-scale, expensive with a long lifecycle, early retirement would result in huge penalty costs and lower the incentives for manufacturers to engage in equipment transition in the short term.

As the petrochemical industry, particularly upstream oil refining, traditionally relies heavily on the electricity supplied by Taiwan Power Company and from CHP on the plants, and the mid-to-downstream processes often require electricity for various molding technologies to manufacture plastic products, yet the power is largely generated from fossil fuels at present, it is essential to increase the proportion of carbon-free electricity used throughout the industry so as to achieve an effective reduction of carbon emissions from the industry.

2. Dependence on Crude Oil

The petrochemical industry relies on crude oil as a raw material. The crude oil is then processed downstream to produce naphtha, which is used to produce bulk

petrochemical raw materials, and finally, plastic products. Although the carbon source is retained in the products, the manufacturing processes often demand high-temperature and high-pressure reaction conditions. Furthermore, when the products are incinerated after use, a large amount of carbon emissions are released into the air. Therefore, low-carbon or carbon-free raw materials are needed to replace traditional petrochemical raw materials in order to reduce carbon emissions.

3. Difficulty in Decarbonization since the Petrochemical Industry Is a Major Export Industry for Taiwan

A very high proportion (63%) of our country's oil supply (domestic production) in 2021 was for transportation-related oil products (gasoline, diesel, fuel oil, and aviation fuel)⁴⁸⁸, which was the main source of revenue for the upstream refining industry (Figure 4.4.2). Nevertheless, with the trend toward net-zero emissions by 2050, light vehicles will be largely electrified (Figure 4.4.3), which may drastically reduce the demand for oil products. Although this is beneficial for achieving the overall net-zero emissions target, it may also affect the revenue and job opportunities of the upstream refining industry.

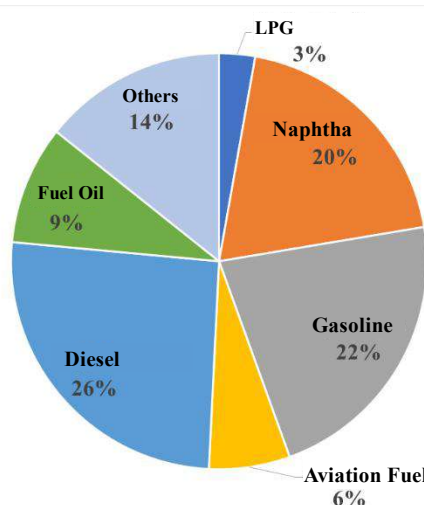


Figure 4.4.2 Production of Petroleum Products in Taiwan in 2021 by Percentage (Domestic Production)⁴⁸⁹

⁴⁸⁸ Bureau of Energy, Ministry of Economic Affairs (2021). *Energy statistics handbook (Individual energy Sources)*. 3-08 Petroleum product supply report download. [https://www.esist.org.tw/upload/3-08.%E7%9F%B3%E6%B2%B9%E7%94%A2%E5%93%81%E4%BE%9B%E7%B5%A6\(110\).xlsx](https://www.esist.org.tw/upload/3-08.%E7%9F%B3%E6%B2%B9%E7%94%A2%E5%93%81%E4%BE%9B%E7%B5%A6(110).xlsx)

⁴⁸⁹ *Ibid.*, note 488.

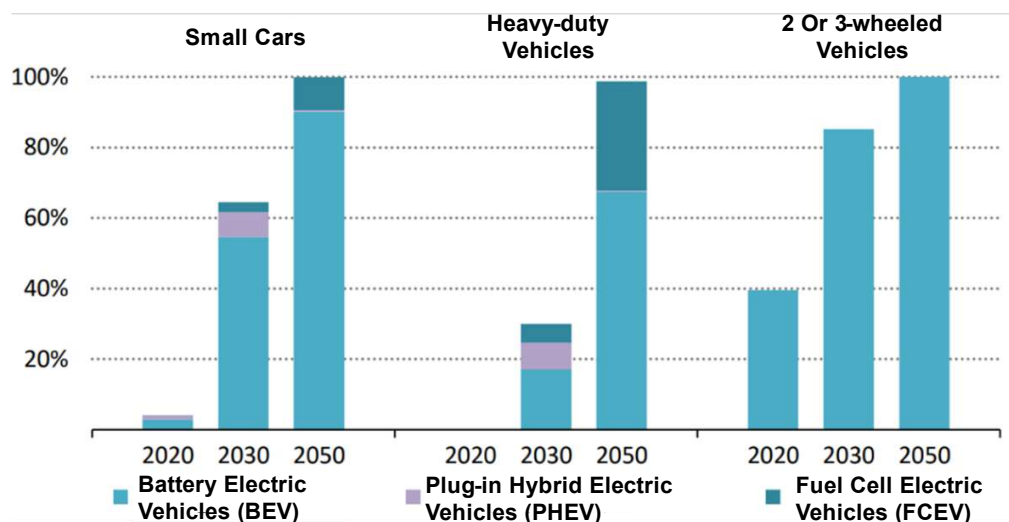
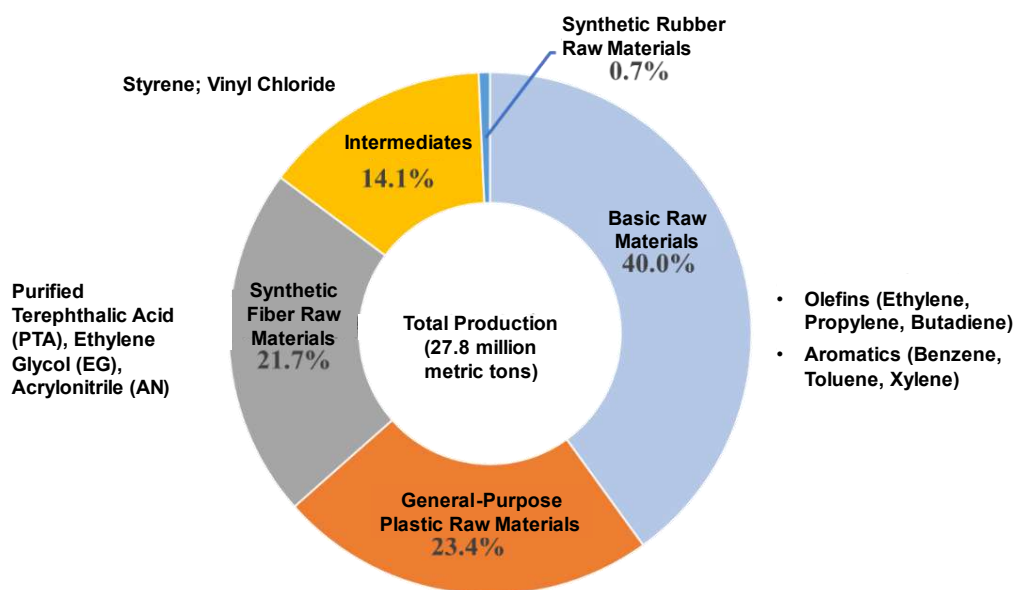


Figure 4.4.3 Estimated Shares of Different Types of Vehicles by Sales under the Net Zero by 2050 Scenario⁴⁹⁰

A major product of oil supply in the petrochemical industry is naphtha (20%), primarily produced to provide raw materials for midstream production (types and shares shown in Figure 4.4.4). An examination of the production and sales of petrochemical raw materials shows that in 2020, the total domestic production of major petrochemical feedstock was 27.8 million tonnes (Mt), with 10.55 Mt for exports and 4.74 Mt from imports. Exports accounted for 38% of production, meaning that over 30% of petrochemical feedstock was for export purposes⁴⁹¹. This segment also represents the area with the highest GHG emissions in the entire industry chain (with the chemical raw materials and chemical products manufacturing industry accounting for 59.02%). Therefore, if the industry can reduce the production of export-oriented traditional petrochemical raw materials and transition towards low-carbon, high-value industries, aiming for self-sufficiency in essential petrochemical raw materials, it will significantly contribute to the achievement of net-zero emissions in Taiwan. Nonetheless, supporting measures are required in the process to mitigate the impact on employment in the industry. Moreover, the petrochemical industry is characterized by economies of scale, meaning cost-effectiveness is highly correlated with production volume. Reducing production may compromise its economic efficiency, posing a significant challenge. The recently advocated Crude Oil to Chemicals (COTC) offers a potential solution, which will be discussed later.

⁴⁹⁰ *Ibid.*, note 錯誤! 尚未定義書籤。

⁴⁹¹ Directorate-General of Budget, Accounting and Statistics, Executive Yuan. (2021). DGBAS national statistics bulletin (2021). April 2021, No. 064. <https://www1.stat.gov.tw/public/Data/1412165523KIDMI9KP.pdf>



PVC, PP, PE, PS, ABS Resins

Figure 4.4.4 Petrochemical Raw Materials by Domestic Production in 2020⁴⁹²

⁴⁹² *Ibid.*, note 491.

4.4.2 Global Trend of Decarbonization in the Petrochemical Industry

Based on the perspective in the report of an international think tank (Figure 4.4.5), before 2030, the world will primarily leverage existing technologies for carbon reduction, such as reducing the demand for primary chemicals (e.g., recycling and reusing plastics or efficient use of nitrogen fertilizers) and improving resource and energy efficiencies. It is estimated that after 2030, innovative technologies will be more extensively adopted for carbon reduction, including innovative manufacturing processes (e.g., electrification of production), using waste or bio-based raw materials (plant fats, sugars, lignin, starch, corn, or algae), and using hydrogen produced by means of electrolysis using green power as a raw material or feedstock. Furthermore, carbon capture, utilization, and storage (CCUS) technologies will be applied to reduce carbon emissions^{493,494}.

In addition, fossil-based carbon in plastic products is expected to be gradually replaced by renewable carbon (Figure 4.4.6). In 2018, the production of virgin plastic was 364 million Mt, while only 36 Mt thereof was recycled. A think-tank report estimates that the global plastic demand will reach 1,200 Mt by 2050, of which 750 Mt will come from recycling, with only 450 Mt from virgin plastic production. Moreover, a portion of it will be derived from renewable carbon (biomass/CO₂ recycling for production)⁴⁹⁵, thus significantly reducing the actual fossil-based carbon.

⁴⁹³ *Ibid.*, note 錯誤! 尚未定義書籤。

⁴⁹⁴ Deloitte Taiwan (2021). 2030 Carbon reduction outlook: Oil, gas and chemical industry. <https://www2.deloitte.com/content/dam/Deloitte/tw/Documents/energy-resources/rp2030-carbon-reduction-outlook.pdf>

⁴⁹⁵ nova-Institut GmbH (2020). The future of the chemical and plastics industry: Renewable carbon. <https://renewable-carbon.eu/news/the-future-of-the-chemical-and-plastics-industry-renewable-carbon/>

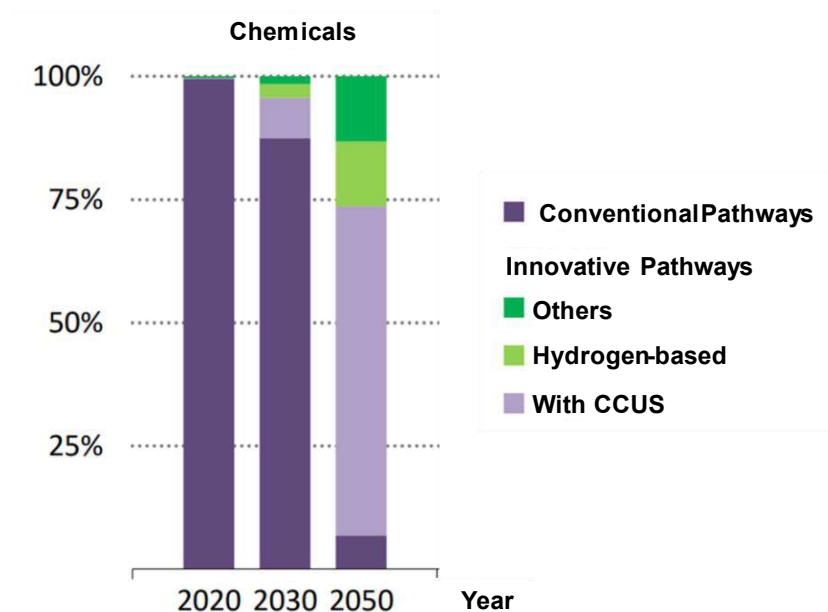


Figure 4.4.5 Medium- and Long-Term Carbon Reduction Options for Decarbonizing Chemicals⁴⁹⁶

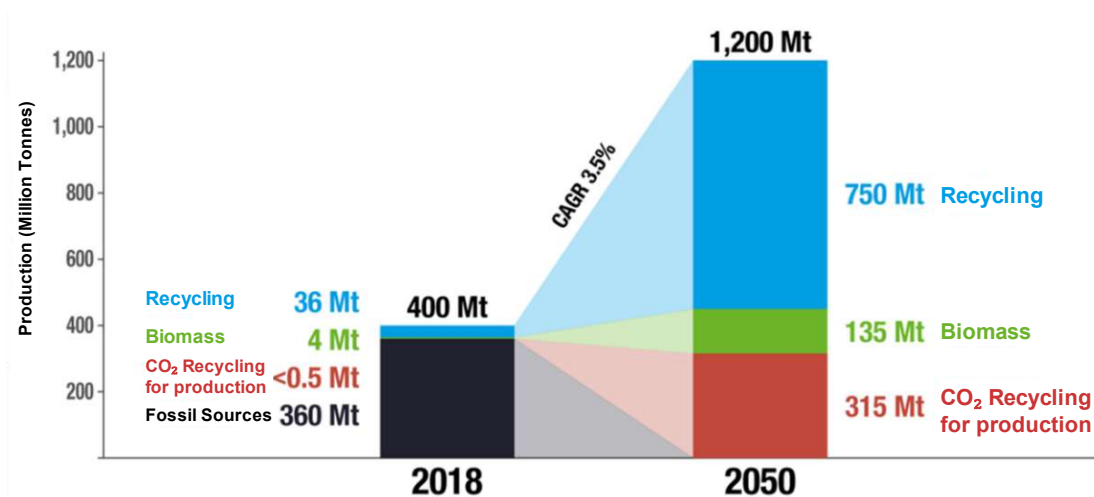


Figure 4.4.6 Estimated World Plastic Production and Carbon Feedstock by 2050⁴⁹⁷

⁴⁹⁶ *Ibid.*, note 錯誤! 尚未定義書籤。.

⁴⁹⁷ *Ibid.*, note 495.

4.4.3 Decarbonization Options and Innovative Case Studies in the Petrochemical Industry

1. Analysis of Decarbonization Options

A review of relevant international reports indicates that decarbonization options for the petrochemical industry broadly fall into seven categories (Figure 4.4.7): alternative fuels, alternative raw materials, innovative processes, efficiency improvement, material recycling, decarbonization technologies, and other innovations^{498,499,500}.



Figure 4.4.7 Decarbonization Options for the Petrochemical Industry

(1) Alternative Fuels⁵⁰¹

A. Hydrogen as fuel: Renewable energy sources can be used to power electrolysis to produce hydrogen fuel. This green hydrogen produced can also be further processed to create methanol or ammonia. For ammonia production, Australia has planned two mid-scale demonstration projects with electrolyzers of 60-160 MW (Germany, the U.K., and the U.S. also have similar plans). For methanol production, Iceland has the George Olah methanol pilot plant (4 kt/y), which utilizes the waste gas of carbon dioxide (CO₂) for methanol production.

⁴⁹⁸ *Ibid.*, note 錯誤! 尚未定義書籤。

⁴⁹⁹ Saygin, D., & Gielen, D. (2021). Zero-emission pathway for the global chemical and petrochemical sector. *Energies*, 14(13), 3772. <https://doi.org/10.3390/en14133772>

⁵⁰⁰ *Ibid.*, note 494.

⁵⁰¹ *Ibid.*, note 錯誤! 尚未定義書籤。

- B. Gaseous fuels produced through biomass gasification.
- C. Electrification of process heat: For example, BASF in Germany uses methane pyrolysis to produce hydrogen (carbon-free hydrogen production). They are currently testing a method of electrically heating methane to produce hydrogen and solid carbon in a pilot plant, aiming for completing an industrial-scale plant by 2030.

(2) **Alternative Raw Materials**⁵⁰²

- A. Use synthetic hydrocarbon feedstocks, primarily through renewable energy electrolysis with a catalyst to create hydrocarbon raw materials in place of primary petrochemical products (using thermochemical and electrochemical processes).
- B. Utilize bio-based raw materials to produce plastics, methanol, ethanol, and ammonia. For instance, ethanol dehydration to produce ethylene, with examples like the Braskem Plant in Brazil (0.2 Mt/y) and the India Glycols Plant in India (0.175 Mt/y).
- C. Employ bio-based processes (applying alternative bio-based processes to make alternative monomers). For example, using lignin for BTX (benzene, toluene, xylene) production. There is already a successful pilot production using BioBTX technology in the Netherlands. In 2018, the ALIGN project, with six partners from Belgium and Germany, also scaled up three lignin extraction processes.
- D. Other raw materials as alternatives: For instance, using methanol to produce olefins or BTX. In 2013, China had three BTX pilot plants put into operation, and multiple commercial-scale demonstration projects are under development.

(3) **Innovative Processes**

The examples include the electrification of steam crackers [see 2. Innovative Cases (1) below], oxidative coupling of methane (OCM) to make ethylene/propylene [see 2. Innovative Cases (2) below], light olefin production technology [direct conversion of syngas to light olefins [see 2. Innovative Cases (3) below] and electrochemical conversion processes [see 2. Innovative Cases (4) below]. In addition, the naphtha catalytic cracking process developed by Chiyoda Corporation in Japan can increase propylene yield by 2 times compared with the traditional thermal cracking process, and achieve 88% in overall energy efficiency, compared with a mere 73% of the traditional

⁵⁰² *Ibid.*, note 錯誤! 尚未定義書籤。

process, saving 15% of energy^{503,504}. Meanwhile, the first commercial plant (with a capacity of 40 kt/y) to catalytically crack naphtha is now operated by the KBR facility in Korea⁵⁰⁵.

(4) Efficiency Improvement⁵⁰⁶

This category includes energy efficiency technology retrofit, system-wide efficiency measures such as electromechanical systems and process heat cascading or integration, and the implementation of new energy-efficient process technologies. In the future, efforts can be directed towards disseminating energy efficiency best practices and utilizing innovative methods such as combining ICT and sensors to apply artificial intelligence (AI) and big data to boost efficiency.

(5) Material Recycling

The primary direction is to move towards a circular economy, by reducing the demand for primary chemicals (recycling plastics or efficient use of nitrogen fertilizers) and building chemical and heat recovery/recycling systems (within the industry, in collaboration with other industries, or by recovering high energy from incineration). For example, recycling plastics (mechanical/chemical recycling) can reduce carbon emissions associated with ethylene-related wastes and reduce the demand for virgin ethylene production. However, using chemical recycling to convert plastics back into monomers of similar quality to the original is currently only applicable to certain polymers (such as nylon). The use of pyrolysis of plastic waste as a feedstock for steam crackers is still in the application research stage. Furthermore, material use efficiency can be improved, and the demand for virgin materials can be reduced, by extending the life cycle of end products, making them more durable, and reducing material losses in the supply chain^{507,508}.

(6) Other Innovations

In response to the net-zero emissions trend, international petrochemical/chemical

⁵⁰³ Materialsnet (2020). Newly developed light oil catalytic cracking process doubles propylene yield and saves 15% energy. <https://www.materialsnet.com.tw/DocView.aspx?id=43934>

⁵⁰⁴ New Energy and Industrial Technology Development Organization (NEDO) (2019). Development of a high-value-added olefin production process. Chiyoda Corporation. <https://www.nedo.go.jp/content/100890969.pdf>

⁵⁰⁵ *Ibid.*, note 錯誤! 尚未定義書籤。

⁵⁰⁶ *Ibid.*, note 錯誤! 尚未定義書籤。

⁵⁰⁷ IEA (2018). The future of petrochemicals: Towards more sustainable plastics and fertilisers. <https://www.iea.org/reports/the-future-of-petrochemicals>.

⁵⁰⁸ *Ibid.*, note 錯誤! 尚未定義書籤。

giants like SHELL, BP, and BASF are successively investing in renewable energy, hydrogen energy, electric vehicles, and creating new business models, such as crude oil to chemicals (COTC) [see 2. Innovative Cases (5) below].

(7) Decarbonization Technologies

For the use of fuels, carbon emissions from the existing use of fuels can be avoided through carbon-free hydrogen combustion technologies (including pyrolysis for decarbonization and carbon reuse, see Section 2.6 Carbon-free Hydrogen Combustion Technologies). For emissions that cannot be reduced through the aforementioned alternative raw materials, innovative processes, efficiency improvement, or material recycling, the traditional CCUS technologies, direct air capture (DAC) technologies, and increasing natural carbon sinks can be considered for the purpose of decarbonization (see Chapter 3 Carbon Sinks, Carbon-zero and Carbon-Negative Technologies).

In addition, regarding electrification, alternative fuels, alternative raw materials, and other emerging innovative models and technologies, the corresponding Technology Readiness Levels (TRLs) and projected technology availability timeline are shown in Figure 4.4.8⁵⁰⁹. For the bio-based processes, the current application of alternative bio-based processing to produce alternative monomers is in the development and experiment stage. Alternative monomers are more similar to bio-based raw material molecules than ethylene molecules, capable of being produced at lower temperatures in steam cracking. Therefore, emissions from fuel combustion and the waste disposal stage can be reduced. Electrochemical processes are to apply electrochemical processes to make monomers. Carbon-zero power sources could be used to drive chemical reactions. Electrochemical processes enable higher and more precise compound production, which are also in the stage of laboratory development at present.

⁵⁰⁹ *Ibid.*, note 錯誤! 尚未定義書籤。.

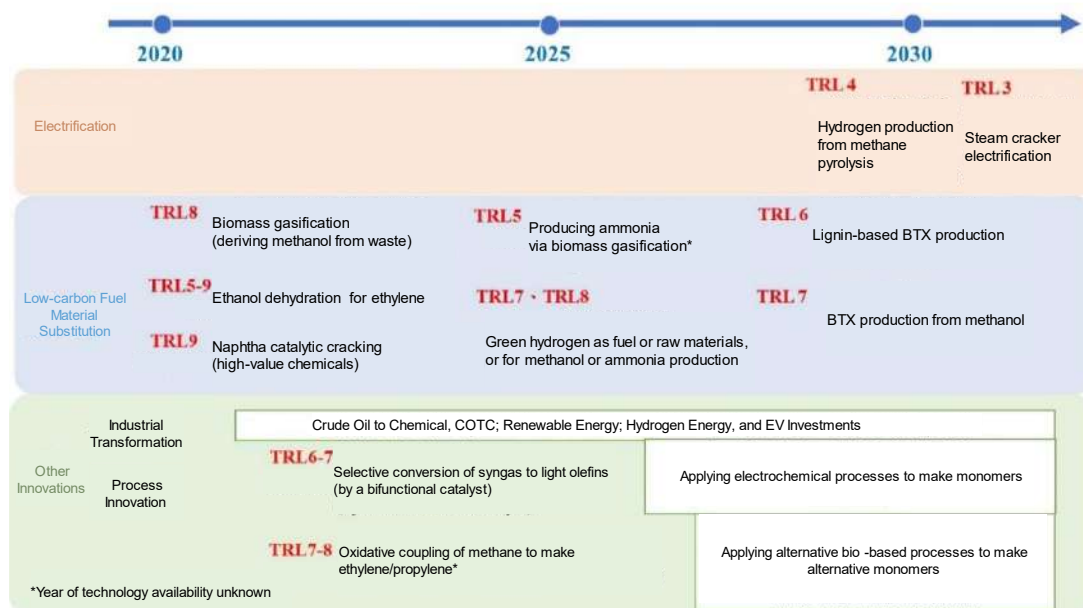


Figure 4.4.8 International Decarbonization Strategies and Innovative Technologies for the Petrochemical Industry to Consider^{510,511}

2. Innovative Cases

(1) Electrification of Steam Crackers

Steam crackers are one of the largest sources of CO₂ emissions in the entire petrochemical value chain. If steam crackers are switched to electrical operation on green power (from renewable energy sources) for cracking (Figure 4.4.9), the issue of carbon emissions caused by the high-temperature combustion of fossil fuels in traditional steam cracker furnaces can be improved. Also, thanks to its carbon reduction potential, since 2019, six international petrochemical companies—BASF, Borealis, BP, LyondellBasell, SABIC, and Total—jointly launched the “Cracker of the Future Consortium” to explore the use of renewable energy to operate naphtha or natural gas steam crackers to produce basic chemicals. At present, BASF, Saudi Basic Industries Corporation (SABIC), and Linde Group are working together to develop a trial production facility for steam crackers (electrically heated oxygen-free cracker furnaces)⁵¹². Through the use of electricity, they seek to achieve net-zero carbon emissions for the current production of basic chemicals. Also, they have applied for

⁵¹⁰ *Ibid.*, note 錯誤! 尚未定義書籤。

⁵¹¹ McKinsey (2018). Decarbonization of industrial sectors: The next frontier. <https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/how%20industry%20can%20move%20toward%20a%20low%20carbon%20future/decarbonization-of-industrial-sectors-the-next-frontier.pdf>

⁵¹² BASF (2021). BASF, SABIC and Linde join forces to realize the world’s first electrically heated steam cracker furnace. <https://www.basf.com/cn/zh/media/news-releases/global/2021/03/p-21-165.html>

EU's Innovation Fund and German funding, and, if approved, trial production can begin in 2023⁵¹³.

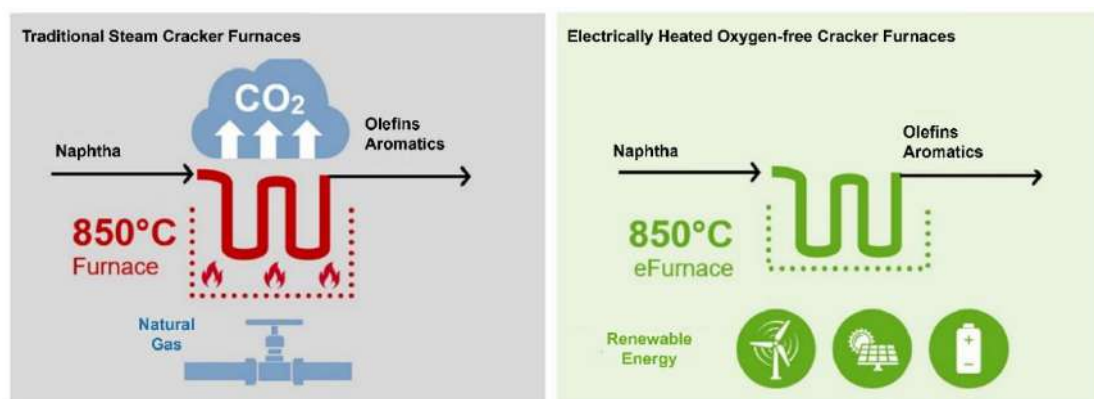


Figure 4.4.9 BASF Aims to Improve Carbon Emissions from Traditional Steam Crackers by Utilizing Electrically Heated Oxygen-Free Cracker Furnaces with Green Energy⁵¹⁴

(2) Production of Ethylene and Propylene via Oxidative Coupling of Methane

The innovative GeminiTM process developed by Siluria Technologies in the U.S. primarily utilizes oxidative coupling of methane (OCM) to produce ethylene and propylene from natural gas (Figure 4.4.10). Compared to the traditional naphtha cracking for ethylene production, this technology offers advantages in cost, GHG emissions, and energy efficiency⁵¹⁵. A significant breakthrough of this technology is the successful development of an innovative nanowire catalyst with activity exceeding traditional catalysts by over 100 times. The catalyst enables a highly efficient conversion of methane to ethylene at operating temperatures lower than those in conventional steam cracking (200-300°C and 5-10 atmospheres)⁵¹⁶. The OCM process also benefits from feedstock flexibility. Methane can be sourced from natural gas or biomass, and oxygen can be supplied as pure oxygen or oxygen-enriched air. The process does not require significant modifications to the existing equipment, either, allowing for the utilization of existing facilities. Hence, it presents a feasible option

⁵¹³ BASF (2021). BASF, SABIC and Linde join forces to realize the world's first electrically heated steam cracker furnace. <https://www.basf.com/tw/en/media/news-releases/global/2021/03/p-21-165.html>

⁵¹⁴ *Ibid.*, note 513.

⁵¹⁵ Wang, S.P. (2019). Impact of new olefin production technology on the petrochemical industry. High-value Petrochemical Industry Promotion Project. Taiwan Research Institute. https://www.pipo.org.tw/Hr/article_more?id=31

⁵¹⁶ *Ibid.*, note 515.

especially for countries with abundant natural gas resources^{517,518}. Nevertheless, as Taiwan relies almost entirely on import for natural gas, it is imperative to overcome the challenge of a stable supply of imported natural gas. Comprehensive consideration and evaluation of natural gas utilization are also necessary in the future.

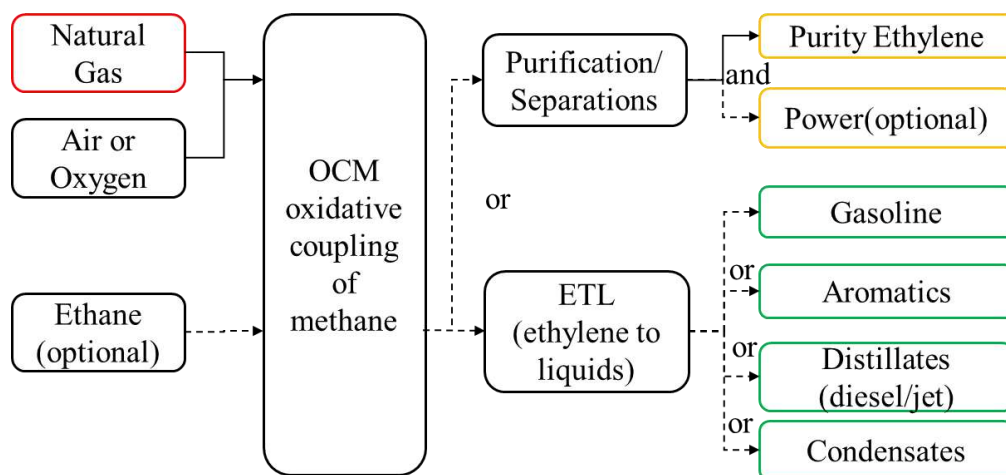


Figure 4.4.10 The High-Efficiency, Low-Emission Process of Siluria Technologies (U.S.A.) for Ethylene/Propylene Production Using Natural Gas as Feedstock⁵¹⁹

(3) Direct Conversion of Syngas to Light Olefins (OX-ZEO Process)

The direct conversion of syngas to light olefins is a technology that has emerged in recent years, mainly aiming to avoid dependence on traditional petroleum raw materials. Instead, coal, natural gas, or biomass resources are used as sources to produce light olefins through syngas (Figure 4.4.11). In particular, an innovative technology published in the *Science* in 2016 by the Dalian Institute of Chemical Physics, Chinese Academy of Sciences⁵²⁰ is the Oxide-Zeolite (OX-ZEO) process. Compared with other indirect syngas-to-light olefin technologies through intermediates (such as methanol and dimethyl ether), it mainly uses a developed OX-ZEO bifunctional nano-catalyst to allow syngas (containing CO and H₂) to form lower olefins through a direct conversion pathway (as shown by the red line in Figure 4.4.11), achieving a highly selective reaction⁵²¹. The process can improve the traditional water-gas shift reaction (WGSR)

⁵¹⁷ Siluria (2020). Overview. <https://siluria.com/Technology/Overview>

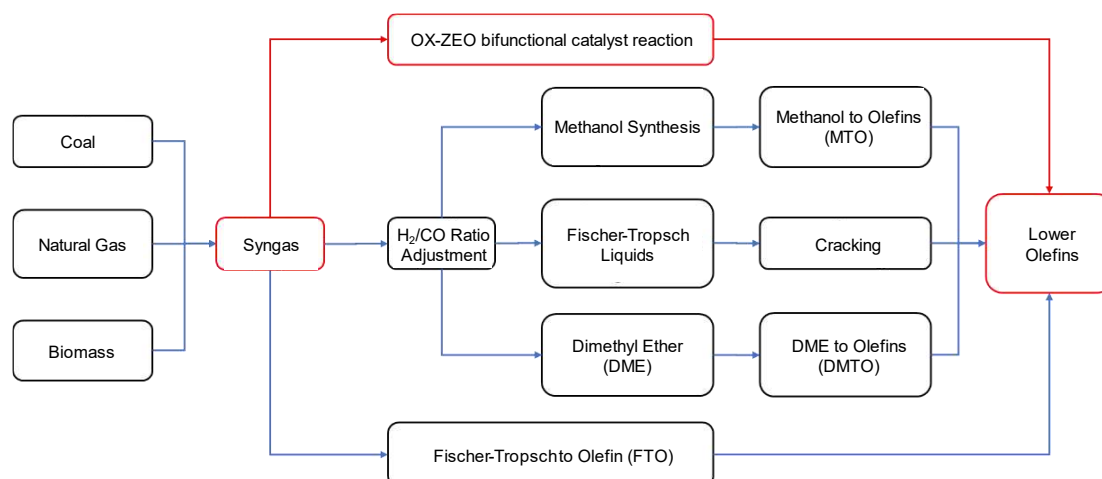
⁵¹⁸ *Ibid.*, note 515.

⁵¹⁹ *Ibid.*, note 517.

⁵²⁰ Jiao, F., Li, J., Pan, X., Xiao, J., Li, H., Ma, H., Wei, M., Pan, Y., Zhou, Z., Li, M., Miao, S., Li, J., Zhu, Y., Xiao, D., He, T., Yang, J., Qi, F., Fu, Q., & Bao, X (2016). Selective conversion of syngas to light olefins. *Science*. 2016 Mar 4; 351(6277):1065-8. doi: 10.1126/science.aaf1835.

⁵²¹ Chen, L. W., Lin, M. W., & Lin, C. C. (Eds.) (2019). *Current challenges and responses to the oil refining and petrochemical industry*. CTCI Foundation. <https://www.ctci.org.tw/8838/publication/10798/42506/>

process with high water and energy consumption for hydrogen production. In 2019, the



technology was also industrially tested at the Yulin Energy and Chemical Co., Ltd., which is affiliated with the Yanchang Petroleum Group in China⁵²².

Figure 4.4.11 The Direct Conversion Process of Syngas to Light Olefins through the OX-ZEO Process⁵²³

(4) Electrochemical Conversion Process for Recycling CO₂ to Produce Chemical Raw Materials⁵²⁴

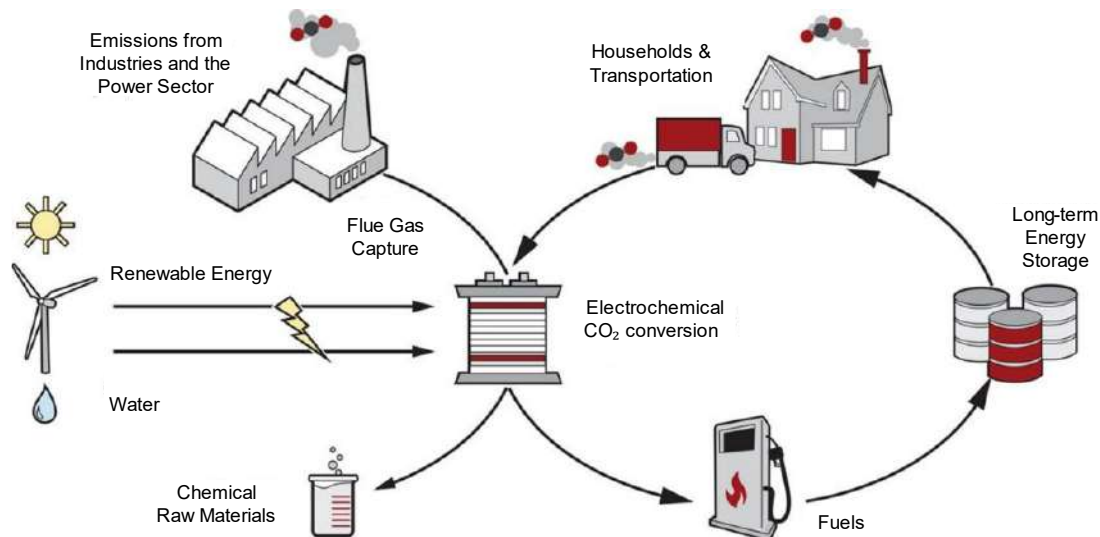
With CO₂ and water as materials, electrocatalytic conversion reactions can reduce CO₂ into single-carbon, double-carbon, or even triple-carbon chemical raw materials. CO₂ reduction can be achieved directly through electrocatalytic reactions, or by electrolyzing water to produce hydrogen, before synthesizing chemical raw materials (such as ethylene and ethanol) from hydrogen and CO₂ (from factory flue gas emissions), or converting into synthetic fuels for utilization. In particular, synthetic fuels can be used for long-term energy storage and provided to households, transportation, and other uses when needed (Figure 4.4.12). If the electricity used comes from renewable energy, there will be nearly zero carbon emissions. Besides, the CO₂ emitted from factories can be used and consumed as a raw material in production. Hence, such operating model is considered to be able to deliver the benefit of net negative carbon emissions. It is suggested that the model may be one of the potential strategies for manufacturers to enter the market in the future, and it can be used to

⁵²² Chinese Academy of Sciences (2019). Industrial pilot test of technology for direct production of light olefins from coal via syngas. https://www.cas.cn/zt/kjzt/2019ndldsx/zyzh/202001/t20200113_4731128.html

⁵²³ *Ibid.*, note 521.

⁵²⁴ Luna, P. D., Hahn, C., Higgins, D., Jaffer, S. A., Jaramillo, T. F., & Sargent, E. H. (2019). What would it take for renewably powered electrosynthesis to displace petrochemical processes? *Science* 364, 350. doi: 10.1126/science.aav3506

replace the energy-intensive thermochemical pathways (high-temperature and high-pressure processes) that the important chemical products mainly rely on currently. Nonetheless, for such technologies to be economically competitive compared with the petrochemical feedstock production pathways, the efficiency of the electrochemical



conversion still needs to reach a minimum of 60%, and the electricity bill of renewable energy needs to be below 4 cents per kilowatt-hour (kWh).

Figure 4.4.12 Circular Economy Model for Electrochemically Converting Waste Emissions into Chemical Raw Materials or Synthetic Fuels⁵²⁵

(5) Industrial Transformation

Under the trend of net-zero emissions, international petrochemical and chemical giants have adopted industrial transformation as their main strategy, including investments in renewable energy, electrification, circular economy, and the creation of new operating models such as crude oil to chemicals, which is summarized as follows:

A. Crude Oil to Chemicals (COTC)

COTC technologies utilize crude oil cracking to directly produce chemicals such as olefins and aromatics, bypassing the traditional production methods that employ ethane or naphtha as feedstock, which can be categorized into: direct crude oil cracking (commercialized in 2014), enhanced chemicals production (commercialized in 2019), and combined crude oil cracking (projected to be commercialized in 2025)⁵²⁶. Regarding the transformation with this operating

⁵²⁵ *Ibid.*, note 524.

⁵²⁶ Chen, Y. C. (2021). Global development of crude oil to chemicals (COTC) plant construction technology. Industrial Economics & Knowledge Center, Industrial Technology Research Institute. Published in Materialsnet. <https://www.materialsnet.com.tw/DocView.aspx?id=45755>

model, the consulting firm Deloitte believes that over 650 listed companies of bulk chemicals with a total market value up to \$700 billion will be disrupted by the large-scale commercialization of COTC plants. COTC is mainly characterized by the omission of the traditional crude oil refining process to produce naphtha, streamlining the process and increasing the chemical conversion rate to 40-80% with the potential for carbon reduction (Table 4.4.3). However, the integration of oil refining and petrochemicals may present challenges due to the significant difference in scale between the two. Therefore, COTC is typically applied in newly built refineries and petrochemical plants. In terms of industry progress, ExxonMobil, Aramco/Sabir JV, Aramco, and Chevron Lummus Global (CLG) collaborated in 2014 to establish a COTC plant in Singapore with an ethylene production capacity of 1 million tonnes per year^{527,528,529,530}.

Table 4.4.3 Comparison of Crude Oil to Chemicals (COTC) Operating Model with Traditional Production Approach⁵³¹

Traditional Production	COTC Technologies
Conversion rate of crude oil to chemicals: 15-25%	Conversion rate of crude oil to chemicals: 40-80%
Refinery-Petrochemical-Integration	Refinery-Petrochemical Integration, where the production focuses on chemicals , while various fuels and lubricating oils are byproducts (reduced production, in alignment with the trend of EV development)
Steam cracking	Direct crude oil cracking Combined crude oil cracking Streamlined process, improved efficiency, and reduced carbon emissions

B. Investments in Renewable Energy

With financial support from the EU, and in partnership with the UK-based

⁵²⁷ *Ibid.*, note 526.

⁵²⁸ *Ibid.*, note 526.

⁵²⁹ *Ibid.*, note 515.

⁵³⁰ *Ibid.*, note 494.

⁵³¹ Fan, C. C. (2020). The advent of crude oil to chemicals technology. Industrial Economics & Knowledge Center, Industrial Technology Research Institute. Published on the website of the Department of Industrial Technology, Ministry of Economic Affairs. https://www.moea.gov.tw/MS/doi/industrytech/IndustryTech.aspx?menu_id=13545&it_id=305

energy storage and clean fuel company/electrolyzer manufacturer ITM Power, Shell is constructing the world's largest (10 MW) hydrogen electrolysis plant, Refhyne, at the Rhineland Energy and Chemicals Park in Wesseling, Germany. Upon completion, the plant will be capable of producing approximately 1,300 tonnes (1.3 kt) of green hydrogen per year, establishing Shell as a supplier of green hydrogen for industrial applications. The electrolyzer will be powered by renewable energy from offshore wind farms. In the future, Shell aims to form an integrated industrial cluster with local public transport companies and other industries to pilot the supply of green hydrogen⁵³². Germany's BASF Group plans to invest up to 4 billion euros in a large-scale offshore wind farm, using renewable energy to replace fossil fuels like natural gas⁵³³. As part of its transition vision for Net Zero by 2050, BP has set targets to reduce oil and gas production by 40% by 2030, increase green energy investments tenfold to \$5 billion, and increase renewable energy generation to 50 GW⁵³⁴.

C. Electrification

BP has identified electrification as one of its key decarbonization strategies. The company is currently partnering with the Volkswagen Group to tap into the locational convenience of BP's retail sites (gas stations) to expand and accelerate the deployment of EV charging infrastructure, develop extensive ultra-fast networks, with an aim to grow their network of public EV charging points by 2030 to over 70,000 worldwide⁵³⁵.

D. Circular Economy

The German BASF Group has established an important demonstration of the circular economy at its Ludwigshafen plant in Germany. Through the integrated production to close the loops, the energy and resources needed by different processing plants in the area can be exchanged via pipelines. Approximately 90% of the waste can be reused (for example, CO₂ generated during ammonia

⁵³² REFHYNE (2022). Project overview. <https://refhyne.eu/>

⁵³³ BASF (2021). BASF presents roadmap to climate neutrality. <https://www.basf.com/global/en/who-we-are/sustainability/whats-new/sustainability-news/2021/basf-presents-roadmap-to-climate-neutrality.html>

⁵³⁴ BP (2021). *BP sustainability report*. <https://www.bp.com/en/global/corporate/sustainability/reporting-centre-and-archive/quick-read.html>

⁵³⁵ BP (2021). Volkswagen Group and BP to join forces to expand ultra-fast electric vehicle charging across Europe. <https://www.bp.com/en/global/corporate/news-and-insights/press-releases/vw-group-and-bp-join-forces-ultra-fast-ev-charging-europe.html>

production is transported via pipelines to processing plants for soda production). The remaining 10% that cannot be utilized directly is incinerated to generate heat for other processes. In the future, renewable energy or recycled waste will gradually replace fossil fuels as well⁵³⁶.

4.4.4 Policy Recommendations

The petrochemical industry will be a key industry in our efforts to strengthen emissions reduction to achieve the goal of Net Zero by 2050. The Policy Proposal puts forward recommendations as follows:

1. Accelerate the investment and development of alternative fuels (e.g., bioenergy or green hydrogen) and alternative material technologies (bio-based plastics, material recycling technologies, etc.), as well as electrification of steam crackers, and acquire technologies related to electrification of steam crackers and green hydrogen in the petrochemical industry through international collaborations, with the goal of widespread adoption between 2030 and 2050

(1) Replace Fuels with Bioenergy, Hydrogen Energy, and Electrification Technologies

At present, the upstream refining and chemical industries in the petrochemical industry largely depend on combustion for heat to carry out high-temperature, energy-intensive processes, consuming a significant amount of fossil fuels and generating substantial carbon emissions. Therefore, it is necessary to replace fossil fuels with suitable and sufficient carbon-free alternatives, such as bioenergy or green hydrogen, to reduce carbon emissions from fuel use. Also, international petrochemical giants are working together on R&D and investment in the electrification of steam crackers, along with investments in technologies using green hydrogen as fuel. Nevertheless, these technologies require high investment, and Taiwan has not yet initiated relevant R&D projects. To seize the opportunity and gain an early advantage in these technologies, investments may be made in developing steam cracker electrification and acquiring technologies related to steam cracker electrification and green hydrogen in the petrochemical industry through international collaboration.

(2) Develop Bio-Based Raw Materials and Bio-Based Processing Technologies to Replace Crude Oil

⁵³⁶ BASF (2021). Circular economy at BASF. <https://www.basf.com/global/en/who-we-are/sustainability/we-drive-sustainable-solutions/circular-economy.html>

The production processes in the petrochemical industry at present primarily rely on crude oil as a raw material. The crude oil is then processed downstream to produce naphtha and bulk petrochemical raw materials, and finally, plastic products. Although the carbon source is retained in the products, the manufacturing processes often demand high-temperature and high-pressure reaction conditions, and when the product is incinerated after consumption, a large amount of carbon emissions will still be released into the air. To solve the abovementioned issue, the use of bio-based raw materials and bio-based processing to replace petroleum and traditional chemical processes with high carbon emissions to produce bulk chemicals and aviation fuels is an international trend. Although this field has been researched and developed in the domestic academia for years, the industry is still in its infancy and requires ongoing investment to be effective. Successful cases overseas in the past include 1,3-PDO, 1,4-BDO, lactic acid, ethylene, PLA, 1-Butanol, isobutanol, succinic acid, etc. In recent years, terephthalic acid, ethylene glycol, diacids, diamines, and other plastic monomers have also been developed and made into bio-based plastics.

Sugar will be the primary bio-based raw material initially for the R&D of bio-based processing with sugar as a raw material to produce various chemicals. Subsequently, technologies with cellulose as a raw material will be developed to replace sugar. In the future, bio-based raw materials can be imported, while bio-based processing can be exported. In addition, with methane (the main component of natural gas and landfill gas) as a raw material, developing bio-based processing to convert methane into other chemical raw materials is also a direction for our effort.

Taiwan has a history of utilizing bio-based processing to produce food additives (e.g., MSG), animal feed (e.g., amino acids), and antibiotics. Thanks to the rapid development in metabolic engineering and synthetic biology in recent years, cell factories utilizing gene editing technology can transform microorganisms to produce various chemicals. Several of the technologies under development in Taiwan are already leading the world, but they have yet to be commercialized. The main reason is that Taiwan's chemical industry has insufficient R&D momentum in biotechnology, in part due to the fact that most domestic biotechnology talents tend to go to pharmaceutical R&D, making biotechnology R&D in the chemical engineering field relatively weak. If Taiwan aims to address the problem of high carbon emissions in the petrochemical industry, all sectors of industry, government, academia, and research community must work together to invest in the bio-based processing of specific

chemicals, utilizing metabolic engineering and synthetic biology technologies in place of traditional chemical processes and petrochemical raw materials. However, in terms of transformation on the ground, food additives, dyes, and fragrances high in unit price can be our short-term goals. Thus, we can cultivate industrial biotechnology capabilities, which can then be leveraged to achieve the goal of Net Zero by 2050.

2. Develop innovative process technologies to raise production yield and achieve carbon reduction (e.g., catalytic cracking of crude oils and catalyst conversion rate enhancement technologies by 2030, and light olefin production technologies between 2030 and 2050)

The petrochemical industry has many processes. In addition to fuel or raw material alternative technologies, it also relies on the development of various innovative process technologies to increase yield and achieve energy conservation and carbon reduction. For example, catalytic cracking of crude oil has reached a considerable level of technology readiness. By utilizing innovative catalyst technology to enhance catalyst conversion rates, compared to traditional thermal cracking processes, it can increase yield while saving energy. Although the technology for direct conversion of syngas to light olefins has not been fully ready, it can still improve the traditional water-gas shift reaction (WGSR) process with high water and energy consumption for hydrogen production through the assistance of new catalysts. Therefore, investing in the development of such innovative process technologies can contribute to carbon reduction to a certain extent.

3. Continuously promote the transformation of the petrochemical industry and provide investment incentives for transformation equipment, such as offering tax credits, subsidies, grants, rewards, or assistance through green finance-related investment and financing tools

Currently, over 30% of petrochemical products are exported, and this segment is also the largest contributor to GHG emissions in the entire industry chain. Thus, if the petrochemical industry can reduce the production of export-oriented traditional petrochemical raw materials and transition towards low-carbon, high-value industries, aiming for self-sufficiency in essential petrochemical materials, it will significantly contribute to the achievement of net-zero emissions in Taiwan. Moreover, the petrochemical industry is characterized by economies of scale, meaning cost-effectiveness is highly correlated with production volume. Reducing production may compromise its economic efficiency. Therefore, crude oil to chemicals (COTC)

technology can be considered as a potential solution for this transition. In addition, since the upstream equipment in the petrochemical industry is mostly large-scale and expensive with a long lifecycle, early retirement would result in huge penalty costs and lower the incentives for manufacturers to have equipment transition in the short term. Hence, regarding the investment in the capital-intensive equipment needed for the transition, the government could provide incentives such as tax credits, subsidies, grants, rewards, or assistance through green finance-related investment and financing tools to facilitate the replacement of outdated equipment.

4. Accelerate the investment and development of CCUS technologies and carbon-free hydrogen combustion technologies

Carbon capture and utilization quintessentially involves traditional chemical processes, while storage is related to petroleum exploration. Therefore, CCUS technology belongs to the broader category of petrochemical technology and is the most accessible carbon reduction technology for the petrochemical industry currently. CO₂ capture is the most mature technology in CCUS. In the petrochemical industry, CO₂ can be captured from flue gas. The utilization of CO₂ requires reduction reactions, generally with hydrogen as a reducing agent, so the source of green hydrogen needs to be considered. At present, CO₂ is mainly used to produce acetic acid, so development of more products is needed to utilize the captured CO₂. As for the unused CO₂, it is injected and stored in oil wells. There are limited storage sites available in Taiwan, so it is necessary to explore other solutions. For further details, please refer to the part pertaining to CCUS in Section 3.3.

Carbon-free hydrogen combustion technology may offer another solution. Yet, the extent of cost increases should be taken into consideration. If such technology is developed successfully, it can decompose hydrocarbons into hydrogen and carbon. The pure carbon can be further developed for various high-value applications to aid in cost recovery. For further details, please refer to the part of carbon-free hydrogen combustion technologies in Section 2.6.

4.5 Electronics Industry

Summary

In 2019, greenhouse gas (GHG) emissions from Taiwan's electronics industry accounted for 10.9% of Taiwan's total emissions. Of this, fluorinated gases (F-gases) accounted for about one-sixth of the total emissions, and carbon emissions from energy use were three times greater than emissions from direct emissions. If we look at the use of electricity, which accounts for the highest percentage of carbon emissions, the electronics industry's use of electricity reached 22.6% of Taiwan's total electricity consumption in 2020, and the number is expected to grow in the future. Taiwan's electronics industry faces significant challenges in making the transition to net zero emission, with finding alternatives to F-gases, insufficient supply of green electricity in Taiwan, and the fact that the international mechanism for calculating carbon emission is unfavorable for manufacturing countries. It is very unlikely that the electronics industry can change its reliance on F-gases for its manufacturing processes in the foreseeable future. Even if sufficient alternatives of F-gases can be used to reduce carbon equivalent emissions, it will take about seven years for a single product to complete the process from experimentation to mass production. On the other hand, in the next few years, the electronics industry's demand for electricity is expected to be greater than electricity generated from green energy sources. At the same time, the international mechanism for calculating carbon emissions is unfavorable for exporting countries. The energy saved by using new electronic products in the consuming countries should be taken into account. Our recommendations are as follows:

1. Join forces with the electronics industry in other countries to lobby for the implementation of life cycle carbon emissions assessment to highlight the contribution of the electronics industry as producers, so a more flexible carbon management mechanism can be established.
2. Invest in the development of a variety of zero-carbon electricity, including wind power, solar energy, geothermal energy, ocean energy, etc., and accelerate industrialization of zero-carbon electricity.
3. Actively develop or apply energy-saving and carbon-reducing technologies. For instance, using artificial intelligence (AI) to improve the monitoring of the clean room and optimize the manufacturing process with better energy efficiency.

4.5.1 Introduction

In 2019, GHG emissions from Taiwan's electronics industry accounted for 21.0% of the total emissions from the manufacturing industry (which in turn accounted for 10.9% of Taiwan's total emissions); companies with the highest carbon emissions included Taiwan Semiconductor Manufacturing Company Limited (TSMC, ranked 7th), Innolux Corporation (12th), AUO Corporation (13th), United Microelectronics Corporation (UMC, 16th) and Micron Technology, Inc. (17th). Taiwan's electronics industry is mainly composed of two sub-industries: semiconductor and optoelectronics. Total GHG emissions of the electronic industry in recent years⁵³⁷ are shown in Figure 4.5.1. Compared with 2013, direct GHG emissions (Scope 1) in 2019 have increased slightly and emissions from energy use (Scope 2) have dropped significantly. One can thus conclude that companies' efforts to reduce emissions have shown some positive results.

Figure 4.5.2 is an overview of semiconductor manufacturing processes⁵³⁸. Energy consumption of each stage is shown in dark green, light green, and orange; crystal growth furnaces, oxidation and diffusion furnaces, wiring, diffusion furnaces for doping, and heat treatment are categorized as high-energy-consuming processes. Wafer grinding and slicing are categorized as medium-energy processes. Resist coating, etching, resist stripping, die cutting, die bonding, wire bonding, and packaging are categorized as low-energy processes. Observing electricity consumption (Figure 4.5.3), we can see that semiconductor manufacturing equipment accounts for the highest proportion of electricity consumption with over 40%. Other electricity consumption of over 3% includes cooling systems (27.2%), clean rooms (7.4%), nitrogen (6.6%), office areas (3.0%) and ultrapure water (3.0%)⁵³⁹. Most output value of the optoelectronics industry comes from the production of thin film transistor liquid crystal display (TFT-LCD). The manufacturing process of TFT-LCD can be divided into three stages: front array (thin-film transistor), middle cell (assembly), and rear module (module). Energy consumption mainly concentrates in the manufacturing process (39.3%), air

⁵³⁷ Mandatory Greenhouse Gas Reporting System, the Environmental Protection Administration of the Executive Yuan.

⁵³⁸ Gopalakrishnan, B., Mardikar, Y., & Korakakis, D. (2010). Energy analysis in semiconductor manufacturing. *Energy Engineering*, 107(2), 6-40.

⁵³⁹ Hu, S. C., & Chuah, Y. K. (2003). Power consumption of semiconductor fabs in Taiwan. *Energy*, 28(8), 895-907.

conditioning (24.2%) and air pressure system (20.2%) (See Figure 4.5.4)⁵⁴⁰.

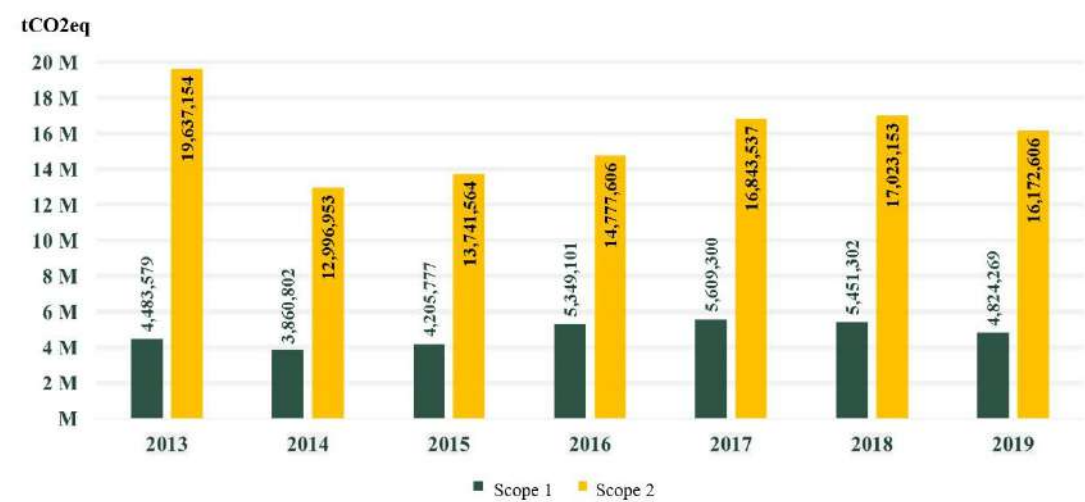


Figure 4.5.1 Historic GHG Emissions of Taiwan’s Electronics Industry

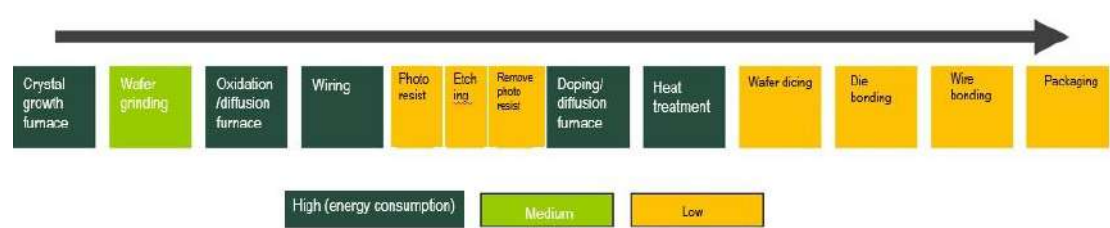


Figure 4.5.2 Overview of Semiconductor Manufacturing Process

⁵⁴⁰ Industrial Development Bureau, Ministry of Economic Affairs (2020). Low-carbon Manufacturing Technologies for the Electro-optical Systems Industry. <https://ghg.tgpf.org.tw/Resources/ResourcesLectureNums?id=0b731df449ee475597f805f95516acd0>

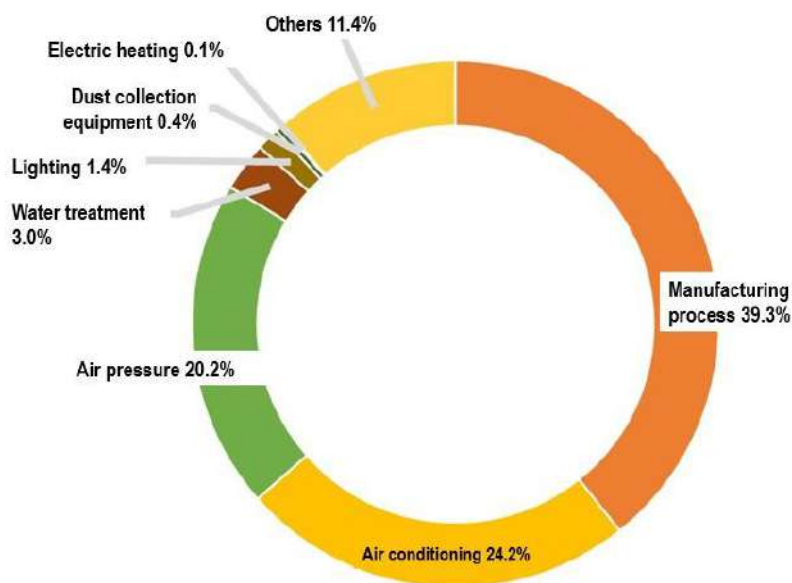


Figure 4.5.3 Electricity Consumption of the Semiconductor Industry

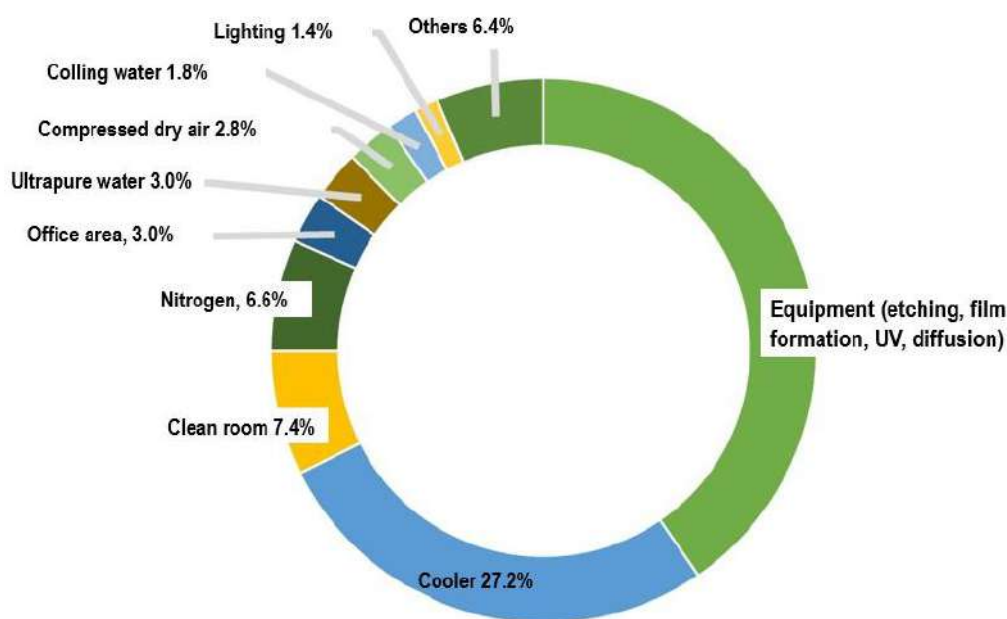


Figure 4.5.4 Electricity Consumption of the Optoelectronic Industry

In addition to energy consumption, GHGs emitted by the electronics industry also include fluorinated gases (F-gases); perfluorocarbons (such as carbon tetrafluoride, hexafluoroethylene and octafluoropropane), as well as sulfur hexafluoride, and nitrogen trifluoride used for cleaning of chemical vapor deposition (CVD) chamber and dry etching. In the past, we believed that hydrofluorocarbons (HFCs) would not damage the ozone layer and so they were used as new refrigerants (such as Difluoromethane, known as Refrigerant gas R32). However, these F-gases have a higher global warming

potential (GWP) than carbon dioxide⁵⁴¹ (Table 4.5.1). Figure 4.5.5 shows the historic emissions of F-gases from Taiwan's electronics industry. Among all the F-gases, sulfur hexafluoride (SF₆) is the most potent greenhouse gas and is used heavily, but its emission has slowed down while the emission of perfluorocarbons, used to replace SF₆, has seen a slight increase. Emissions of nitrogen trifluoride and hydrofluorocarbons remain steady, but the greenhouse effect caused by the overall emissions is considerable. For instance, the aforementioned emission of F-gases, if converted into carbon dioxide equivalent, would account for about one-sixth of the total emissions from the electronics industry⁵⁴².

Table 4.5.1 Comparison of Global Warming Potential (GWP) between F-Gases and CO₂

Type of gas	Atmospheric lifetime (years)	Centennial global warming potential (GWP) ⁵⁴³
CO ₂	-	1
Difluoromethane (CH ₂ F ₂)	5	550
Carbon tetrafluoride (CF ₄)	50,000	5,700
Octafluoropropane (C ₃ F ₈)	2,600	8,600
Octafluorocyclobutane (C ₄ F ₈)	3,200	10,000
Nitrogen trifluoride (NF ₃)	> 500	10,800
Hexafluoroethane (C ₂ F ₆)	10,000	11,900
Sulfur hexafluoride (SF ₆)	3,200	22,200

⁵⁴¹ Houghton, J. T., Ding, Y. D. J. G., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., ...⁵⁴¹ & Johnson, C. A. (2001). *Climate Change 2001: The Scientific Basis*. The Press Syndicate of the University of Cambridge.

⁵⁴² Environmental Protection Administration, the Executive Yuan (October 2020). 2020 Taiwan's National Greenhouse Gas Inventory Report. https://unfccc.saveoursky.org.tw/nir/tw_nir_2020.php

⁵⁴³ For example, the greenhouse warming potential of difluoromethane is 550, so the carbon dioxide equivalent emitted by 1 kg of difluoromethane is 550 kg.



Figure 4.5.5 Historic Emissions of F-Gases from Taiwan's Electronics Industry

4.5.2 Global Trends of Carbon Reduction in the Electronics Industry

With the leadership of the World Semiconductor Council (WSC), the semiconductor industry is the first industry to jointly set targets to cut down global GHGs emissions. WSC voluntarily agreed to reduce the emission of F-gases in 1999. Participating members (semiconductor industry associations of the United States, the European Union, Japan, South Korea, and Taiwan) used the emissions in 1999 as the baseline and set the target to reduce emissions of F-gases by at least 10% by the end of 2010. By 2010, emissions were reduced 32% below the baseline, surpassing the original target. WSC (with new members, including the semiconductor industry association in China) issued the second voluntary target to reduce the emission of F-gases in 2011. The baseline is the overall emissions in 2010 and the goal is to reduce the normalized emission rate (NER) by 30% in 2020 (in kilograms of carbon equivalents per area of silicon wafers processed). To check if the above-mentioned targets have been reached, annual reviews would be carried out to optimize the manufacturing process of new factories, along with regular updates and sharing of best practice guidance for emission reduction, and progress report in the annual WSC joint statements. The latest information indicates that NER has dropped by 22.9% in 2020⁵⁴⁴.

The Clean Development Mechanism (CDM) Executive Board of the United

⁵⁴⁴ World Semiconductor Council (2021). Joint statement of the 25th meeting of the World Semiconductor Council. <http://www.semiconductorcouncil.org/public-documents/joint-statements-from-prior-wsc-meetings/>

Nations Framework Convention on Climate Change (UNFCCC) has recognized a series of methodologies for carbon reduction, known as CDM Methodologies.⁵⁴⁵ The CDM allows a developed country with an emission-reduction commitment to implement emission-reduction projects in developing countries to earn emission-reduction credits, which can be counted towards meeting targets. Among all the CDM methodologies published, methodologies that can be used in the electronics industry include (1) control, treatment and replacement of fluorinated gases (F-gases), (2) process energy efficiency improvement, (3) building energy efficiency improvement, and (4) resource recycling. CDM urges governments to make reduction commitments, set benchmarks and standards to determine reduction, and promote reductions of greenhouse gases. Take Taiwan as an example, the Environmental Protection Administration (EPA) of the Executive Yuan used CDM as a reference to propose two projects to reduce greenhouse gas emissions: the Greenhouse Gases Offset Project (GHG Offset Project) and the Greenhouse Gases Early Action Project (Early Action). The Offset Project uses methodologies listed in the CDM or designated by the EPA of the Executive Yuan as the standards. Implementation of the methodologies to reduce carbon emissions will enable entities to earn reduction credits or allowances. The Early Action Project used the "announced emission intensity" as the standard. If the actual emission intensity of an emission source is better than the emission intensity announced by the EPA, reduction credits or allowances will be granted. The promotion of CDM encourages industries in various countries to be more active in introducing the latest reduction technologies and management methods so they can receive reduction credits or allowances. At the same time, governments can also utilize the data to establish a database of successful reduction cases for analysis and management of reduction policies.

⁵⁴⁵ UNFCCC (2022). CDM Methodologies. <https://cdm.unfccc.int/methodologies/index.html>

4.5.3 Carbon Reduction Options in the Electronics Industry and Innovative Case Studies

1. Analysis of Carbon Reduction Options

Taiwan's electronics industry faces the following challenges to make the transition to net-zero: (1) difficulty in finding alternatives to F-gases; (2) insufficient green electricity in Taiwan; (3) the carbon emission calculation method used in the international community is unfavorable to manufacturing-oriented countries. As can be seen from Figure 4.5.5, sulfur hexafluoride (SF₆) has the highest global warming potential and the use of which accounted for the largest proportion before 2013. Although the use of SF₆ has dropped significantly and may be replaced by materials with lower global warming potential in the future, it is extremely difficult to reduce current usage to reach the target of net-zero emissions by 2050. The target set by the government is to increase the proportion of power generated by renewable energy to 20% in 2025. However, the electronic component manufacturing industry alone (which covers semiconductors, passive components, printed circuit board (PCB), optoelectronic materials and components, and other electronic components) used 22.6% of Taiwan's total power⁵⁴⁶ and the proportion of energy use continues to grow over the years. In other words, it is getting more and more difficult for the electronics industry to reach the goal of net-zero emission goal by 2050. The carbon emissions of electronic products mainly come from the manufacturing stage, and international carbon emissions use this as the basis for the calculation. However, in reality, it is more reasonable for consumers to share some responsibility. The current methods to calculate carbon emissions are unfavorable for manufacturing-oriented countries.

As for options to reduce carbon emissions, apart from those mentioned in the CDM methodologies discussed in the previous section, i.e. (1) control, treatment and replacement of F-gases, (2) process energy efficiency improvement, (3) building energy efficiency improvement and (4) resource recycling, the most favorable option for the electronics industry is actually increasing the proportion of green electricity as the carbon emissions from energy use in the electronics industry are three times more than the direct emissions (See Figure 4.5.1). To use green electricity, one can generate electricity through independent power generation or by purchasing certificates and

⁵⁴⁶ Taiwan Power Company (2021). *Monthly electricity consumption data for Taiwan Power Company's customers by industry over the years*. <https://data.gov.tw/dataset/31966>

carbon credits. For instance, TSMC offset 100% of its carbon emissions from many of its overseas locations in 2018 by purchasing renewable energy, renewable energy certificates (RECs), and carbon credits. By the end of 2020, TSMC has achieved the goal for all its global offices to use only renewable energy. By 2021, TSMC has signed a power purchase agreement (PPA) to get 1.2 GW of renewable energy. The solar panels installed in 2020 and 2021 have helped to generate 416 kW and 227 kW of power, respectively.

Replacing fluorinated gases is extremely difficult because the replacement of materials involves a heavy workload to adjust parameters, trial and calibration and check potential damage to the equipment and machines. It requires companies to go through the entire process of research and development, and so it is easier said than done. UMC, for example, established a greenhouse gas reduction team back in 1999, and they carried out experiments to replace hexafluoroethane (C_2F_6) with octafluoropropane (C_3F_8) in large quantities in the manufacturing process (See Table 4.5.1 for a comparison of global warming potential). The outcomes of the experiments were officially applied in actual production in 2006, and UMC successfully reduced its carbon emissions and tens of millions in costs every year. Then, in 2009, on the advice of DuPont, UMC started to use octafluorocyclobutane. Although the global warming potential of octafluorocyclobutane is higher, the total use is lower. So, in 2020, compared with the numbers in 1999, UMC increased the production of wafers to 3.6 times, but the GHG emissions were reduced to 25% of the figure in 1999⁵⁴⁷. New alternative materials will continue to be developed in the future, and these technological advances will also become options to reduce direct GHG emissions.

To improve energy efficiency, TSMC, for example, continues to implement its production plan to ensure that "the production energy efficiency of the same manufacturing technology should be doubled after 5 years of mass production" in 2020. Through the implementation of energy-saving practices and the introduction of energy-saving components and smart energy-saving equipment, TSMC was able to increase the production energy efficiency of 16-nanometer (nm) and above process technologies by 1.8 times. The production energy efficiency of 10-nm and 7-nm process technologies increased by 1.4 times after the fourth year of mass production. Consequently, TSMC

⁵⁴⁷ Wei-Hsuan Huaug (2021). Carbon reduction model: Sustainability in energy-intensive and high-pollution industries. Overcoming adverse conditions to achieve good ESG. *Business Today* 1267, 66-70.

has already reached its 2030 goal⁵⁴⁸. The above-mentioned energy-saving practices include using smart energy-saving equipment (such as an AI-powered chilled water energy-saving system), a highly efficient air-conditioning system, improvement of the cooling mechanism of the compressed dry air (CDA) system and an efficient cooling tower fan. Energy-saving components include heat pumps that could recover waste heat and more⁵⁴⁹.

Ways of recycling resources include establishing zero-waste manufacturing centers, equipment to recycle and reuse resources, management of water resources, and production of recycled products.⁵⁵⁰ The zero waste manufacturing center of TSMC turns by-products that were originally considered to be waste produced during the manufacturing process into industrial-grade products or electronic products. These by-products include electronic-grade isopropanol and fluorite, which can be used by TSMC, and can also be provided as commodities to other industries. Equipment to recycle and reuse resources is used to turn by-products that were originally considered to be waste into industrial-grade products. Products produced by such equipment include industrial-grade ammonium sulfate, silicon slurry and copper, which can be reused by TSMC or sold as commodities. As for the management of water resources, ISO 46001 water efficiency management systems can be used to increase the amount of recycled water and reduce the need to produce ultrapure water, which is energy-intensive. AUO Corporation has obtained the UL 3600 circularity certification and continues to increase the proportion of recycled products in its revenue.

2. Innovative Cases

(1) Green Hydrogen Used in Extreme Ultraviolet Lithography (EUV)

Tainan has the world's largest ultrapure hydrogen low-carbon production facility, supplying the hydrogen used in EUV systems in TSMC's branch in Southern Taiwan Science Park⁵⁵¹. The systems generate 50,000 laser pulses per second to hit tiny tin droplets to form tin plasma. The EUV light produced is directed by a mirror onto the

⁵⁴⁸ Taiwan Semiconductor Manufacturing Company (2021). *TSMC 2020 corporate social responsibility report*. <https://esg.tsmc.com/csr/ch/resources/documents.html>

⁵⁴⁹ Industrial Development Bureau, Ministry of Economic Affairs (2019). Low-carbon manufacturing technologies for the electrooptical systems industry. <https://ghg.tgpf.org.tw/Resources/lecture?id=e2d61c527f544928a98b68fc87c45995>

⁵⁵⁰ AUO Corporation (2021). *2020 CSR report*. <https://csr.auo.com/tw/download/c1>

⁵⁵¹ Kwangyin Liu (April 15, 2021). The future of TSMC's advanced wafer processing is hidden in a hydrogen station in Tainan. *Commonwealth Magazine*. <https://money.udn.com/money/story/5612/5389183>

wafers to be exposed. Hydrogen must be injected to react with tin to form gaseous tin hydride (SnH_4) and prevent tin from condensing on the mirror and forming a tin mist. Air Liquide Far Eastern (ALFE) is a joint venture between France's Air Liquide SA and Far Eastern New Century Group. The hydrogen station of Air Liquide is expected to produce hydrogen by electrolysis of water from renewable electricity within 2 years. Compared with hydrogen produced from natural gas, a hydrogen station that produces hydrogen by electrolysis of water from renewable electricity can reduce carbon emissions by about 8,000 metric tons per year. With 5 hydrogen stations producing hydrogen by electrolysis of water from renewable electricity, the amount of carbon emissions reduced is equivalent to the amount of carbon absorbed by growing 1 million trees.

(2) Big Data Analysis to Improve the Energy Efficiency of EUV Systems

EUV lithography systems consume 10 times more energy than traditional DUV lithography systems. A special mirror is needed when we use an EUV lithography system. In the past, EUV lost 30% of its energy with each reflection. A lithography process requires at least 10 reflections on average. The light used for lithography is less than 2%. TSMC used big data to analyze the principle of reflection and power consumption of EUV systems and identified the main factors of EUV power consumption: reflection efficiency and pulse efficiency. TSMC first optimized the laser pulse of the EUV system in 2020 by changing the program. At the same time, the reflection structure was redesigned to increase the reflectivity by 3%. With further analysis of the operation data of the CO_2 laser amplifier used in EUV, TSMC found that changing the frequency of the laser pulse from a fixed-frequency clock to a variable-frequency clock can boost the laser energy efficiency by 10%. These changes helped TSMC to increase the overall energy efficiency of EUV lithography systems by 5%.

(3) Improving the Capacity to Treat Waste Liquid by Improving the Ammonium Sulfate Crystallization System

TSMC improved its ammonium sulfate crystallization systems by improving (a) automated rinsing mechanism, (b) digital monitoring dashboard, and (c) heating equipment. The automated rinsing mechanism can effectively and efficiently isolate solids and liquids and prevent blockage of process routes; the digital monitoring dashboard is used to monitor ion concentration of the crystallization system to stabilize evaporation capacity. The heating equipment is introduced to accelerate the heating cycle and reduce production loss after regular maintenance. These upgrades help to

increase the treatment capacity of ammonium sulfate wastewater by 400%. The monthly average treatment capacity was increased from 400 metric tons in the first half of 2020 to 2,000 metric tons in the second half of the year. Since 2018, TSMC has reduced the amount of ammonium sulfate wastewater to be treated by its contractors, which has accumulated to over 15,800 metric tons, and the production of industrial-grade ammonium sulfate crystals has reached 4,200 metric tons. The benefits of recycling and reuse, as well as the decreased need for waste removal, have exceeded NT\$35 million. The annual treatment capacity of ammonium sulfate wastewater is expected to reach 60,000 metric tons in 2022, and the annual production capacity of industrial-grade ammonium sulfate crystals can reach 15,000 metric tons, creating benefits worth over NT\$130 million. In addition, the electronics industry has made a lot of effort in recycling and reusing resources and waste treatment (Box 4.5.1).

Box 4.5.1 Other ESG efforts in the electronics industry⁵⁵²

- **N-Butyl Acetate (NBA) Waste Liquid Recycling and Reusing System**

When a photoresist coating machine is used continuously, photoresist residue will stay on the surface of the machine. In the past, a solvent used in photolithography for dilution of photoresist would be used for edge bead removal. AUO Corporation found that n-butyl acetate (NBA), originally used for edge bead removal in photolithography can be a great solvent to dilute photoresist. The NBA waste solution can replace EBR.

- **Recycling of Liquid Crystals**

The calibration of LCDs requires the use of liquid crystals, which results in a large amount of liquid crystals. In the past, the waste liquid crystals would be sent to a qualified treatment plant to be incinerated. AUO Corporation rigorously verifies the liquid crystals generated after calibration to check their purity and quality. After going through a rigorous product verification process carried out by contractors, the liquid crystal can be processed and reused for calibration. In 2020 alone, the recycle ratio of liquid crystals reached 13%, which is equivalent to 29.8 tons per year.

- **Recycling and Reuse of Packaging**

AUO Corporation collects the packaging removed from its LCD panels and sends the packaging to the contracted recycling plant to be processed to make garbage

⁵⁵² *Ibid.*, note 錯誤! 尚未定義書籤。.

bags. The original waste is reused to make new products, so limited resources can be reused and waste can be reduced. This approach creates value and minimizes the impact on the environment.

4.5.4 Policy Recommendations

To achieve the goal of net-zero emissions by 2050, available approaches include (1) the use of green energy, (2) improvement of energy efficiency, (3) carbon capture, utilization and storage and introduction of negative emissions technologies, (4) reduction of GHG emission from production, and (5) investment in green energy and carbon credits. To increase the ratio of power generated from green energy, it is vital to develop new technologies for green energy (such as geothermal, hydrogen, etc., see Chapter 3). To improve energy efficiency, it is necessary to upgrade equipment and plants. The technologies of carbon capture, utilization and storage, negative emissions technologies as well as reduction of GHG from production all require new research and development results and their applications. Apart from power generated from green energy, Taiwan can also purchase carbon-neutral energy certificates and carbon credits. At present, Taiwan's supply of green energy cannot keep up with industrial demand, and government involvement is needed to establish a mechanism that allows companies to obtain carbon credits.

Our policy recommendations include the following: (1) Join forces with the electronics industry in other countries to lobby for life cycle carbon emissions assessment (product carbon footprint) and highlight the efforts made by the electronics industry to reduce their carbon footprints and promote the development of a more flexible carbon management mechanism; (2) Invest in the development of various types of zero-carbon power, including wind power, solar energy, geothermal energy and ocean energy to accelerate its industrial development process; (3) Actively develop or introduce various energy-saving and carbon-reduction technologies. For example, using AI to improve efficiency and monitor energy consumption of the clean room and the manufacturing process. In terms of the mechanism of carbon management, at present, the Taiwanese government has decided to postpone the trading of carbon credits⁵⁵³, so companies cannot quantify the performance of the investment in carbon

⁵⁵³ Wenlin Sun (2021). Lawmakers expressed concern over the carbon trading mechanism. Environmental Protection Administration said carbon credits are not financial commodities. <https://e-info.org.tw/node/232506>

reduction technology or use carbon credits to offset their carbon emissions. If the electronics industry can present the results of the life cycle carbon emissions assessment product life cycle, it can help the government clarify the value and distribution of carbon credits and do a better job in drafting Taiwan's carbon management mechanism. In addition, Taiwan has been promoting the installation of solar panels on inarable land to increase Taiwan's green energy. However, the environmental impact assessment usually takes a long time, and supporting measures need to be improved. Issues related to carbon credit will be discussed in detail in Chapter 7. As for the development of zero-carbon electricity as well as technologies for energy saving and carbon reduction, which may include emerging or immature clean energy technologies, carbon capture, utilization and storage technologies, and negative emissions technologies, it is vital for the government is share the risks of research and development with the private sector and it is even necessary for the government to strategically invest in the research and development. By establishing a national team composed of academic and research institutions and the industry for carbon reduction, Taiwan can increase the likelihood of meeting the targets of net-zero emissions by 2050.

4.6 Conclusion

In 2019, GHG emissions from Taiwan's manufacturing sector were about 149.6 Mt CO₂eq, accounting for 52.1% of the total emissions. The emissions mainly come from manufacturing processes, electricity consumption and burning of fuel, of which electricity consumption accounted for 63%. The top four industries with the largest emissions from Taiwan's manufacturing sector are petrochemicals, electronics, steel and cement. The total emissions of the four industries are 112.2 Mt CO₂eq, accounting for 75% of the emissions from the manufacturing sector and 39.1% of Taiwan's total emissions. Hence, it is essential for Taiwan to reduce the emissions from the manufacturing sector if Taiwan wants to meet the target of net-zero emissions.

Among the top four industries with the largest emissions in the manufacturing sector, **steelmaking** is energy-intensive with high carbon emissions, so the steel industry needs to accelerate its speed to use and develop low-emission manufacturing processes. Regarding the fuel used for steelmaking, the steel industry can first increase the proportion of natural gas and replace natural gas with carbon-neutral natural gas or hydrogen. The steel industry will also need to invest in technologies such as steelmaking with green hydrogen and direct reduction, as well as circular use of material for steelmaking to reduce the carbon emissions of the steelmaking process.

For the **cement industry**, it is extremely difficult to reduce carbon emissions with both chemical reactions happening during the manufacturing processes and the process to heat raw materials to high temperatures to produce cement, a process that is energy-intensive and results in substantial CO₂ emissions. Cement companies need to upgrade old equipment to advanced energy-saving equipment by renovating existing factories, and they also need to adopt new technologies to improve energy efficiency in order to achieve the goal of carbon neutrality. At the same time, the cement industry needs to lobby for revision of relevant regulations for them to use biomass energy and waste combustion to replace coal burning to reduce the use of coal and natural resources. However, they also need to take measures to ensure that these approaches will not lead to air pollution. Apart from carrying out research and development of alternative materials and new cement, with the support of the government, the cement industry should actively invest in the development of carbon capture, utilization and storage technologies, with relevant infrastructure in place to supply low-carbon electricity, such as natural gas, hydrogen, and renewable energy.

The **petrochemical industry** emits the highest amount of carbon in Taiwan's manufacturing sector, and most emissions come from the chemicals and materials industry as well as the oil and gas refining industry. These industries burn fossil fuels as most of the manufacturing processes are energy-intensive and require high temperatures. At the same time, crude oil is mainly used as the raw material to produce light oil, petrochemical products and plastic products for downstream supply chain operators. To make the situation worse, most of the electricity used in the manufacturing process comes from the burning of fossil fuels for power generation. It is thus vital for the petrochemical industry to launch research and development of decarbonization and MPTP technology (including catalytic cracking and carbon capture and utilization). They also need to find alternative fuels (such as biomass energy and green hydrogen) as well as alternative raw materials (bio-plastics and material recycling technology, etc.) and replace old facilities with electric steam crackers. The petrochemical industry can collaborate with other countries to acquire electric steam crackers and technologies related to green hydrogen, so as to increase the use of these facilities and technologies between 2030 and 2050. It is also essential to develop innovative manufacturing processes and encourage the petrochemical industry to make the transformation by providing incentives for investing in equipment, such as tax deductions, subsidies, rewards or financing tools through green financial mechanisms to assist industries in making the transition.

In 2019, the GHG emissions of the **electronics industry** accounted for 10.9% of Taiwan's total emissions, of which the carbon equivalent of F-gases accounted for about one-sixth of the total emissions, while the emissions from energy use were three times greater than emissions from direct emissions. If we look at the use of electricity, which accounted for the highest percentage of carbon emissions, the electronics industry's use of electricity reached 22.6% of Taiwan's total electricity consumption in 2020 and the number is expected to grow in the future. It is not easy for Taiwan's electronics industry to make the transition to net zero emissions with challenges like difficulty in finding alternatives to F-gases, insufficient supply of green electricity in Taiwan, and the fact that the international mechanism to calculate carbon emission is unfavorable for manufacturing countries. The electronics industry should consider joining forces with the electronics industry in other countries to lobby for the implementation of product life cycle emissions inventories to highlight the contribution of the electronics industry as producers and lobby for the establishment of a more flexible mechanism for carbon

management. The electronics industry should also invest in zero-carbon electricity, including wind power, solar energy, thermal energy and ocean energy and support the government to promote the use of green energy. At the same time, they also need to actively develop or apply energy-saving and carbon-reducing technologies. For instance, using artificial intelligence (AI) to improve the monitoring of the clean room and optimize the manufacturing process with better energy efficiency.

Chapter 5: Carbon Reduction in Other Sectors

Sections

5.1 Introduction

5.2 Transportation Sector

5.3 Residential/Commercial and Building Sector

5.4 Agriculture and Waste Processing Sector

5.5 Conclusion

5.1 Introduction

The primary sources of Taiwan's carbon emissions are the energy/electricity and industrial sectors, with other sectors contributing a smaller share. However, the smaller sectors affect a broad range of stakeholders: emissions from the transportation sector account for 12.9% of total emissions, the residential sector 10.3%, the commercial/service sector 9.8%, the agricultural sector (including agriculture, forestry, fishery, and livestock) 2.1%, and the waste processing sector about 1%. The emissions from these sectors reflect the lifestyle patterns of the general population in Taiwan. To achieve Taiwan's 2050 net-zero emissions target, in addition to overall reduction goals and actionable technological or policy measures, it is essential to consider social factors and establish supportive systems to increase public awareness of carbon reduction and encourage active participation.

This chapter will analyze carbon emission sources in the transportation, residential/commercial building, and agriculture/waste processing sectors to identify the main challenges each sector might face in transitioning to net-zero by 2050, as well as to provide specific recommendations for feasible carbon reduction options. Emissions in the transportation sector arise from road, rail, and marine systems, with the primary challenge being that most vehicles still have gasoline and diesel fuel and face obstacles in transitioning to electric alternatives. For international aviation and maritime shipping, carbon emissions are already subject to regulatory measures, requiring the development of new technologies and low-carbon fuels to meet international standards (see Section 5.2).

In the residential/commercial building sector, emission sources include air conditioning, lighting, and household appliances. The main challenges involve both technical and behavioral energy-saving measures and incorporating the building sector into these efforts (see Section 5.3). In the agriculture and waste sectors, emissions from agriculture primarily stem from the manufacture and application of chemical pesticides and fertilizers, while waste processing emissions mainly result from anaerobic fermentation in various waste management processes, including industrial and household wastewater, landfill, and composting. Although emissions from these sectors are relatively low, they are diverse and decentralized, making it challenging to design efficient systems for effective carbon reduction (see Section 5.4).

Additionally, as these sectors significantly impact the lifestyles of a majority of

people, effective carbon reduction will require not only the measures and recommendations outlined in this chapter but also complementary economic and social incentives to accelerate transformation in people and society. This aspect will be discussed further in Chapter 7.

5.2 Transportation Sector

Summary

Due to the growing threats of global warming and climate change, achieving net-zero emissions by 2050 has become a global goal. According to the International Energy Agency's greenhouse gas reduction scenarios, the transportation sector is the only area where global electricity demand is expected to increase. This makes electrification in transportation one of the most pressing needs internationally. Based on the Environmental Protection Administration's statistics for Taiwan, the main source of greenhouse gas emissions in the transportation sector comes from road transport, such as motorcycles, passenger cars, and heavy trucks. Thus, reducing greenhouse gas emissions from road transport will be the primary carbon reduction goal in Taiwan's transportation sector. The following policy recommendations are proposed to help the transportation sector reach the 2050 net-zero emissions target:

1. Promoting the electrification of cars and motorcycles in line with the trend of international markets, and expanding the installation of charging infrastructure to facilitate electrification and increase public use.
2. Establishing regulations to introduce renewable fuels as a transitional measure until full electrification is achieved.
3. Developing and expanding public transportation based on assessed transportation needs and transport efficiency, while providing incentives to encourage usage, thus reducing emissions from the transportation sector.
4. Accelerating R&D into low-carbon aviation and marine fuels in line with global trends.

5.2.1 Introduction

In 2019, Taiwan's transportation sector emitted a total of 37 Mt CO₂eq, representing about 12.9% of total emissions. Of these emissions, road transport fuel combustion accounted for the vast majority, at 96%, followed by domestic aviation and marine transport, as well as electricity used for rail transport. A further breakdown of emissions within the road transport system shows that passenger cars contribute the largest share (50.5%), followed by heavy trucks (18.3%), motorcycles (12.9%), light trucks (11.8%), and buses (6.4%) (see Figure 5.2.1).

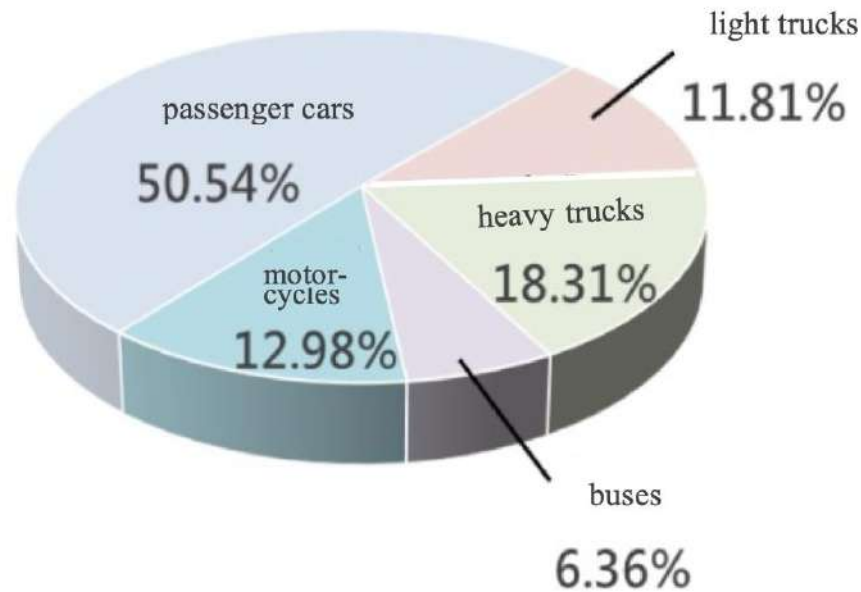


Figure 5.2.1 Emissions from On-Road Vehicles in 2019

These data indicate that, for the transportation sector to reach the net-zero emissions goal, reducing emissions from fuel-powered vehicles within the road transport system is a primary task, with the main pathway being vehicle electrification. The International Energy Agency (IEA) noted in its 2021 *Global EV Outlook* report that 2020 was a pivotal year for transportation electrification, with over 10 million electric vehicles (EVs) on the road globally, and EV sales increasing by 70% worldwide, accounting for 4.6% of total global car sales. China leads with 4.5 million EVs, making it the country with the highest number of electric vehicles, while Europe recorded the largest annual growth, with 1.4 million new EV registrations in 2020, surpassing China's 1.2 million and the United States' 295,000. These figures show that despite the COVID-19 pandemic and a global economic downturn that led to a decrease in new car sales total, EV sales were not adversely affected.

According to statistics from the Ministry of Transportation and Communications, Taiwan has over 8 million registered cars and more than 14 million motorcycles, indicating that nearly every household owns a car or motorcycle. For the transportation sector to continue reducing carbon emissions, substantial changes in the transportation habits of a majority of the population will be necessary, such as switching to low-carbon public transportation or more energy-efficient electric vehicles. This shift will impact daily life for the public; therefore, in addition to technical solutions, social and economic factors must also be considered, as they present a significant challenge for the transportation sector in achieving the net-zero emissions target.

5.2.2 Global Carbon Reduction Trends in the Transportation Sector

The 26th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 26) primarily used the Nationally Determined Contributions (INDC) as a platform for each party to declare their carbon reduction commitments. At COP 26 in 2021, the consensus to "gradually reduce fossil fuels" was achieved and documented in the official text. Key commitments related to transportation made at COP 26 include⁵⁵⁴ the Zero Emission Vehicle (ZEV) Pledge and the Green Shipping Commitment. In the ZEV Pledge, 11 automakers, including Ford, General Motors, Jaguar Land Rover, and Mercedes-Benz, pledged to transition all vehicles sold in major markets to zero-emission models by 2035, indicating that electric vehicles are set to become mainstream in the future. However, some concerns remain, as major automakers such as Volkswagen, Toyota, and Hyundai have not yet signed the pledge.

Another significant commitment was the Green Shipping Commitment, where approximately 200 companies pledged to scale and commercialize zero-carbon ships and fuels by 2030, marking a focal point of the conference. Additionally, the Clydebank Declaration, signed by 22 countries, aims to establish six green shipping corridors using low- or zero-carbon fuel vessels by 2025, with routes spanning from Asia to the Americas, Saudi Arabia to China and India, with an expectation to add new routes after 2030.

The global net-zero emissions strategies in the transportation sector generally follow the three main pillars outlined by the United Nations Department of Economic and Social Affairs (UN-DESA) in its 2016 report, *Mobilizing Sustainable Transport for Development*: Demand Reduction (Avoid), Transport Mode Shift (Shift), and Technological Improvement (Improve)⁵⁵⁵. Most countries have implemented strategies that fall into the following three categories (Box 5.2.1):

1. Optimization and Management of Transport and Travel Demand Systems: Providing incentives to encourage public transportation use, managing systems to enable seamless transportation and freight, and reducing the use of private vehicles to achieve carbon reduction goals.
2. Use of Low-Carbon Vehicles and Electrification: Promoting low-carbon

⁵⁵⁴ COP26 sustainability report, The 26th UN Climate Change Conference, 2021

⁵⁵⁵ United Nations - High-level Advisory Group on Sustainable Transport (2016). Mobilizing sustainable transport for development.

vehicles through incentives (e.g., EV purchase subsidies, tax benefits), establishing CO₂ emissions standards, and enhancing infrastructure to support low-carbon vehicle adoption.

3. Enhancement of Vehicle Energy Efficiency and Use of Alternative Fuels: Improving logistics and mobility management to increase vehicle energy standards, and upgrading vehicle and fuel technologies to enhance energy efficiency in transport⁵⁵⁶.

Box 5.2.1 Approaches Taken by Various Countries in the Transportation Sector⁵⁵⁷

Table 5.2.1 Approaches Taken by Various Countries in the Transportation Sector

Strategy	Approach
Optimization and Management of Transport and Travel Demand Systems	• Germany's Lufthansa Rail & Fly integrated rail and air ticketing system⁵⁵⁸ • Japan's strategy to improve bus schedule punctuality⁵⁵⁹ • Certificate of Entitlement (COE) in Singapore⁵⁶⁰ • South Korea's car-sharing system and Car-Free Day promotion⁵⁶¹ • Reduction of parking spaces in the city center in Oslo, Norway
Use of Low-Carbon Vehicles and Electrification	<u>Incentive Measures:</u> • In the United States, a tax credit of up to \$12,500 is available for electric vehicle purchases⁵⁶². • In Canada, a federal rebate of up to \$5,000 is available for electric vehicle purchases at the consumer level⁵⁶³. • Japan's budget for electric vehicle subsidies is set at 33.49 billion yen⁵⁶⁴. • South Korea's electric vehicle subsidies include deductions on individual consumption tax and education tax.

⁵⁵⁶ SLOCAT (2018). *Transport and climate change global status report*.

⁵⁵⁷ Institute of Transportation, Ministry of Transportation and Communications (2013). Study on the relationship between intelligent transportation systems and energy conservation and carbon reduction.

⁵⁵⁸ Institute of Transportation, Ministry of Transportation and Communications (2020). Discussion on international railway transport development issues and policies—A case study on digital transformation.

⁵⁵⁹ International Transport Forum (2012). Seamless transport: Making connections - Highlights of the International Transport Forum 2012.

⁵⁶⁰ Singapore infopedia (2019). Certificate of entitlement.

⁵⁶¹ C40 (2011). Seoul car-free days have reduced CO₂ emissions by 10% annually.

⁵⁶² Green Car Report (2021). US EV sales have been record-breaking so far in 2021, despite supply chain issues.

⁵⁶³ Feltmate, T. (2021). The Canada/US electric vehicle market: Navigating the road ahead. TD Economics.

⁵⁶⁴ Automobile Division, Ministry of Economy, Trade and Industry (2020). Current status of automobiles and the advancement of electrification. <https://www.esisyab.iis.u-tokyo.ac.jp/symposium/20200804/20200804-01.pdf>

	<u>Regulatory Measures:</u> • Emission standards in Canada, China, and the United States: 114g CO₂/km • Emission standard in India: 134g CO₂/km • In some regions of the EU, the vehicle emission standard is 95g CO₂/km⁵⁶⁵. <u>Infrastructure Enhancement:</u> • EU target for electric vehicle charging stations (by 2030, a ratio of 1 charging device for every 10 electric vehicles)⁵⁶⁶ • China's public spending plan for digital infrastructure (\$1.4 trillion), includes electric vehicle charging stations (target of installing 1.2 million chargers by 2025)⁵⁶⁷ • U.S. infrastructure incentive plan includes 500,000 charging installations and 100,000 charging stations⁵⁶⁸. • Canada's Zero-Emission Vehicle Infrastructure program (\$112 million), includes the installation of Level 2 chargers in buildings and workplaces.
Enhancement of Vehicle Energy Efficiency and Use of Alternative Fuels	• The UK Clean Growth Strategy develops low-carbon transportation technologies and fuel innovation technologies⁵⁶⁹ • The UK established the Renewable Transport Fuel Obligation Program (RTFO) to encourage the production of biofuels⁵⁷⁰; • The California Air Resources Board (ARB) in the United States promotes the Low Carbon Fuel Standard (LCFS) program⁵⁷¹, requiring oil refineries, gasoline and diesel importers, and wholesalers of vehicle transport fuels to produce and use low-carbon fuels. • Canada promotes the development, use, and adoption of clean technologies and low-carbon fuels and has established the Renewable Fuels Regulations, which mandate a renewable fuel blend ratio of 5% in gasoline (e.g., ethanol) and 2% in diesel⁵⁷²; • Japan's Basic Hydrogen Strategy⁵⁷³ promotes the development of hydrogen-powered vehicles.

⁵⁶⁵ Zhongqing Wang (2017). Current status and future trends of global electric vehicle development. Today Heku, Issue 509, 2017.

⁵⁶⁶ EU (2014). European alternative fuels infrastructure directive.

⁵⁶⁷ National Energy Administration of China (2015). Development guide for electric vehicle charging infrastructure.

⁵⁶⁸ The White House (2021). Biden administration advances electric vehicle charging infrastructure.

⁵⁶⁹ UK (2018). Clean growth strategy: Executive summary.

⁵⁷⁰ UK (2012). *Guidance of renewable transport fuel obligation*.

⁵⁷¹ California Air Resources Board (2020). *Monthly LCFS credit transfer activity reports*.

⁵⁷² Government of Canada (2019.06.28). Canada's clean fuel standard: Reducing pollution, fighting climate change and driving clean growth.

⁵⁷³ CMS Expert Guides (2017). Hydrogen law and regulation in Japan.

Nearly 90% of global trade relies on maritime transport, with carbon emissions from ships accounting for approximately 3% of total global emissions. The shipping industry is therefore under pressure to achieve net-zero emissions by 2050⁵⁷⁴. The International Maritime Organization (IMO) has established relevant emissions regulations, such as the 1997 International Convention for the Prevention of Pollution from Ships (MARPOL) and, starting in 2011, regulations on the energy efficiency of ships, including the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). In 2018, the IMO announced international shipping carbon reduction targets, aiming for a 40% reduction in CO₂ emissions by 2030 and a 70% reduction by 2050, using 2008 as the baseline year⁵⁷⁵.

The aviation industry's carbon emissions account for approximately 2.5% of global emissions. In 2016, the International Civil Aviation Organization (ICAO) launched the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) as a global carbon management measure, which regulates carbon emissions on international flight routes, based on standards such as ISO/IEC 17011 and ISO 14065⁵⁷⁶. Additionally, CO₂ emissions standards for newly manufactured aircraft have been implemented to promote the development and adoption of new technologies and to ensure the phasing out of older aircraft. Aircraft already in production must comply with these standards by 2028. ICAO set two key targets in 2019: (1) improve fuel efficiency by 2% per year until 2050; (2) achieve carbon-neutral growth from 2020 onward. The International Air Transport Association (IATA), using 2005 as baseline year, set a goal to improve fuel efficiency by an average of 1.5% per year through 2020, achieve carbon-neutral growth by 2020, and reduce emissions to 50% of 2005 levels by 2050⁵⁷⁷.

⁵⁷⁴ Institute of Transportation, Ministry of Transportation and Communications (2020). Preliminary study on international green shipping incentive mechanisms.

⁵⁷⁵ Institute of Transportation, Ministry of Transportation and Communications (2019). Analysis of strategies adopted by various countries in response to the 2020 low-sulfur fuel oil regulations for ships.

⁵⁷⁶ ICAO (2019). News release: CORSIA implementation on course, ICAO (Mar. 6, 2019).

⁵⁷⁷ Institute of Transportation, Ministry of Transportation and Communications (2018). Preliminary analysis of international aviation emissions control development.

5.2.3 Analysis of Carbon Reduction Options in the Transportation Sector

The transportation sector is currently heavily reliant on fossil fuels. To achieve carbon reduction goals, the following carbon reduction options are analyzed: alternative fuels, vehicle electrification, and innovative technologies. In terms of alternative fuels, road, rail, maritime, and aviation, each have corresponding fuel solutions. For short-distance transport (e.g., cars and motorcycles), electrification has a significant advantage, whereas for long-distance transport like maritime and aviation, alternative fuels such as biojet fuel and liquid hydrogen are more promising. Additionally, Sustainable Aviation Fuels (SAF)—biojet fuels made from plant-based materials, recycled vegetable oil, animal fats, or waste⁵⁷⁸—represent an important area for further development.

Vehicle electrification will be the key to reducing carbon emissions in the transportation sector, especially when combined with a smart grid to function as an energy storage carrier. Currently, the industry is focused on developing battery technology to convert road transport vehicles, such as cars and trucks. Most of today's electric vehicles use lithium-ion batteries, with ongoing improvements in battery performance and safety, as well as the development of various battery types, including lithium-air, sodium-ion, and solid-state batteries. Hydrogen fuel cells are also advancing rapidly, offering a new option for low-carbon vehicles with the recent emergence of hydrogen-powered vehicles. However, issues related to hydrogen sourcing and hydrogen refueling infrastructure remain to be solved, and overall energy efficiency of hydrogen vehicles is much lower than that of electric vehicles. Thus, hydrogen vehicle technology will need breakthrough advancements to remain competitive with electric vehicles. From another perspective, if both electric and hydrogen vehicles are powered by green electricity, the process for hydrogen vehicles would involve using green electricity to produce hydrogen, store and transport the hydrogen, and then converting it back to electricity in a fuel cell inside the vehicle (essentially making the vehicle a mobile power plant). This indicates that direct use of electric vehicles would result in simpler energy utilization. Unless Taiwan achieves a substantial increase in renewable energy generation, with excess green electricity

⁵⁷⁸ BP. Sustainable aviation fuel – What is it and why is it important? <https://www.bp.com/en/global/air-bp/news-and-views/what-is-sustainable-aviation-fuel-saf-and-why-is-it-important.html>

available during low-demand periods that could be used for hydrogen production as an energy storage medium, the competitiveness of hydrogen vehicles may remain limited.

Enhancing the overall public transportation system, improving the feasibility of public transport in remote areas, and increasing rail transport efficiency offer substantial carbon reduction potential. Shared mobility is an emerging transportation service that can change the way people move in cities, with options like shared scooters, bicycles, and cars. As technology advances and internet access becomes more widespread, shared mobility services are increasingly comprehensive. Introducing shared vehicles in urban areas is expected to address issues such as traffic volume and greenhouse gas emissions.

5.2.4 Current Carbon Reduction Initiatives in Taiwan's Transportation Sector

The transportation sector's strategies for reducing greenhouse gas emissions are focused on three main areas: public transportation, green low-carbon vehicles, and vehicle energy efficiency. The transportation systems in metropolitan areas contribute significantly to greenhouse gas emissions, with the six major cities in Taiwan accounting for 65% of national emissions. This highlights the need for metropolitan areas to develop public transportation systems and enhance transportation demand management measures to reduce emissions, such as increasing the capacity of public road transport, boosting rail system capacity, and providing seamless transfer services.

The primary source of carbon emissions in the transportation sector is vehicles, with Taiwan's vehicles highly dependent on fossil fuels—97% of the vehicles use gasoline or diesel. In addition to producing a high volume of greenhouse gases, exhaust emissions from gasoline and diesel engines are a major cause of air pollution.⁵⁷⁹ Taiwan's current policy direction is gradually shifting towards vehicle electrification and encouraging the use of public transportation. Efforts are being made to transition the energy demand for road vehicles, trains, ships, and aircraft from fuel to electricity or low-carbon fuels, including the electrification of island-wide trains, subsidies for electric vehicles, and the development of green transport by local governments. Comprehensive charging infrastructure is also essential. With the global trend toward banning the sale of fuel-powered vehicles between 2035 and 2040 and fully electrifying

⁵⁷⁹ Institute of Transportation, Ministry of Transportation and Communications (2018). Preliminary study on measures to reduce emissions from urban buses.

cars and motorcycles by 2050, estimates based on Taiwan's current fleet of 7.93 million cars and 13.76 million motorcycles suggest that full electrification would increase daily electricity demand by approximately 40 million kilowatt-hours, or about 14.6 billion kilowatt-hours annually. According to daily power load curves, more than 40 million kilowatt-hours of electricity are available during off-peak nighttime hours in summer and winter, which could meet the electricity demand under full vehicle electrification⁵⁸⁰.

Furthermore, as technology continues to evolve, innovative technologies that enhance the energy efficiency of vehicles and transport systems are one approach for carbon reduction. The growing application of intelligent transportation technologies can optimize driving routes, reduce congestion and idling, and thus yield energy-saving and carbon-reduction benefits⁵⁸¹. To maintain the quality of existing transportation infrastructure, early planning for upgrades to the island's maritime, rail, and road systems is necessary to construct a high-efficiency green transportation network. Improving the quality of public transportation services to reduce reliance on private vehicles would also contribute to carbon reduction. Energy consumption per person-kilometer for cars and motorcycles is 1.1–1.3 times that of buses and 3–4 times that of rail transport, indicating that vehicle occupancy rates directly impact energy efficiency. However, compared to private vehicles, public transportation's lack of convenience is a barrier to its adoption⁵⁸².

⁵⁸⁰ Lang Ruofan (2018). Challenges of electric vehicle promotion policies to traditional power grids, current affairs perspective, Taiwan Institute of Economic Research.

⁵⁸¹ Institute of Transportation, Ministry of Transportation and Communications (2013). Evaluation and feedback on the effectiveness of public transportation development policies—Analysis of changes in mode choice behavior and establishment of a decision support system.

⁵⁸² Institute of Transportation, Ministry of Transportation and Communications (2009). Discussion on development policies for green transportation systems.

5.2.5 Policy Recommendations

The following policy recommendations are proposed for the transportation sector:

1. Promoting Electrification of Cars and Motorcycles in Line with International Markets, and Expanding the Installation of Charging Infrastructure to Facilitate Electrification and Increase Public Use

A clear timeline for phasing out fuel-powered vehicles should be established, and efforts should be made to stimulate the electric vehicle (EV) market. Currently, EV infrastructure in Taiwan remains insufficient, with only a few counties and cities having more than 100 charging stations. Meanwhile there is an inadequate number of chargers in outdoor and public parking areas. This lack of infrastructure may discourage public participation in carbon reduction efforts. Therefore, it is recommended to establish EV charging regulations as soon as possible, specifying installation locations and ratios for charging facilities and incorporating penalties to ensure compliance by government agencies, businesses, and the public.

2. Establishing Regulations to Introduce Renewable Fuels as a Transitional Carbon Reduction Measure Until Full Electrification Is Achieved

As the transportation sector transitions to electrification, energy demand will shift from fuel to electricity or low-carbon fuels. In this interim period, before all vehicles are electrified and as fossil fuel use is gradually reduced to lower carbon emissions, Taiwan could introduce renewable fuel regulations. These regulations would set progressive standards for renewable fuel usage to reduce the reliance on imported fossil fuels, allowing vulnerable car owners more time to complete vehicle upgrades and replacements.

3. Developing and Expanding Public Transportation Systems Based on Assessed Transportation Needs and Transport Efficiency, While Providing Incentives to Encourage Usage, thus Reducing Emissions from the Transportation Sector

Developing public transportation is an effective energy-saving and carbon-reduction measure. Integrated planning and construction of a low-emission, low-pollution transportation system would reduce greenhouse gas emissions. Enhancing the quality of public transportation services should make public transit more attractive, and transport demand management should be strengthened to encourage the use of public transport and bicycles as green transport options, aiming to reduce the current high reliance on private vehicles.

4. Accelerating R&D into Low-Carbon Aviation and Marine Fuels in Line with Global Trends

Since the aviation and maritime industries are not yet technologically ready to rely solely on electric power, using low-carbon fuels in the interim is a primary method for significantly reducing emissions in these sectors. Many countries are promoting mid- to long-term plans for low-carbon fuel usage and production facilities. Although Taiwan has research institutions developing low-carbon fuel technology, there is still room for growth in terms of policy, technological maturity, and market environment. Fostering Taiwan's development momentum is recommended to facilitate alignment with international standards.

5.3 Residential, Commercial and Building Sector

Summary

The global building and construction sector accounts for over one-third of final energy consumption and carbon emissions, with primary emission sources including daily electricity use (such as air conditioning, lighting, and other equipment) and emissions from building material production. To reduce carbon emissions from the residential/commercial and building sectors, it is essential to lower electricity demand, enhance the energy efficiency of existing buildings, and extend building lifespans. Based on Taiwan's circumstances, the following actions are recommended for the residential/commercial and building sectors:

1. Promptly Promoting the Renovation and Refurbishment of Existing Buildings: This includes using lightweight construction, extending building lifespans, reducing material waste, or using alternative materials, such as replacing construction materials with natural resources, to reduce carbon emissions from building material production.
2. Accelerating Research and Development Investment in Emerging Cooling Technologies: Reducing electricity consumption from cooling equipment in the residential/commercial and building sectors can lower carbon emissions.
3. Achieving Full Integration and Deployment of System Infrastructure in the Residential/Commercial and Building Sector by 2050: This should include widespread adoption of smart energy management and flexible power dispatch systems to maximize energy-saving and carbon-reduction benefits in the sector.

phase of building materials (including cement/steel production and other miscellaneous items) accounts for 25.4% of total emissions. The construction phase (mainly energy use) accounts for 1%, while the highest share is from the operational phase of buildings at 73.6% [including coal, oil, and natural gas at 22.9%, and electricity and heat (indirect emissions) at 50.7%]. Emissions from building material production mainly originate from the cement and steel industries, as the global building and construction sector accounts for 50% of cement demand and 30% of steel demand⁵⁸⁷.

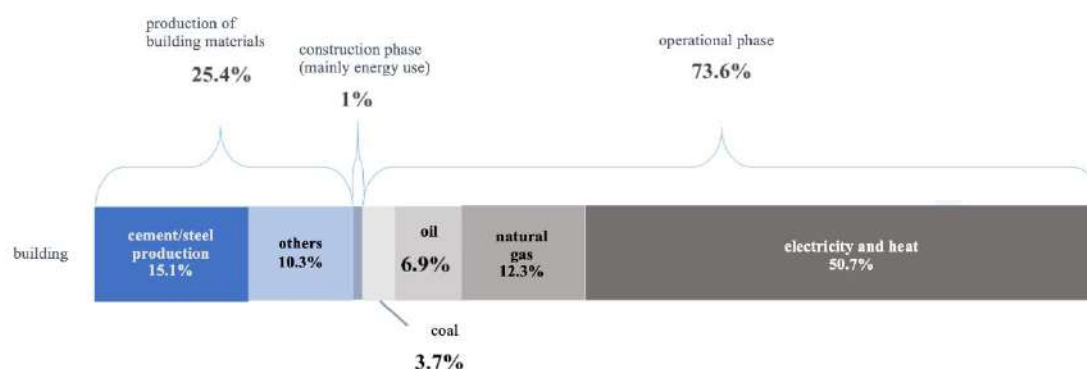


Figure 5.3.2 Emission Sources across the Building Sector Value Chain⁵⁸⁸

Further analysis of emission sources from the daily use and operations of Taiwan's residential/commercial sector (see Figure 5.3.3) shows that in 2019, carbon emissions from the residential sector totaled 28.5 Mt CO₂eq, with electricity emissions as the primary source (accounting for 84%). Within electricity emissions, air conditioning contributed approximately 20%, lighting 30%, and other equipment (mainly household appliances) 50%. In the same year, carbon emissions from the commercial sector amounted to 27.1 Mt CO₂eq, with electricity emissions also as the main source (accounting for 87%). Within these emissions, air conditioning contributed about 50%, lighting 30%, and other equipment 20%^{589,590}.

⁵⁸⁷ *Ibid.*, note 591.

⁵⁸⁸ *Ibid.*, note 591.

⁵⁸⁹ Ministry of the Interior and Ministry of Economic Affairs (2021). Presentation on the Pathway Assessment for Net-Zero Emissions in the Residential/Commercial Sector, Project Task Force Meeting, Executive Yuan, April 1 (unpublished data).

⁵⁹⁰ Lin, Hsiang-Te (2015). Carbon footprint of buildings. Jans Publisher. Cited in Ministry of the Interior and Ministry of Economic Affairs (2021), Presentation on the Pathway Assessment for Net-Zero Emissions in the Residential/Commercial Sector, Project Task Force Meeting, Executive Yuan, April 1 (unpublished).

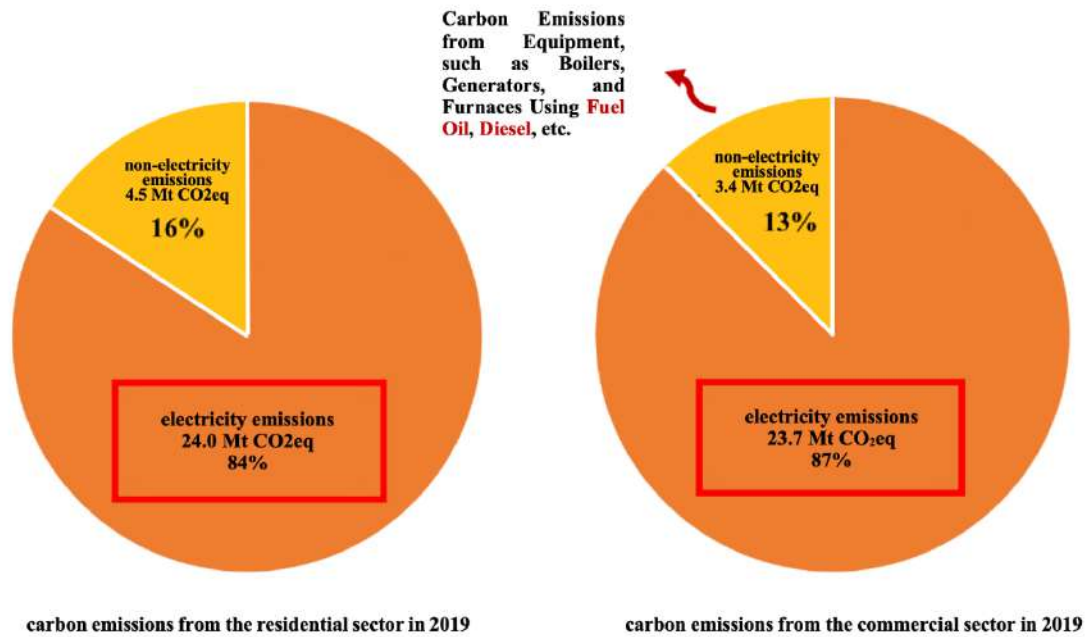


Figure 5.3.3 Carbon Emissions from Daily Use and Operations in Taiwan's Residential/Commercial Sector⁵⁹¹

In summary of the previous analysis of carbon emissions from daily use and operations in Taiwan's residential/commercial sector, the main challenges for transitioning this sector to net-zero emissions are as follows. For building daily use and operations, it is essential to (1) reduce emissions from electricity used in daily operations and (2) reduce carbon emissions from fuel use (such as natural gas, fuel oil, diesel, etc.).⁵⁹² For emissions not associated with daily use and operations, the challenge lies in carbon emissions from construction materials. According to Tatsuo Oka (2013), who analyzed the proportion of carbon emissions from building materials based on industry input-output tables for several countries, at least 10%⁵⁹³ of Taiwan's total emissions can be attributed to building materials. Therefore, (3) reducing carbon emissions from construction material usage is another challenge Taiwan must address in its net-zero emissions transition.

For Taiwan, (1) reducing emissions from electricity in daily use requires considering ways to lower electricity demand in the residential/commercial and

⁵⁹¹ *Ibid.*, note 596.

⁵⁹² *Ibid.*, note 596.

⁵⁹³ Architecture and Building Research Institute, Ministry of the Interior (2019). *Study on the establishment of a carbon footprint data system for building materials*. <https://ws.moi.gov.tw/Download.ashx?u=LzAwMS9VcGxvYWQvT2xkRmlsZV9BYnJpX0dvdi9yZXNIYXJjaC8yOTMzLzE1ODYwNzM0MDV4NWU4ZGQucGRm&n=MTnlu7rnr4nmnZDmlpnnorPotrPot6Hos4fmlpnn s7vntbHlu7rnva7kuYvnoJTnqbYucGRm>

building sectors or increasing the use of carbon-free electricity. (2) Reducing carbon emissions from fuel use necessitates lowering fuel demand in these sectors or increasing the adoption of carbon-free fuels. (3) Reducing carbon emissions due to construction materials can be approached by extending building lifespans, reducing cement and steel usage, or opting for materials with lower embodied carbon as solutions.

5.3.2 Global Carbon Reduction Trends in the Residential/Commercial and Building Sector

Global carbon reduction efforts in the residential/commercial and building sector can be categorized into (1) residential/commercial activities (see Figure 5.3.4) and (2) building envelope (see Figure 5.3.5)⁵⁹⁴. In terms of residential/commercial activities, the most direct CO₂ reduction strategies are electrification (especially for heating systems) and improving energy efficiency (equipment and building design), which together can reduce approximately 70% of carbon emissions. Other strategies include behavioral changes/reducing demand and utilizing renewable energy (including biomass, hydrogen, and other renewables) (see Figure 5.3.4).

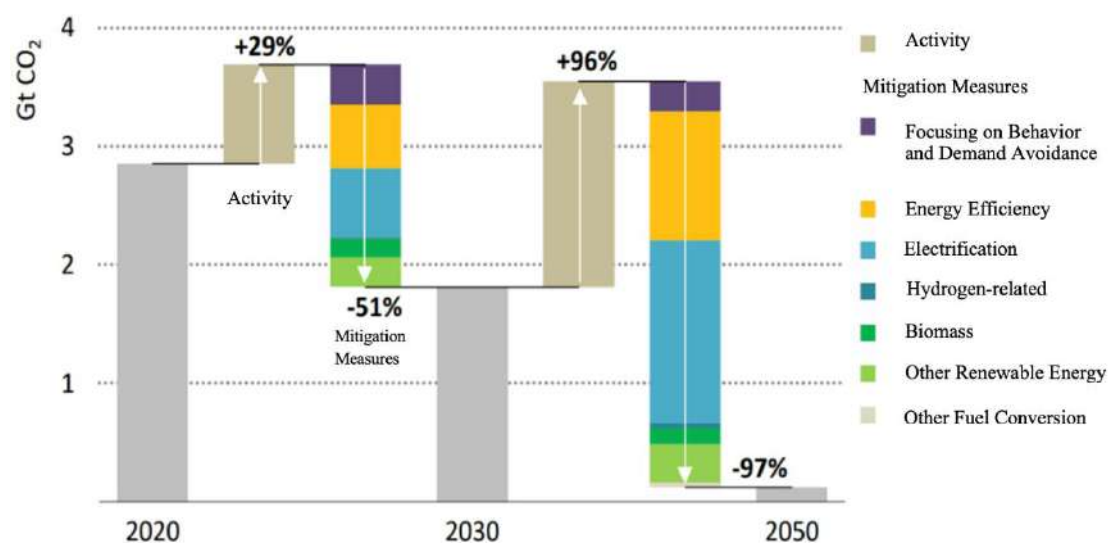


Figure 5.3.4 Global CO₂ Reduction Options for Residential/Commercial Activities under a Net-Zero Emissions Scenario⁵⁹⁵

⁵⁹⁴ IEA (2021). *Net zero by 2050: A roadmap for the global energy sector*. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroBy2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

⁵⁹⁵ *Ibid.*, note 601.

In terms of the building envelope, structural improvements to retrofit existing buildings and designing new buildings are the key to reducing the energy intensity (heating and cooling) within buildings. According to the International Energy Agency (IEA)⁵⁹⁶, to achieve net-zero emissions, by 2050 over 85% of buildings, including New Zero Carbon Ready Buildings (New ZCRB) and retrofitted Zero Carbon Ready Buildings (Retrofit ZCRB), must meet zero-carbon building energy code requirements (ZCRB energy codes). From now until 2030, mandatory zero-carbon building energy codes need to be introduced for new buildings globally, and after 2030, 2.5% of existing buildings should be retrofitted annually to comply with zero-carbon standards (see Figure 5.3.5).

Additionally, key development trends include grid-interactive efficient buildings that use artificial intelligence to manage energy systems and positive energy zones, where specific areas comprised of buildings and renewable energy facilities achieve energy balance or net positive energy output.⁵⁹⁷ However, given the slow pace of urban renewal in Taiwan, relying solely on new zero-carbon construction may not be timely enough. A more feasible approach would be to promote retrofitting existing buildings to enhance their carbon reduction potential, without requiring full urban renewal. Improving building durability in the residential/commercial sector and enhancing internal energy efficiency and insulation offer a more practical means of achieving carbon reduction goals.

⁵⁹⁶ *Ibid.*, note 601.

⁵⁹⁷ Industrial Technology Research Institute (2021). Presentation on the Development of Energy-Saving Equipment Technologies for "Net-Zero Buildings" Vision Workshop.

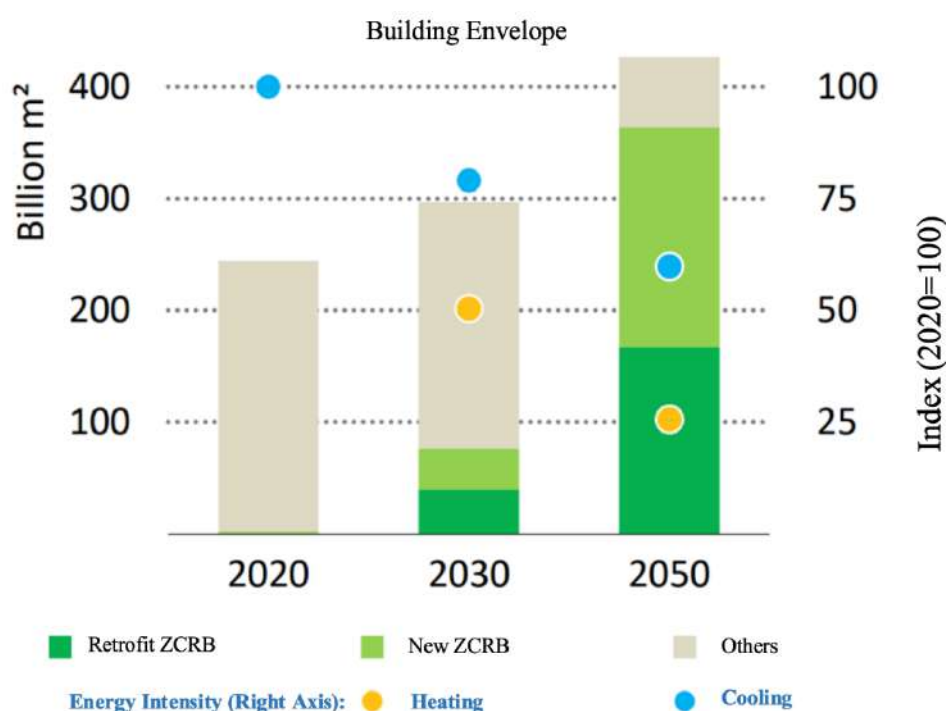


Figure 5.3.5 Trends in Building Envelope Improvements (Area) and Changes in Energy Intensity for Heating and Cooling from 2020 to 2050⁵⁹⁸

5.3.3 Carbon Reduction Options in the Residential/Commercial and Building Sector

As noted earlier, excluding the construction phase, the main emission sources in the residential/commercial and building sector are electricity (approximately 50.7%), building materials (25.4%), and fuel use (22.9%) (see Figure 5.3.2). These can be improved through three main approaches⁵⁹⁹: enhancing equipment efficiency, building construction and renovation, and system integration.

1. Enhancing Equipment Efficiency

- Heating/cooling equipment (e.g., air conditioners, heat pumps, boilers)
- Lighting equipment (e.g., light fixtures, lighting systems)
- Integrating ICT and sensors, utilizing artificial intelligence and big data to improve equipment efficiency

2. Building Construction and Renovation

- Renovation of existing buildings (e.g., improving building design, ventilation, envelope structure, and installing structural insulated panels)

⁵⁹⁸ *Ibid.*, note 601.

⁵⁹⁹ IEA (2021). *ETP clean energy technology guide*. <https://www.iea.org/articles/etp-clean-energy-technology-guide>

- Lightweight construction (e.g., enhanced tendon floor systems, use of composite materials)
- Extending building lifespans (e.g., using modular components that can be recycled)
- Reducing material waste (e.g., using additive manufacturing or prefabrication methods)
- Establishing net-zero buildings (e.g., implementing zero-carbon building energy codes, integrating renewable energy such as rooftop solar PV, energy storage facilities, and transportation system integration such as charging stations)

3. System Integration

- Smart meters and smart grids
- Automated demand-response technology
- DC buildings and microgrid systems
- Regional energy balancing
- Energy management systems

Most technologies have a high level of maturity; however, some heating/cooling equipment and building lightweighting technologies remain in the experimental research phase (TRL 4 or below), such as active latent heat storage, membrane-integrated evaporative cooling, liquid or solid desiccant evaporative cooling systems, integrated heat pumps with storage functionality, solid-state cooling systems (barocaloric, elastocaloric), and enhanced tendon floor systems (see Box 5.3.1).

Given Taiwan's subtropical climate, winter heating demand is relatively low, but there is a high demand for cooling in summer, making cooling efficiency technologies especially relevant. Additionally, if building materials and structures can move toward reduced use of cement and steel or replacement with lower embodied carbon materials without compromising seismic and disaster resistance, it would significantly contribute to reducing emissions in Taiwan's residential/commercial building sector.

Box 5.3.1 Rib-Stiffened Funicular Floors for the HiLo Unit⁶⁰⁰

The rib-stiffened funicular floors were developed by ETH Zürich as part of the Regional Sustainable Building Technology Project (Hilo) under the Swiss Federal Laboratories for Materials Science and Technology. It is a thin concrete component that primarily relies on a hyperbolic shell structure to bear loads. The slab and fin thickness do not exceed 20 mm, allowing 70% of the concrete to be replaced with low-density insulation material to improve thermal insulation performance. Prototype testing of the previous generation demonstrated the ability to produce 2 cm thin concrete walls and shells without cracking. However, further testing is required for using reduced cement quantities.

5.3.4 Existing Carbon Reduction Efforts in Taiwan's Residential and Commercial Building Sectors

According to Article 9 of the Greenhouse Gas Reduction and Management Act, in order to implement Taiwan's greenhouse gas reduction policy, the central competent authority shall develop a National Climate Change Action Guideline and Greenhouse Gas Reduction Action Plan reflecting Taiwan's economy, energy supplies, and environment, and shall implement the Action Guideline and Action Plan in consultation with the central industry competent authorities after requesting approval from the Executive Yuan⁶⁰¹.

As the authority overseeing the residential and construction sectors, the Ministry of the Interior, in line with the Greenhouse Gas Reduction and Management Act and Article 6 of its Enforcement Rules, collaborated with various ministries, including the Ministry of Economic Affairs, to develop the Greenhouse Gas Emission Control Action Plan for the residential and commercial sectors. This plan was approved in September 2018, with the first phase covering the period from 2016 to 2020. The plan includes sector-specific greenhouse gas reduction targets, timelines, and measures with

⁶⁰⁰ Zeiba D. (2019). Swiss researchers develop high-tech floor that minimizes concrete use. <https://www.archpaper.com/2019/01/eth-functionally-integrated-funicular-floor-system>

⁶⁰¹ Environmental Protection Administration, Executive Yuan (2015). Greenhouse Gas Reduction and Management Act. Laws & Regulations Database of The Republic of China (Taiwan). <https://law.moj.gov.tw/LawClass/LawAll.aspx?pcode=O0020098>

economic incentives^{602, 603}. Current carbon reduction strategies include improving energy efficiency and performance control banding, strengthening energy-saving regulations, and providing incentives for existing buildings. Additionally, efforts are being made to implement reduction measures for both new and existing buildings and to develop low-carbon urban living circles.

Current carbon reduction measures include disclosing energy consumption data of building envelopes, setting a 1% energy efficiency improvement target for major energy users in the service industry, ensuring retail chain businesses meet energy-saving performance guarantees, and collaborating with local governments on residential and commercial electricity-saving actions.

Internationally, greater emphasis is being placed on different aspects of building construction and renovation, such as building design, ventilation, applying structural insulation plates to building envelopes and devices, lightweight construction, extending building lifespans, reducing material waste, and establishing net-zero buildings. However, these areas have not been as prioritized or emphasized in Taiwan. From a long-term perspective aimed at achieving net-zero emissions, given the relatively slow pace of urban renewal in Taiwan, the short to mid-term focus should be on retrofitting and renovating existing buildings. Meanwhile, greater attention should be paid to adjustments and changes in the upstream design phase of new buildings to prevent operational carbon emissions in the future. Furthermore, improving the efficiency of electrical equipment in the residential and commercial sectors, strengthening technical regulations for new construction, and developing mandatory regulations for older buildings should continue to be key areas of focus.

⁶⁰² National Greenhouse Gas Reduction Regulations Information Network (2021). Greenhouse Gas Emission Control Action Plan by Sector. https://ghgrule.epa.gov.tw/action/action_page/52

⁶⁰³ *Ibid.*, 590.

5.3.5 Policy Recommendations

This proposal offers three key policy recommendations as follows:

1. Accelerate the renovation and retrofitting of existing buildings by employing methods such as lightweight construction, extending building lifespans, reducing material waste, and using alternative materials, such as natural resources, to replace traditional building materials, thereby reducing carbon emissions from material production

In the area of building construction and renovation, due to the slow pace of urban renewal in Taiwan, promoting the construction of new net-zero buildings following international trends may not be immediately feasible. A more practical approach would be to focus on retrofitting existing buildings to enhance their carbon reduction potential. Rather than relying solely on urban redevelopment, improvements can be made by increasing the durability of buildings in the residential and commercial sectors, and by enhancing internal energy efficiency and insulation. Additionally, in the application of building materials, carbon emissions from material production can be reduced by employing lightweight construction, extending building lifespans, and minimizing material waste. Alternative materials, such as wood, natural resources, and low-carbon materials, can also be considered as substitutes for conventional building materials. This approach not only conserves energy and reduces emissions but also has the potential to increase carbon sequestration. Through sustainable forest management, mature trees can be harvested, allowing for new growth that absorbs atmospheric carbon dioxide more rapidly. However, deep renovations and energy upgrades require significant upfront investment, which may be a challenge for most property owners. Therefore, innovative economic models with policy incentives will be necessary to drive these initiatives effectively.

2. Develop emerging cooling technologies

Excluding the construction phase, the primary source of emissions in the residential and commercial/building sectors largely comes from electricity usage. Past action plans for greenhouse gas emission control in these sectors have focused on improving the energy efficiency of equipment to reduce carbon emissions from electricity consumption. According to the International Energy Agency, emerging cooling technologies, such as evaporative cooling systems with osmotic membranes and liquid or solid desiccant evaporative cooling systems, are still in the experimental

stage and not yet commercially viable. Therefore, further R&D investment is needed to accelerate the commercialization of these technologies. Taiwan has built considerable expertise in energy-saving technologies and industrial development, so collaborative efforts between academia and industry should be considered to co-develop these technologies. Field applications and testing can be used to verify the feasibility of these innovations and enhance their effectiveness in reducing carbon emissions in the residential and commercial building sectors.

3. By 2050, system integration infrastructure in the residential and commercial/building sectors should be fully established and widely adopted, along with the implementation of smart energy management and flexible power dispatch systems to enhance energy saving and carbon reduction efforts in these sectors

In addition to retrofitting and insulating existing buildings and improving the energy efficiency of electrical appliances in the residential and commercial sectors to achieve significant carbon reductions, it is also important to consider system integration. Enhancing energy management and optimizing power dispatch should be key strategies for improving energy efficiency and reducing consumption. The government has already implemented concrete plans to promote technologies such as smart meters, smart grids, and automated demand response to increase energy efficiency on the user end. However, these technologies have not yet reached widespread adoption. Continued efforts are needed to expand this infrastructure and ensure smooth implementation, utilizing smart energy management and flexible power dispatching to further enhance energy efficiency and carbon reduction in the residential and commercial/building sectors.

5.4 Agricultural and Waste Sectors

Summary

In 2018, the agricultural and waste sectors accounted for approximately 3% of Taiwan's total carbon emissions. Although this is a relatively small share, agricultural operations—such as soil fertilization and rice cultivation—constitute the largest source of emissions in the agricultural sector, responsible for nearly half of the total. As Taiwan works toward achieving its 2050 net-zero emission target, a critical consideration is how to reduce carbon emissions in agriculture while ensuring the stability of the domestic food supply. On the other hand, emissions in the waste sector predominantly come from waste disposal processes, which account for about 90% of the sector's total emissions. Therefore, accelerating the adoption of innovative technologies and promoting waste recycling will be key to achieving significant carbon reductions.

Given the broad scope of carbon reduction measures required for both sectors, which cover agriculture, forestry, fisheries, animal husbandry, and ecological conservation, the following actions are recommended for the agricultural and waste sectors in Taiwan:

1. Adopt low-carbon farming, such as nitrogen-free fertilizers or low-methane feed additives for poultry and livestock, to improve emission reduction outcomes in agricultural and livestock practices.
2. Promote the electrification of agricultural, forestry, fishing, and animal husbandry facilities, including greenhouses, aquaculture systems, and transportation equipment such as fishing vessels, while accelerating the integration of renewable energy sources.
3. Collect agricultural and forestry residues to produce biochar, which can reduce air pollution from open burning, lower carbon emissions, and encourage resource reuse.
4. Establish a fair and transparent carbon credit trading mechanism for the agricultural sector, leveraging the sector's natural carbon sink capabilities to alleviate pressure on the energy sector during Taiwan's transition to net zero.
5. Cultivate bioenergy crops on non-arable farmland, such as fast-growing Napier grass (*Pennisetum alopecuroides*) (details provided in the bioenergy section).
6. Implement existing technologies and develop new ones to address methane emissions from waste.

5.4.1 Introduction

Taiwan has historically been an agricultural nation, but with the development of industry and technology, commerce and industry have become dominant. This shift is reflected in Taiwan's greenhouse gas emissions, where the agricultural sector accounted for only 2% of the total carbon emissions in 2018, and the waste sector made up just 1%. However, if effective emission reduction measures are implemented in these sectors, and a more proactive approach is taken to support comprehensive carbon reduction efforts across other sectors, it could significantly contribute to Taiwan's goal of achieving net-zero emissions by 2050. This chapter begins with an analysis of emission sources in these sectors, followed by a discussion of the major challenges in the transition to net-zero. It also reviews the current carbon reduction efforts and options available in Taiwan. The goal is to consolidate this information and provide appropriate policy recommendations for reducing emissions in the agricultural and waste sectors.

5.4.2 Emissions from the Agricultural and Waste Sectors

1. Agricultural Sector

Greenhouse gases (GHGs) from the agricultural sector, including carbon dioxide, methane, and nitrous oxide, are primarily emitted due to the use of pesticides and fertilizers derived from fossil fuels. The production process of these pesticides and fertilizers indirectly generates greenhouse gases, and when applied to soil, synthetic fertilizers release nitrous oxide into the atmosphere⁶⁰⁴. As a result, many countries have increasingly focused on reducing the use of chemical pesticides and fertilizers to lower energy consumption and greenhouse gas emissions. Additionally, in agricultural countries worldwide, large-scale farming of ruminant animals such as cattle, sheep, and deer produces significant amounts of methane and nitrous oxide through digestion and excretion. This makes the agricultural sector a substantial contributor to global greenhouse gas emissions⁶⁰⁵. Research also indicates that approximately 11.9% of

⁶⁰⁴ Juan, Y.-M. (2021). The role of organic agriculture in climate change. Organic Agriculture Promotion Center. <https://www.oapc.org.tw/氣候變遷下有機農業所扮演的角色/>

⁶⁰⁵ Council of Agriculture, Executive Yuan (2020). Taiwan's agricultural and forestry sectors absorb b more greenhouse gases than they emit, contributing to both food security and carbon reduction. Council of Agriculture, Executive Yuan. https://www.coa.gov.tw/theme_data.php?theme=news&sub_theme=agri&id=8266

global greenhouse gas emissions come from agriculture^{606,607}.

In Taiwan, the agricultural sector is primarily focused on crop cultivation. Since joining the World Trade Organization (WTO) and embracing trade liberalization, domestic agricultural production has been significantly impacted, with both cultivated land area and livestock numbers declining annually. Additionally, Taiwan's livestock industry is not primarily focused on raising ruminant animals, while the outbreak of foot-and-mouth disease further reduced pig farming. According to Taiwan's National Greenhouse Gas Inventories⁶⁰⁸, the majority of greenhouse gas emissions in the agricultural sector come from the application of nitrogen fertilizers to soil. However, these emissions have shown a declining trend, with agricultural sector emissions in 2018 reduced by approximately 13.4% compared to 2005.

In 2018, Taiwan's agricultural sector (including agriculture, forestry, fisheries, and animal husbandry) emitted 5.8 Mt CO₂eq, representing about 2% of Taiwan's total emissions of 297 Mt CO₂eq for that year. These emissions included CO₂, CH₄, and N₂O, all of which have high global warming potential. As shown in Figure 5.4.1, agricultural operations account for the majority of agricultural emissions, reaching 47%. These emissions result from the use of lime for soil pH adjustment, urea-based nitrogen fertilizers (which release CO₂ and N₂O), methane produced during the anaerobic decomposition of organic matter in rice paddies, methane and N₂O emissions from livestock enteric fermentation digestion, and methane generated from livestock waste. Emissions from electricity use, primarily for aquaculture, livestock farming automation, and greenhouses, account for 27%. The remaining 26% comes from fuel combustion, mainly for fishing vessels and agricultural pumps. Emissions from electricity use in agriculture rank second, accounting for 27%, primarily used for aquaculture, livestock automation, and greenhouses. The remaining 26% comes from fuel combustion, mainly from the use of fuel in fishing vessels and agricultural pump equipment^{609,610}.

⁶⁰⁶ Intergovernmental Panel on Climate Change (IPCC) (2019). Climate change and land. IPCC. https://www.ipcc.ch/site/assets/uploads/2019/08/4.-SPM_Approved_Microsite_FINAL.pdf

⁶⁰⁷ Chien, Y.-T. & Chang, C.-W. (2020). Translation extract of the summary for policymakers from special report on climate change and land by IPCC. https://tccip.ncdr.nat.gov.tw/km_abstract_one.aspx?kid=20201111172619

⁶⁰⁸ Environmental Protection Administration, Executive Yuan (2020). *2020 national greenhouse gas inventories*. National Greenhouse Gas Reduction Regulations Information Network. <https://ghgrule.epa.gov.tw/admin/resource/files/2020年國家排放清冊報告.pdf>

⁶⁰⁹ *Ibid.*, 615.

⁶¹⁰ Council of Agriculture, Executive Yuan (2021). Presentation on the Timeline and Actions for Taiwan's Net-Zero Emissions Target at the 3rd Review Meeting (April 1).

Agricultural Sector Emission Sources

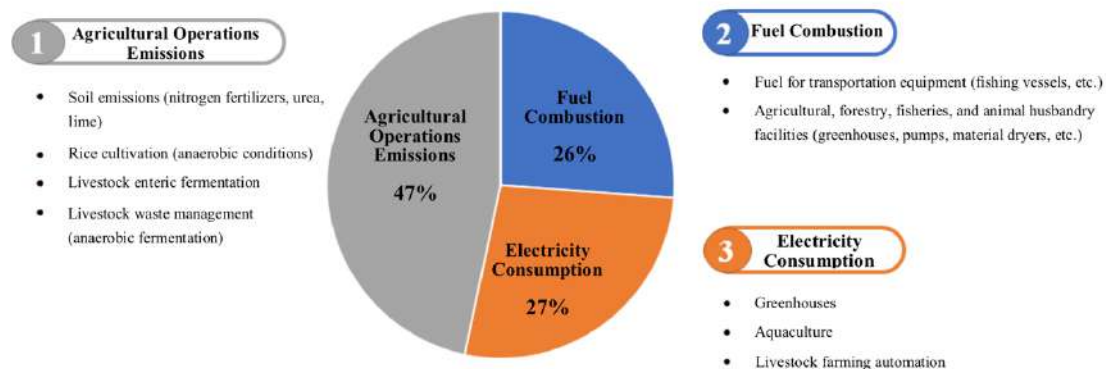


Figure 5.4.1 Emission from the Agricultural Sector^{611,612}

2. Waste Sector

In 2018, the waste sector in Taiwan emitted 2.9 Mt CO₂eq, accounting for 1% of the nation's total carbon emissions of 297 Mt CO₂eq. Waste disposal processes themselves were the largest source, contributing 89% of sector emissions. This includes emissions from industrial wastewater (34%), household sewage (29%), and landfills (25%). Other emissions come from waste incineration (6%) and electricity use by various waste treatment facilities (5%).

The largest share of emissions comes from industrial wastewater, primarily generated by industries such as pulp and paper manufacturing, meat processing, alcohol and starch production, organic chemical production, food processing, electronics, textile dyeing and finishing, and leather manufacturing. Methane from industrial wastewater is produced during both the aerobic and anaerobic stages of wastewater treatment, while nitrous oxide is released from nitrification and denitrification reactions. The second-largest source of emissions is household sewage, where anaerobic digestion in septic tanks produces methane. Additionally, organic matter containing substances like proteins undergoes nitrification and denitrification in water, resulting in the production of nitrous oxide. The third-largest source is landfill waste, where methane is primarily generated from the production of biogas⁶¹³.

⁶¹¹ *Ibid.*, 615.

⁶¹² *Ibid.*, 617.

⁶¹³ *Ibid.*, 615.

5.4.3 Carbon Reduction Options in the Agricultural and Waste Sectors

1. Agricultural Sector

The agricultural sector's carbon reduction options include changing traditional farming practices, addressing the increased costs associated with carbon reduction measures, and trialing carbon credit trading within the agricultural sector. Below is a summary of each option:

(1) Shifting Traditional Agricultural Practices Requires Long-term Monitoring and Trust: Scholars have pointed out that Taiwan relies heavily on conventional farming practices (refer to BOX 5.4.1), importing and using large quantities of chemical pesticides and fertilizers, which are fossil-fuel-based products. These products emit greenhouse gases during their production, transportation, and use. There are also hidden emissions that have not been fully accounted for in Taiwan's greenhouse gas inventories, such as agricultural product transportation (including imported food), food processing, and food waste⁶¹⁴. Achieving net-zero emissions will count on the cooperation of farmers, who will need to adjust their current agricultural practices, which are largely based on conventional farming methods. These adjustments include reducing or replacing the use of pesticides and fertilizers. However, the potential impact of such changes on crop yields and quality requires further research and evaluation. Additionally, since farmers have long-standing operational experience and personal considerations, building consensus among them on the net-zero transition, and guiding them towards organic, ecological, or regenerative agriculture, will be critical for the success of carbon reduction efforts.

According to Taiwan's *Basic Agricultural Statistics* for 2019⁶¹⁵, there were 775,250 farming households, covering an agricultural workforce of 2,694,472 people. Taiwan's arable land, which includes both cultivated and idle land, totaled 790,197 hectares, with 742,162 hectares actively cultivated (arable land refers to land that can be cultivated for crops, regardless of whether it is currently being

⁶¹⁴ Huang, S.-M. (2021). Taiwan's 2050 agricultural net-zero strategy to be released: Council of Agriculture plans to pilot agricultural carbon trading and price farmers' carbon reduction contributions. Environmental Information Center. <https://e-info.org.tw/node/232037>

⁶¹⁵ Council of Agriculture, Executive Yuan (2021). Agricultural statistical abstract (2020). Agricultural Statistics Data Query. <https://agrstat.coa.gov.tw/sdweb/public/book/Book.aspx>

planted). According to the *2019 Taiwan Area Farm Household Sampling Survey*⁶¹⁶, the total arable land area in Taiwan that year was 632,634 hectares. The number of farming households in Taiwan is categorized based on the size of their arable land. There are 769,063 households with farmland, of which 79.29% have less than 1 hectare, and 56.88% have less than 0.5 hectares. For the public sector, this means a significant investment of time and manpower is required to communicate with each household by region, assist with technological improvements, and monitor changes in yield and quality over time. Building a relationship of trust and cooperation with each household will be essential for the net-zero transition.

(2) Increased Costs and Lower Profit Margins: Beyond changes to farming methods, transitioning to renewable energy sources, such as green electricity, for electricity use and fuel combustion in the agricultural sector could lead to higher overall production costs for agricultural producers. The impact of these costs on the profitability of agricultural products, and whether there are support mechanisms to mitigate these effects or provide sufficient economic incentives to encourage participation, are key considerations the government must address when designing carbon reduction policies.

(3) Carbon Sink Pricing Requires Balance Between Productivity, Soil Fertility, and Fairness: To make the agricultural sector an effective carbon sink for Taiwan, the Council of Agriculture has recently been actively trialing a carbon sink pricing program in the sector⁶¹⁷. Achieving a balance between agricultural productivity, soil quality, and the rights of agricultural producers is essential. Moving forward, the government should design mechanisms with adequate communication channels and transparent information disclosure to foster consensus among all stakeholders. This will help ensure the successful implementation of the program and maximize the agricultural sector's potential as a carbon sink.

⁶¹⁶ Agriculture and Food Agency, Council of Agriculture, Executive Yuan (2020). *2019 Taiwan area farm household sampling survey report*. Agriculture and Food Agency, Council of Agriculture, Executive Yuan. <https://www.afa.gov.tw/cht/index.php?act=download&ids=117339>

⁶¹⁷ Council of Agriculture, Executive Yuan (2021). Council of Agriculture establishes dedicated net-zero office to plan and promote new climate change strategies for the agricultural sector. Council of Agriculture, Executive Yuan. https://www.coa.gov.tw/theme_data.php?theme=news&sub_theme=agri&id=8482

Box 5.4.1 Conventional Agriculture

To improve crop quality and yield, conventional farming practices primarily involve the use of chemical pesticides and fertilizers. This method of cultivation is known as conventional agriculture, also referred to as traditional agriculture.

2. Waste Sector

With the net-zero transition ahead, the waste sector in Taiwan faces several challenges in its carbon reduction efforts, including: (1) improving the relatively low wastewater treatment rate, (2) increasing the relatively low methane recovery rate, and (3) enhancing the reuse model of agricultural waste. Although Taiwan's wastewater treatment rate has improved over the years, it has yet to reach 70%, lagging behind neighboring countries like Japan (78.0%) and South Korea (92%), and far behind Singapore, which boasts a treatment rate of 99%⁶¹⁸. Among Taiwan's six municipalities, only New Taipei City and Taipei City have wastewater treatment rates close to 90%, while the other municipalities are below 70%, and the average for other counties is just 41%⁶¹⁹. Although wastewater infrastructure projects have been planned and implemented across various regions, there is still a long way to go before achieving proper disposal.

Wastewater treatment is only the first step, and methane recovery from treated wastewater and landfills is another critical component. Currently, there are minimal methane recovery mechanisms in Taiwan's wastewater treatment systems, with methane emissions from industrial wastewater reaching 0.94 Mt CO₂eq in 2018, while methane recovery was zero. Even in properly managed landfills, methane recovery for power generation only reached 0.062 Mt CO₂eq in 2018, accounting for just 10.2% of the total 0.603 Mt CO₂eq emitted, with unmanaged landfills emitting 0.12 Mt CO₂eq of methane in 2018 錯誤！尚未定義書籤。.

Table 5.4.1 provides a summary of Taiwan's residual agricultural resources for

⁶¹⁸ Huang, S.-H. (2020). The challenges of Taiwan's water resource recycling and how to achieve sustainable development. Research Portal. <https://portal.stpi.narl.org.tw/index/article/10611>

⁶¹⁹ Construction and Planning Agency, Ministry of the Interior (2021). National sewerage user connection and overall wastewater treatment rate statistics (August 2021). <https://www.cpami.gov.tw/最新消息/業務新訊/51-下水道工程處/9995-全國污水下水道用戶接管普及率及整體污水處理率統計表.html>

2020⁶²⁰. The largest categories are in-situ plowing and burial (2.184 million tons) and composting (2.538 million tons). Although these methods are defined as proper disposal by Taiwan's Council of Agriculture, over 60 wt% of organic carbon typically escapes into the atmosphere as CO₂ within a year⁶²¹, indicating that these disposal methods have a significant impact on emissions. For example, composting can be used for biogas power generation, with the remaining solids being used as fertilizer. The depth of in-situ plowing and burial, along with the duration of air exposure, also affects the amount of gas produced. Therefore, there is still significant room for improvement in the reuse practices of agricultural waste.

Table 5.4.1 Taiwan's Residual Agricultural Resources in 2020⁶²²

Unit: 10,000 tons/year

Residual Agricultural Resources	Unused Agricultural Residues	Surplus Production Materials	Livestock Manure
<i>In-Situ</i> Plowing and Burial	211.3	7.1	-
Crop Cultivation Cover	13.8	-	-
Incineration and Burial	19.3	1.3	-
Warehouse Bedding	6.0	-	-
Seedling Cultivation Medium	11.3	-	-
Compost	11.2	15.6	227.0
Feed (Raw Materials)	10.3	-	-
Livestock Housing Bedding	8.7	-	-
Firewood and Fuel	7.0	-	-
Rendering Materials	11.4	-	-
Other	3.2	-	-
Resource Recycling	-	1.9	0.2

⁶²⁰ Council of Agriculture, Executive Yuan (2021). Report on the processing and utilization of agricultural surplus resources.

⁶²¹ Weil, R. R., & Brady, N. C. (2016). Soil Organic Matter. In *The Nature and Properties of Soils* (15th ed., pp. 544-600). Harlow, England: Pearson.

⁶²² *Ibid.*, 錯誤! 尚未定義書籤。.

Innovative examples in the waste sector include the mobile containerized biomass gasification power generation system and the Yuen Foong Yu Packaging Inc.'s biogas power generation system. The mobile containerized biomass gasification power generation system, developed by the Ministry of Education's Yilan-Hualien-Taitung Regional Promotion Center, leverages the abundant biomass waste resources in eastern Taiwan (such as rice straw, pruned fruit tree branches, driftwood, bamboo waste, and forestry thinning materials). This system is not only convenient for installation in remote areas where power plants are difficult to establish but can also connect to the Taiwan Power Company's grid, giving eastern Taiwan a competitive edge in developing a biomass energy industry. It also helps cultivate local talent in biomass energy and promotes rural regeneration and energy transition⁶²³.

On the other hand, Yuen Foong Yu Packaging Inc.'s Hsinwu mill houses the largest biogas power generation system in Taiwan⁶²⁴, which began commercial operations in the third quarter of 2019, with an annual power generation capacity of nearly 20 million kWh. At the mill, process water in the pre-acidification tank forms specific organic matter, which is then introduced into anaerobic digesters as nutrients for anaerobic bacteria in sludge form. The bacteria, through anaerobic digestion, produce biogas while multiplying. The methane concentration in the biogas from the mill's anaerobic digesters reaches 80%, close to the concentration of natural gas and much higher than the 65% typical in the livestock industry. With a power generation efficiency of 40%, the electricity produced is connected to the Taiwan Power Company grid. Additionally, residual heat from the generators is reused in the papermaking process, and approximately 2,500 tons of anaerobic bacteria are sold annually.

⁶²³ Pai, Y.-H. (January 26, 2021). Turning Agricultural and Forestry Waste into Energy: Biomass Gasification Technology. Energy Education Resource Center. <https://learnenergy.tw/index.php?inter=knowledge&id=601>

⁶²⁴ Wang, I.-C. (September 16, 2019). Traditional papermaking industry transforms! Seizes green opportunities by establishing Taiwan's largest biogas power generation system. TVBS News. Source: <https://news.tvbs.com.tw/life/1201460>

5.4.4 Carbon Reduction Initiatives in Taiwan's Agricultural and Waste Sectors

1. Agricultural Sector

In response to international efforts promoting agricultural net-zero carbon policies (for global carbon reduction trends in the agricultural sector, refer to Appendix 5A), Taiwan's Council of Agriculture is exploring a carbon sink pricing program for the agricultural sector and assessing its feasibility through pilot projects⁶²⁵. The aim is to reduce carbon emissions while increasing carbon sinks. This program envisions pricing carbon sinks or carbon reduction contributions of environmentally friendly agricultural practices, allowing these to be sold to companies as carbon offsets. The revenue from these transactions would be reinvested to support sustainable agricultural practices for producers. In other words⁶²⁶, this approach focuses on enhancing the value of carbon sinks from agriculture, crops, and soil (refer to Section 3.2 on Natural Carbon Sink). Based on the aforementioned three main emission sources in Taiwan's agricultural sector, the following outlines the carbon reduction initiatives being implemented by both public and private entities:

(1) Carbon Reduction Options in Agricultural Operations

In Taiwan, some farmers have already begun researching no-till farming methods from Europe and the United States⁶²⁷. The first cover crop rollers and no-till seeders have been introduced to reduce soil tillage and cover crops during cultivation, aiming to enhance the soil's carbon fixation effectiveness.

Additionally, some farmers are using crop rotation between paddy fields and uplands to maintain soil fertility⁶²⁸. Legumes, being one of the most effective nitrogen-fixing systems in nature due to their symbiotic rhizobia, are used in rotation with rice and grains (such as soybeans and red beans), which reduces the need for fertilizers and lowers the incidence of pests and diseases, such as golden apple snails (*Pomacea canaliculata*) and rice blast.

⁶²⁵ *Ibid.*, 624.

⁶²⁶ Huang, S.-M. (2021). Taiwan's 2050 agricultural net-zero strategy to be released: Council of Agriculture plans to pilot agricultural carbon trading and price farmers' carbon reduction contributions. Environmental Information Center. <https://e-info.org.tw/node/232037>

⁶²⁷ Lin, I.-C. (2018). New trial in eco-friendly farming! The nation's first no-till seeder to hold demonstration meeting tomorrow. AgriHarvest. <https://www.agriharvest.tw/archives/12625>

⁶²⁸ AgriHarvest (2020). [High-tech agriculture leads the way] Collecting big data in fields and using automated monitoring for rice fields and uplands to scientifically save labor – Xinfeng rice mill. <https://www.agriharvest.tw/archives/49932>

Furthermore, with technologies like IoT sensors to collect field data on temperature, humidity, and other water information, farmers can remotely manage and adjust paddy water levels in real-time, minimizing methane emissions.

Research teams in Taiwan are also conducting genetic modifications to develop drought-resistant rice varieties and have restarted studies such as the cultivation of Taiwan's endemic drought- and climate-resilient species, oil millet (*Eccolopos formosanus* [Rendle] A. Camus)^{629,630}. These efforts present both direct and indirect carbon reduction options for the agricultural sector.

(2) Carbon Reduction Options for Electricity Use and Fuel Combustion

As mentioned earlier, in Taiwan's agricultural sector, the main production activities that consume electricity are greenhouses and aquaculture. Additionally, for certain transportation equipment (such as fishing vessels) and machinery (like pumps and material dryers), fuel combustion serves as the primary power source. In recent years, as part of the efforts to develop quality agriculture, producers have gradually upgraded the necessary equipment and automated various production processes, incorporating technologies such as artificial intelligence. Many transportation tools and equipment have transitioned to electric power or were already electric-powered, leading to an increase in electricity demand within Taiwan's agricultural sector.

A 2019 energy consumption survey in the agricultural sector conducted by the Bureau of Energy, Ministry of Economic Affairs⁶³¹, showed that electricity use grew by 12.1% annually from 2012 to 2017, with overall electricity consumption continuing to rise. As a result, the government is accelerating the adoption of green energy, including increasing the use of renewable energy, such as installing solar panels on fish ponds and the rooftops of farmhouses and livestock housing, and utilizing biogas produced from livestock manure for self-use in electricity generation or heat production. These initiatives are actively being assessed, planned, and implemented.

⁶²⁹ Stein, E. (2019). Achieving both drought resistance and yield: Academia Sinica team develops improved rice varieties. TechNews. <https://technews.tw/2019/11/15/mybs2-%CE%B1amy-mybs1-gf14-rice-gene-editing/>

⁶³⁰ Ku, P.-L. (2020). Globally unique, superfood of the future: Taiwan's oil millet reemerges! More nutritious than rice and wheat, with high tolerance to drought, salt, and adverse conditions. News & Market. <https://www.newsmarket.com.tw/blog/131220/>

⁶³¹ Bureau of Energy, Ministry of Economic Affairs (2019). Ministry of Economic Affairs completes five-year agricultural energy consumption survey – Quality agriculture and green energy development driving changes in agricultural energy supply and demand. Excellent Solar System Award by the Bureau of Energy, MOEA. http://www.topsolar.org.tw/show_news.php?PID=357

(3) Utilizing Agricultural and Forestry Residues for Emission Reduction

Agricultural and forestry residues, such as rice straw, grain crop residues, pruned fruit branches, forestry residues, bamboo residues, and driftwood, were traditionally disposed of through open burning, releasing large amounts of carbon dioxide and fine particulate matter (PM_{2.5}) into the environment. The resulting thick smoke further contributed to the deterioration of air quality⁶³². While burying shredded rice straw in the soil is an alternative, the straws and stalks often fail to decompose before the next planting season, reducing soil nitrogen due to microbial decomposition and producing organic acids and methane that hinder seedling growth⁶³³.

An alternative approach is to convert these residues into biochar through pyrolysis, which involves heating biomass materials like wood, leaves, or dead plants in a low or oxygen-free environment. Biochar can store carbon in solid form for centuries and act as a carbon sink when buried⁶³⁴.

For the agricultural sector, turning agricultural and forestry residues into biochar is a viable carbon reduction option. This process promotes the recycling of surplus materials, reduces air pollution and carbon emissions, and the resulting biochar can be added to soil to improve its physical and chemical properties, thereby increasing crop yields per unit of land. This approach addresses resource management, environmental protection, and economic benefits simultaneously. However, the properties of biochar vary depending on the type of residue used to produce it. Therefore, soils amended with biochar require ongoing monitoring of their chemical and biological properties to assess potential impacts^{635,636}.

⁶³² Agriculture and Food Agency, Council of Agriculture, Executive Yuan (2018). Avoid open burning of rice straw to protect air quality. Join us in this effort. https://srb.afa.gov.tw/index.php?act=article&code=print&ids=186&article_id=40504&flag=detail

⁶³³ Chang, F.-Y. (2019). The debate on burning rice straw: Farmers vs. government perspectives. CCU eNews. <https://enews.ccu.edu.tw/稻草燒不燒-農民政府看法不同-e2229a26386d>

⁶³⁴ Jiang, W. (2019). The endless potential of biochar: Offsetting one billion tons of carbon annually. Environmental Information Center. <https://e-info.org.tw/node/221739>

⁶³⁵ Chen, Y.-C., Hsu, C.-Y. & Ni, L.-F. (2018). A brief discussion on the application of biochar in agriculture. Bulletin of the Hualien District Agricultural Research and Extension Station, No. 106. https://www.hdares.gov.tw/upload/hdares/files/web_structure/12695/04.pdf

⁶³⁶ Tsai, C.-J. & Wu, K.-T. (2016). Future prospects of biochar production from agricultural waste in Taiwan. *Agricultural Biotechnology Industry Quarterly*, No. 46. http://www.biotaiwan.org.tw/mag/image_doc/46/04_臺灣農業廢棄物製備生物炭之未來與展望.pdf

2. Waste Sector

In the waste sector, waste processing technologies are largely mature. The primary reason carbon emissions have not continued to decrease effectively is due to a lack of sufficient incentives, rather than a shortage of technology (for global carbon reduction trends in the waste sector, refer to Appendix 5B). For wastewater treatment, the Upflow Anaerobic Sludge Bed (UASB) developed by the Industrial Technology Research Institute became a valuable methane recovery option from 2015⁶³⁷. It is widely used in Taiwan's photoelectronic, chemical, food, fermentation, and paper industries and has also been adopted by the food and brewing sectors in Malaysia and Vietnam. It separates the solid, liquid, and gas produced after biogas generation through a three-phase separator. The anaerobic sludge settles in the sedimentation zone and is then returned to the reactor, while the treated water is discharged. Meanwhile, the biogas is collected for use as fuel.

For landfill management, improvements do not require advanced technology. Regular maintenance of gas collection systems and proper collection of leachate is required. The government is aware of these improvement methods and has implemented several landfill enhancement projects, such as the "2019 Bali Landfill Slope and Drainage Facility Improvement Project," awarded on July 2, 2019, with a contract amount of NT\$3,171,636, and the "2021 A196 Project to Promote Advanced Household Waste Treatment Technology Support for Eight Counties with Non-Operational Incinerators (Nantou, Yunlin, Hsinchu, Offshore Islands, and Hualien-Taitung)," with tenders opened on March 22, 2021, with a budget of NT\$15 million. However, progress on these improvement initiatives has been slow, limiting their effectiveness in reducing carbon emissions. Additionally, overall management needs to be strengthened, as at least 10 landfill fires occurred in Taiwan between November 2020 and March 2021⁶³⁸.

⁶³⁷ Chang, C.-C. (April 19, 2015). ITRI becomes micron's consultant, ousting global leader. YamNews. <https://n.yam.com/Article/20150419984243>

⁶³⁸ Sun, W.-L. (March 2, 2021). Smoldering fire continues at New Taipei's Bali landfill. Environmental Protection Department: Preliminary findings indicate spontaneous combustion of dry batteries. Environmental Information Center. <https://e-info.org.tw/node/229757>

5.4.5 Policy Recommendations

To achieve Taiwan's 2050 net-zero emission target, the agricultural and waste sectors face challenges in collaborating with agricultural producers to drive behavioral and mindset changes and in adopting innovative technologies to reduce emissions during waste disposal, as well as increasing the proportion of waste reuse. Given the broad scope of these sectors—encompassing agriculture, forestry, fisheries, animal husbandry, and ecological conservation—the following key areas and directions are recommended for carbon reduction efforts:

1. The agricultural sector is tasked with ensuring Taiwan's food security. In the pursuit of reducing the use of chemical pesticides and fertilizers and adopting other farming practices that maintain soil fertility, it is crucial to carefully evaluate how to achieve both net-zero emissions and food security. Additionally, methane emissions can be reduced through improvements in livestock feed, and domestic rice genetic modification also holds potential for emission reductions, though it may not meet reduction targets in the short term. Overall, the key challenge lies in motivating agricultural producers to adopt low-carbon farming practices, leveraging already mature carbon reduction technologies within the agricultural sector.
2. Achieving net-zero emissions in the agricultural sector's electricity use and fuel consumption requires replacing fossil fuels with renewable energy and bioenergy, or transitioning machinery and equipment to electrification and automating production environments powered by green energy. This would further enhance emission reduction results. To accelerate the adoption of renewable energy, existing agricultural operations can integrate green energy solutions, such as installing solar panels on fish ponds and the rooftops of barns and stables, or using biogas generated from livestock waste for electricity or heat production.
3. Properly managing and converting agricultural and forestry residues into biochar not only promotes resource regeneration but also reduces air pollution and carbon emissions. Moreover, adding biochar to soil improves its physical and chemical properties, boosting crop yields per unit of land, thereby achieving a synergy of resource conservation, environmental protection, and economic benefits.
4. To fully utilize the natural carbon sink potential of the agricultural sector,

Taiwan should continue advancing its agricultural carbon sink pricing program, while adopting verification methods from international organizations such as the United Nations Clean Development Mechanism (CDM) to help farmers apply for carbon offset credits and lay the foundation for a carbon trading mechanism^{639,640}. The goal is to establish effective nature-based carbon sink solutions through appropriate economic incentives and a fair, transparent carbon trading mechanism for the agricultural sector, helping to alleviate Taiwan's reliance on carbon-free energy during its transition to net-zero emissions.

5. To enhance methane recovery incentives in the waste sector, companies and farmers could be rewarded with additional electricity discounts for every kWh of electricity generated from biogas produced from wastewater or agricultural waste. Public wastewater facilities and landfills should set annual targets to reduce methane emissions, ensuring that the fugitive emission rate decreases year by year. Taiwan's waste-related greenhouse gas emissions primarily come from wastewater treatment, landfills, and the improper use of agricultural waste. For example, the largest biogas power generation system in Taiwan has been built by the Yuen Foong Yu Packaging Inc. using wastewater from paper production, while methane collection for power generation at landfills has been implemented for years⁶⁴¹. While the technology for methane collection and utilization is highly mature, further research is needed for low-flux, low-concentration methane collection and utilization. For instance, Taiwan's National Greenhouse Gas Inventory has shown zero methane removal from industrial wastewater for decades, and methane power generation utilization rates for properly managed landfills remain around 10 wt%, with the remaining 90 wt% being released into the atmosphere. Composting also leads to a carbon fugitive emission rate of over 60 wt%.

The government should invest in R&D of cutting-edge technologies, bringing together experts from fields such as biology and chemical engineering, to develop

⁶³⁹ Chen, H.-P. (2022). Minister of the Council of Agriculture, Chi-Chung Chen, Faces climate change head-on: Moving toward agricultural net-zero emissions. Harvest Magazine, April 2022. AgriHarvest. <https://www.agriharvest.tw/archives/79644>

⁶⁴⁰ Council of Agriculture, Executive Yuan (2022). Minister Chi-Chung Chen: Taiwan's agricultural carbon credit industry estimated to generate NT\$7.5 billion annually. Agriculture Science & Technology Decision-Making Information Platform. <https://news.ltn.com.tw/news/life/breakingnews/3862149>

⁶⁴¹ Chang, C.-Y. (2014). Exploring the effectiveness of landfill biogas power generation by the Environmental Protection Bureau, Kaohsiung City. Environmental Protection Bureau, Kaohsiung City. <https://ksepb.kcg.gov.tw/FileDownload/FileUpload/20191027121536893437.pdf>

practical solutions for collecting and utilizing low-flux, low-concentration methane, effectively reducing methane carbon emissions in the relevant sectors. Additionally, the government should also introduce policy incentives, such as offering proportional electricity discounts to companies or farmers who generate electricity from biogas produced from wastewater or agricultural waste to meet part of their energy needs. Public sector entities that do not operate for profit should directly set targets to ensure all landfills are properly managed as quickly as possible, with landfill leachate fully recovered, and methane power generation utilization rates at public wastewater treatment facilities and landfills increased year by year.

5.5 Conclusion

Based on Taiwan's 2019 greenhouse gas emissions statistics, the transportation sector emitted approximately 37 Mt CO₂eq, accounting for around 12.9% of total emissions, primarily from road transport. The residential and commercial sectors' emissions stood at 57.7 Mt CO₂eq, making up about 20.1% of total emissions, largely from electricity consumption in residential buildings and various service industries. The agricultural sector emitted about 6.0 Mt CO₂eq, or 2.1% of total emissions, primarily from farming, livestock, and forestry activities. The waste sector accounted for 2.9 Mt CO₂eq, representing 1% of total emissions. The combined emissions from the transportation, residential/commercial, agricultural, and waste sectors total 103.6 Mt CO₂eq, accounting for approximately 36.1% of Taiwan's total emissions—a significant portion that cannot be overlooked. To achieve the 2050 net-zero greenhouse gas emissions target, the following are recommended zero-carbon initiatives for each sector.

In the transportation sector, Taiwan should align with international trends by transitioning toward full electrification, with a particular focus on the road transport system as the primary source of greenhouse gas emissions. To support this shift, it is recommended to establish extensive charging station networks, fostering the electrification of cars and motorcycles and increasing public willingness to adopt electric vehicles. During the transitional period toward full electrification, regulations on renewable fuels should be established to reduce fossil fuel usage and lower emissions. Additionally, promoting and expanding public transportation infrastructure will play a crucial role in substantially reducing greenhouse gas emissions, and incentivizing public transit infrastructure and usage will help curb excessive reliance on private vehicles. Finally, low-carbon fuels should be prioritized for the aviation and maritime industries as they move toward electrification to facilitate significant emission reductions.

Taiwan's transportation sector should align with international trends by fully transitioning to electrification. The primary source of greenhouse gas emissions in this sector is the road transport system. As the global market increasingly electrifies cars and motorcycles, it is recommended to establish extensive charging station networks and encourage public adoption of electric vehicles. During the transition to full electrification of transport vehicles, implementing regulations on renewable fuels and promptly establishing usage standards for these fuels would help reduce fossil fuel

dependency and lower carbon emissions. Additionally, expanding and promoting public transportation is essential for significantly reducing greenhouse gas emissions; encouraging the development and use of public transit options will help limit the overuse of private vehicles. Finally, in the aviation and maritime industries' path toward full electrification, the rapid development of low-carbon fuels should be prioritized to support substantial reductions in carbon emissions.

In the residential and commercial building sectors, the main sources of emissions are the production of building materials and daily energy consumption. It is recommended to implement retrofits and renovations for existing buildings, such as through lightweight construction materials, extending building lifespans, and using wooden structures in place of steel and concrete to reduce emissions from building material production. Additionally, to reduce emissions associated with air conditioning electricity use, investment should be made in developing emerging cooling system technologies. Infrastructure development should incorporate smart energy management systems and flexible power dispatching to optimize energy efficiency and achieve maximum carbon reduction outcomes.

In the agricultural and waste sectors, emissions primarily stem from agricultural operations and waste processing. To address this, it is recommended that agricultural producers adopt low-carbon farming practices and transition from traditional farming methods to maximize carbon reduction. Additionally, agricultural, forestry, fishery, and livestock equipment should undergo full electrification, integrating green energy technologies where possible. Proper management of agricultural and forestry residues can further support carbon reduction; converting these residues into biochar for soil enhancement not only improves crop yields but also reduces air pollution and carbon emissions. Finally, investment in advanced methane collection and power generation technologies is essential, along with incentives for businesses and farmers to promote methane recovery from waste.

Chapter 6 Breakthrough Technologies

Sections

6.1 Introduction

6.2 Direct Air Capture (DAC)

6.3 Biological and Chemical CO₂ Utilization Technologies

6.4 Future Nuclear Technology

6.5 Conclusion

6.1 Introduction

Previous chapters have discussed technologies with the potential to help reduce carbon emissions in different fields. This chapter will focus on some forward-looking and breakthrough technological developments that, if they succeed, could have a significant impact on the progress of carbon reduction. Based where in the cycle these technologies can be used, they can be roughly divided into back-end treatment technologies and front-end prevention technologies. Back-end treatment technologies aim to reduce the concentration of carbon dioxide (CO₂) in the atmosphere, while front-end prevention technologies work to prevent carbon emission at the source, by developing new energy or energy-saving technologies⁶⁴². The breakthrough technologies to be discussed in this chapter include direct air capture (DAC) and biological/chemical/electrochemical CO₂ utilization, which are considered back-end treatment technologies, as well as future nuclear technology, which is considered to be a front-end prevention technology.

The idea of capturing CO₂ was proposed years ago. Basically, the idea is to use solvent or sorbent material to capture CO₂ in the air (including industrial waste gas). The success of CO₂ capture depends on (1) the contact area of CO₂ when it passes through the capture agent, (2) the ability of the agent to capture CO₂, and (3) the economic benefits of the capture process. Compared with liquids, atoms in gases are much more spread out. It is thus critical to increase the likelihood for the capture agent to come in contact with CO₂. Large-scale DAC is only possible if one can develop a capture process with high adsorption efficiency and economic benefits. CO₂ captured through DAC can be processed biologically, chemically and electrochemically and converted to various chemical feedstocks, which can further reduce human beings' dependence on petrochemical materials. Most plants or microorganisms can convert CO₂ into biomass through photosynthesis, but plants also release CO₂ through respiration. Biological utilization aims to harness the carbon fixation mechanism of organisms. On the other hand, chemical utilization needs to find reactions with higher efficiency. At present, chemical utilization requires the addition of reducing agents, such as hydrogen, for the reaction. Hence, it is important to determine if the production

⁶⁴² Sanz-Pérez, E.S., Murdock, C.R., Didas, S.A., & Jones, C.W. (2016). Direct capture of CO₂ from ambient air. *Chem. Rev.*, 116(19), 11840-11876. <https://pubs.acs.org/doi/10.1021/acs.chemrev.6b00173>

of hydrogen will lead to carbon emissions. Electrochemical carbon dioxide reduction can produce other chemicals, but the electricity used must come from green electricity; otherwise, the use of conventional electricity will lead to more carbon emissions and defeat the purpose of carbon sequestration. In short, the availability of green electricity plays an important role in the application of electrochemical utilization of carbon dioxide.

Although most people in Taiwan have doubts about the use of nuclear energy, the truth is after decades of development, the safety of new nuclear technology is very different from the technology used in existing nuclear power plants operating in Taiwan. This chapter will focus on the development of the latest nuclear fission technology, specifically the development of the Generation IV reactor. In addition, as the chances of commercializing nuclear fusion technology increase, this chapter will also discuss the latest developments in nuclear fusion technology and make policy recommendations on the commercialization of nuclear fusion technology and the international industrial chain. The following sections will discuss the above-mentioned breakthrough technologies in detail.

6.2 Direct Air Capture (DAC)

Summary

Direct air capture (DAC) is an innovative technology that can remove carbon dioxide (CO₂) from the atmosphere. As it is very challenging, only some pilot plants abroad are carrying out experiments. In addition, the operation of DAC systems will consume a certain amount of energy, so apart from costs, it is also important to consider the carbon emissions from the source of energy used (green energy or fossil fuels) to ensure that the capacity of the DAC system is higher than the carbon emissions from energy consumption to achieve net-zero or negative emissions. Compared with traditional CCUS, a DAC system can be installed at a suitable location to store carbon and limit the cost of long-distance transportation. If we can reduce the cost of DAC and the problem of high energy consumption, DAC has the potential to become a competitive negative emissions technology in the future. Considering Taiwan's situation, our recommendations are as follows:

1. Promote the development of DAC and invest in research and development of DAC that can reduce energy consumption and costs through international collaboration and technology exchange.
2. Once the issues of high costs and energy consumption of DAC can be solved, Taiwan can then initiate research on the utilization of carbon captured or explore suitable locations for carbon storage.

6.2.1 Introduction

Direct air capture (DAC) is a technology that can capture CO₂ directly from the air. High-concentration CO₂ can then be permanently stored in deep geological structures or used for food processing. CO₂ can also be combined with hydrogen to produce synthetic fuels. Generally speaking, if the exhaust gas emitted has a high concentration of CO₂, for instance, from natural gas processing plants, the cost to capture CO₂ is lower (25 USD/tCO₂eq). However, if the concentration of CO₂ in the exhaust is low, the cost to capture CO₂ will be higher. For power plants and cement plants, the cost to capture CO₂ is above 50 USD/tCO₂eq and the cost of DAC is above 300 USD/tCO₂eq⁶⁴³. According to a research report from the International Energy

⁶⁴³ IEA (2021). Is carbon capture too expensive? <https://www.iea.org/commentaries/is-carbon-capture-too-expensive>

Agency (IEA), there are currently 19 DAC plants around the world that can capture more than 0.1 Mt of CO₂ per year. To reach net zero emissions by 2050, CO₂ captured through DAC technology will need to exceed 90 Mt CO₂eq/year by 2030, and the capture volume will need to reach 985 MtCO₂eq/year by 2050⁶⁴⁴. Hence, it will be necessary to expand the scale of DAC infrastructure, improve DAC technology development and reduce the costs of carbon capture to achieve the outcome of net-zero or negative emissions.

6.2.2 Case Studies of Different Types of DAC

DAC technologies can be categorized into solid and liquid-based systems. The solid-based system primarily uses sorbent filters that can chemically bind with CO₂. The CO₂ will be heated to increase the concentration. At present, different companies have different rates of progress. For example, Climeworks AG of Switzerland and Carbfix of Iceland have completed the demonstration phase of their DAC systems.

Liquid-based systems (known as Liquid DAC) uses a chemical solution (such as potassium hydroxide) to draw in CO₂. The CO₂ captured will be released (via heating) to interact with chemical substances. At present, some Liquid DAC technologies are still in the demonstration phase while others have started to be commercialized. (Figure 6.2.1)⁶⁴⁵

⁶⁴⁴ IEA (2021). *Net zero by 2050: A roadmap for the global energy sector*. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroBy2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

⁶⁴⁵ Climeworks (2020). The rapid construction of Climeworks' new direct air capture and storage plant Orca has started. <https://climeworks.com/news/climeworks-makes-large-scale-carbon-dioxide-removal-a-reality>

	Principle	Case	Status	Cost & Energy Consumption
Liquid-based	Air passes through a chemical solution (e.g. potassium hydroxide) to adsorb CO ₂ (>850°C)	Carbon Engineering, Canada	Demonstration to Commercialization	- Renewable energy 1,500kWh/ton - Cost 100 USD/ton
Solid-based	Sorbent filters adsorb CO ₂ , which is then heated to increase the concentration (80-100°C)	- Climeworks, Switzerland - Soletair Power, Finland - Global Thermostat, US - MechanicalTree, US	Demonstration to Commercialization	- Electricity 650kWh & thermal energy 2000 kWh/ton - Cost 100-200 USD/ton or higher

Figure 6.2.1 The Mechanisms, Cases, Status, Cost and Energy Consumption of DAC^{646,647}

1. Solid-Based DAC

Climeworks AG of Switzerland and Carbfix of Iceland completed the construction of Orca, the world's largest DAC and storage plant located in Iceland, in September 2021. CO₂ is stored safely in nearby basaltic rock formations to be turned into stone. Orca is expected to store 4,000 tons of CO₂ per year (Figure 6.2.2). DAC facilities draw the air in through a fan located inside a collector. When the air passes through a filter with porous particles in the collector, CO₂ will be trapped by the filter. Once the filter is full of CO₂, the collector will be closed and the temperature will be raised to 80 to 100 degrees Celsius to release high-concentration CO₂. The concentrated CO₂ will be subsequently stored underground or used as raw material to produce fuel via chemical synthesis, as shown in Figure 6.2.3. The source of energy (for fan operation and heating up to 100 degrees Celsius) mainly comes from renewable energy (or factory waste heat) from the Hellisheiði geothermal power plant in Iceland. Capturing 1 metric ton of CO₂ will consume 600 kWh of electricity and 1.8 to 2.5 kWh of thermal energy. At present, the cost is about 500 to 600 USD/tCO₂eq, and it is hoped that the cost will drop to 200 to 300 USD/tCO₂eq in 2030^{648,649,650,651}. According to research published by the

⁶⁴⁶ Viebahn, P., Scholz, A., & Zelt, O. (2019). The potential role of direct air capture in the German Energy Research Program - Results of a multi-dimensional analysis. *Energies*, 12(18), 3443. <https://doi.org/10.3390/en12183443>

⁶⁴⁷ Chalmin, A. (2021). Quarterly review #3: DAC & CCUS developments in 2021. geoengineeringmonitor.org/2021/12/quarterly-review-3-geoengineering-developments-in-2021/

⁶⁴⁸ Chuang, D. (2021). The world's largest CCS plant to be completed in Iceland, turning 4,000 tons of CO₂ into rocks every year. TechNews. <https://technews.tw/2021/09/09/direct-air-capture/>

⁶⁴⁹ Reuters (2021). World's largest plant capturing carbon from air starts in Iceland. <https://www.reuters.com/business/environment/worlds-largest-plant-capturing-carbon-air-starts-iceland-2021-09-08/>

⁶⁵⁰ McQueen, N., Gomes, K. V., McCormick, C., Blumanthal, K., Pisciotto, M., & Wilcox, J. (2021). A review of direct air capture (DAC): Scaling up commercial technologies and innovating for the future. *Prog. Energy*, 3, 032001. <https://iopscience.iop.org/article/10.1088/2516-1083/abf1ce/pdf>

⁶⁵¹ Doyle A. (2021). Feature-firms sucking carbon from air see boost from 'code red' climate crisis. Thomson Reuters Foundation. <https://www.reuters.com/article/climate-change-carboncapture-idUSL8N2QF2PA>

Lamont-Doherty Earth Observatory at Columbia Climate School in 2021, if easily available low-cost minerals can be used to passively react with and capture atmospheric CO₂, it is expected that the cost and energy consumption of existing DAC technologies can be reduced. When limestone (calcium carbonate, CaCO₃) is heated, we can obtain calcium oxide (CaO) and CO₂. This principle is applied to store or reuse CO₂ while the calcium oxide produced can absorb atmospheric CO₂ and convert it to limestone, so calcium oxide can be used to remove atmospheric CO₂. At present, laboratory tests can convert 75% of calcium oxide into limestone in less than two weeks. The process is really simple, so it is indeed possible to remove CO₂ at low cost⁶⁵². This technology is currently being developed by Heirloom Carbon Technologies in California. Hopefully, through the recycling of calcium oxide and calcium carbonate, it will be possible to remove 1 billion tons (1 Gt) of atmospheric CO₂ by 2035⁶⁵³.

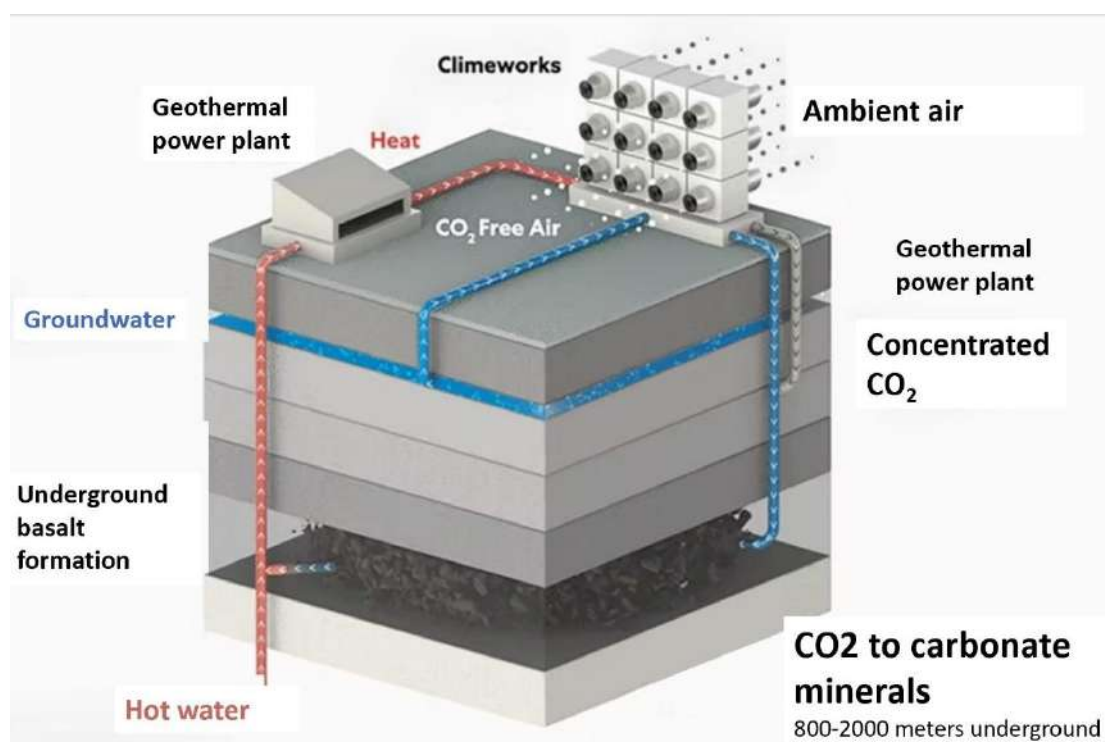


Figure 6.2.2 DAC and Underground Carbon Mineralization in Basalt Developed by Climeworks AG of Switzerland and Carbfix of Iceland⁶⁵⁴

⁶⁵² Aronsohn, M. D. (2022). Clearing the air: Decarbonization technologies take a giant step forward. <https://news.climate.columbia.edu/2022/01/06/clearing-the-air-decarbonization-technologist-take-a-giant-step-forward/>

⁶⁵³ *Ibid.*, note 652.

⁶⁵⁴ Climeworks (2022). How Climeworks does CO₂ removal. <https://climeworks.com/company-gifts>

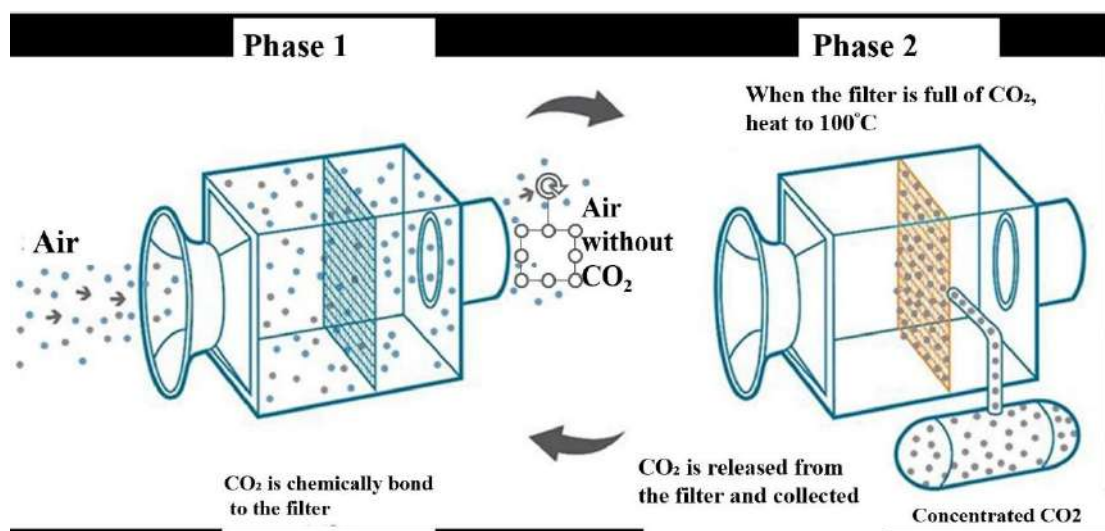


Figure 6.2.3 DAC Technology of Climeworks AG⁶⁵⁵

Soletair Power, a Finnish company, uses electricity generated by solar power and amine particles to absorb atmospheric CO₂. After going through a thermal cycle (120 degrees Celsius), CO₂ in the amine particles is released and stored. Hydrogen is produced through electrolysis of water and sent to the methanation reactor, so hydrogen will react with CO₂ to produce methane, as well as other liquid and solid hydrocarbons⁶⁵⁶.

Global Thermostat's DAC technology uses porous materials to fix amine adsorbents and capture atmospheric CO₂. The CO₂ captured is then stored underground or used to manufacture chemicals, consumer products or building materials. The release and collection process uses low-temperature steam (100 to 130°C), so ideally, Global Thermostat can work with nearby factories or power plants to obtain low-temperature or free waste heat^{657,658}. For example, Global Thermostat signed a joint development agreement with ExxonMobil in 2019 to build an industrial-scale plant for Global

⁶⁵⁵ Beuttler, C., Charles, L., & Wurzbacher, J. (2019). The role of direct air capture in mitigation of anthropogenic greenhouse gas emissions. *Frontiers in Climate*, 1, 10. <https://www.frontiersin.org/articles/10.3389/fclim.2019.00010/full>

⁶⁵⁶ Vázquez, FV, Koponen, J., Ruuskanen, V., Bajamundi, C., Kosonen, A., Simell, P., Ahola, J., Frilund, C., Elfving, J., Reinikainen, M., Heikkinen, N., Kauppinen, J., Piermartini, P. (2018). Power-to-X technology using renewable electricity and carbon dioxide from ambient air: SOLE TAIR proof-of-concept and improved process concept. *Journal of CO₂ Utilization*, 28, 235-246. <https://www.sciencedirect.com/science/article/pii/S2212982018305213#fig0005>

⁶⁵⁷ Chichilnisky, G. (2019). Direct air capture: The key to reversing climate change. The Digest. <https://www.biofuelsdigest.com/bdigest/2019/11/20/direct-air-capture-the-key-to-reversing-climate-change/>

⁶⁵⁸ Hai-chen Lin (2018). Trends of energy--Briefing on carbon reduction and clean coal. Establishing and strengthening the mechanism to manage the performance of the National Energy Program (NEP) and exploring issues on energy technologies (unpublished).

Thermostat to use its DAC technology to capture and concentrate CO₂ emitted from industrial sources (including exhaust of power plants and CO₂ in the atmosphere). At the same time, the waste heat from the plant is used to release CO₂ from the adsorbent after the capture process⁶⁵⁹. This technology is also designed in a way to ensure that the factory uses the heat from large-scale solar panels and turns solar farms into carbon sinks. The captured CO₂ is sold to increase profit. With a suitable business model, it is possible that the DAC facility can be self-sustainable and even make a profit without government subsidies or carbon credits^{660,661}.

Carbon Collect Limited (formerly Silicon Kingdom Holdings, SKH) in Dublin, Ireland, collaborated with Arizona State University in the United States to develop MechanicalTree for direct air capture air). The captured CO₂ can be stored or released to be reused to make synthetic fuels, enhance oil recovery or be used in the food and beverage or agricultural industries. Unlike other DAC technologies, the MechanicalTree acts like a tree. The system does not use any energy-intensive equipment to draw air into the system. Instead, the system simply captures atmospheric CO₂ when the wind blows through the system from any direction. It is considered to be a passive solution with relatively low costs and suitable for large-scale deployment. Evaluation of this technology shows that it can significantly reduce the concentration of atmospheric CO₂ and help combat global climate change. At present, Carbon Collect Limited has built 1,200 MechanicalTrees in California, which are expected to capture 36,500 tons of CO₂ in a year. When MechanicalTree can be commercially deployed on a large scale in the future, the cost is expected to be less than 100 USD/tCO₂eq^{662,663}.

2. Liquid-Based DAC

The air capture technology developed by Canadian company Carbon Engineering is divided into two parts: (1) Air is drawn into a contactor unit to meet a liquid sorbent running across a PVC structure. Once the sorbent reacts with CO₂ molecules in the air, a carbonate solution is formed, and CO₂ is captured from the air. (2) The CO₂-rich

⁶⁵⁹ *Ibid.*, note 錯誤! 尚未定義書籤。

⁶⁶⁰ Global Thermostat (2018). A unique capture process. <https://globalthermostat.com/a-unique-capture-process/>

⁶⁶¹ *Ibid.*, note 665.

⁶⁶² ASU News (2021). Carbon Collect's MechanicalTree selected for US Department of Energy Award. <https://news.asu.edu/20210702-carbon-collect-mechanicaltree-selected-us-department-energy-award>

⁶⁶³ ASU News (2019). Popular science picks ASU professor's 'MechanicalTree' as a 2019 top technology. <https://news.asu.edu/20191205-popular-science-picks-lackner-mechanicaltree-2019-top-technology>

sorbent will then go through a series of chemical processes to increase its concentration and purity. The CO₂ can also be compressed to be delivered as gas for further use or storage⁶⁶⁴.

6.2.3 Case Studies of DAC Technology with Mineralization for Storage

A startup company based in Oman called 44.01⁶⁶⁵ began to collaborate with Climeworks in May 2021. Under natural conditions, peridotite reacts with CO₂ and water to form carbonate⁶⁶⁶. The same principle is applied in the project. CO₂ is captured with DAC technology in Oman and the captured CO₂ reacts with water vapor to form carbonated water, which is then transported underground through a drilling well to react with peridotite to form carbonate and mineralize. Engineering technology is used to accelerate the reaction, hoping to remove CO₂ from the atmosphere and store it permanently in solid form^{667,668}.

Peridotite is a dense igneous rock rich in olivine and pyroxene, usually found 20 kilometers below the Earth's surface or deeper. Peridotite is the dominant rock of Earth's mantle, but may also exist on the Earth's surface, such as the easternmost point of the Arabian Peninsula and the northern coast of Oman. Plate tectonic movements had resulted in hundreds of square miles of peridotite exposed at the surface. Since 2006, researchers from the Lamont-Doherty Earth Observatory at Columbia Climate School of the United States have used peridotite exposed on the Earth's surface as a research material to test the possibility of using peridotite in Oman for mineralization and carbon storage. They found that it is possible to use certain strategies to accelerate CO₂ mineralization and storage in peridotite and reduce the overall costs⁶⁶⁹.

One of the innovative strategies adopted by 44.01 for CO₂ mineralization and storage is to provide CO₂ with a higher concentration than those found in the atmosphere. This is the main reason why 44.01 collaborated with Climeworks. In addition, 44.01 also uses drilling to maximize the mineral reactive surface area. A third

⁶⁶⁴ Carbon Engineering (2021). Our technology. <https://carbonengineering.com/our-technology/>

⁶⁶⁵ 44.01 is the molecular mass of CO₂, and the company name.

⁶⁶⁶ This type of carbonate, such as calcite, is a stable form of calcium carbonate and is a common and harmless mineral.

⁶⁶⁷ TechCrunch (2021). 44.01 secures \$5M to turn billions of tons of carbon dioxide to stone. <https://techcrunch.com/2021/08/10/44-01-secures-5m-to-turn-billions-of-tons-of-carbon-dioxide-to-stone/>

⁶⁶⁸ *Ibid.*, note 652.

⁶⁶⁹ Jidong Zhao (2008). Research showed that the carbonation of peridotite can absorb carbon dioxide. Chinese National Science Digital Library, Chinese Academy of Sciences. <http://www.llas.cas.cn/kxjckbzb/dqkxjzj/201412/P020141215634848928013.pdf>

strategy is to use locally generated solar energy and biofuels to power the facilities for mineralization and storage and reduce the cost of fuels. 44.01 hopes to reach the goal of mineralization and storage of 1 billion tons (1 Gt) of CO₂ by 2040⁶⁷⁰.

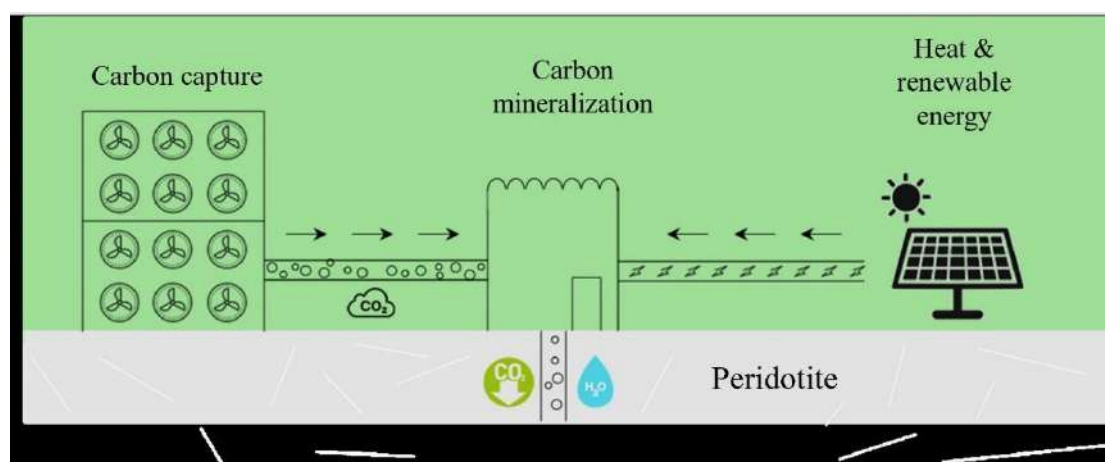


Figure 6.2.4 44.01 Works with Climeworks to Use DAC in Combination with Carbon Mineralization and Storage⁶⁷¹

6.2.4 Policy Recommendations

At present, some (chemical-based) DAC systems can already effectively capture CO₂ if used in combination with sufficient zero-carbon electricity or low-cost waste heat (from the manufacturing processes). With a suitable business model, DAC developers have demonstrated that the systems are affordable and even profitable without government subsidies or carbon credits. Compared with traditional carbon capture, utilization, and storage (CCUS) technology, DAC systems do not need to be set up in areas near the emission sources, so there is greater flexibility when we need to choose a location. Hence, DAC technology can help Taiwan expand its capacity for carbon capture. It is recommended that the government provides appropriate funds to support relevant research to promote the development of DAC technology that can reduce energy consumption and costs with international research outcomes as the benchmarks.

The captured CO₂ can be reused or stored, as already discussed in Sections 3.3 and 6.3 of this report. This section will focus on comparing the differences between DAC and carbon storage in traditional CCUS (see Section 3.3 for details). Traditional CCUS captures CO₂ emitted from power plants or flue gas. This approach can capture CO₂ of

⁶⁷⁰ Ibid., note 錯誤! 尚未定義書籤。.

⁶⁷¹ Ibid., note 錯誤! 尚未定義書籤。.

higher concentration with lower capture cost. However, if the CO₂ captured cannot be reused on-site, it will be necessary to transport the CO₂ to a storage site through pipelines and other methods. Hence, it is essential to choose storage sites close to power plants/factories with CCUS to reduce the cost of transportation. In Taiwan, depleted gas and oil reservoirs to be used for CCUS are in set locations, so it is not possible to ensure that these reservoirs are close to industrial zones with high emissions. If Taiwan wants to ensure that industrial zones are close to the reservoirs, it will be necessary to find suitable sites along the coastal or offshore areas, which will lead to the issues of coastal surveys, as well as higher development risks and exploration costs. As mentioned earlier, DAC systems do not need to be set up near the emission sources, so such systems boast greater flexibility as it is possible to set up the system next to the storage site. CO₂ captured via DAC can be stored on-site to greatly reduce the costs of communicating with society and transportation for the installation of pipelines. At the same time, like biomass carbon sinks, DAC technology has the potential to develop a business model for cross-border carbon removal⁶⁷². In short, if the existing challenges of high cost and energy consumption of DAC can be overcome, and suitable ways of storage or utilization can be found, DAC can be regarded as an effective technology for carbon reduction.

⁶⁷² *Ibid.*, note 錯誤! 尚未定義書籤。.

6.3 Biological and Chemical CO₂ Utilization Technologies

Summary

Whether the goal is net-zero or even net-negative emissions, captured carbon dioxide (CO₂), directly from the atmosphere or from flue gas, needs an appropriate destination. In addition to sequestration, CO₂ utilization is an important approach. The utilization requires CO₂ reduction first, which can be achieved by means of biological, chemical, or electrochemical (photoelectrochemical) processes. After reduction, CO₂ can be converted into various chemical raw materials to replace some fossil-based raw materials, further reducing CO₂ emissions while synthesizing high-value chemicals. In consideration of the various factors in Taiwan, it is recommended to continuously promote the development of CO₂ utilization technologies in the long term, including biological, chemical, and electrochemical (photoelectrochemical) methods, as well as conversion technologies that combine different approaches to produce high-value chemicals.

6.3.1 Preface

Current socioeconomic progress heavily relies on fossil fuels, gravely hindering efforts towards energy conservation and emission reduction. In 2019, Taiwan's total greenhouse gas emissions reached 287 Mt CO₂eq, with carbon dioxide accounting for the largest share at 95.28%⁶⁷³. The CO₂ emissions from energy combustion in the industrial sector (including allocated electricity consumption) accounted for nearly 50% of the total emissions from fuel combustion (48.74% in 2020). Since the vast majority of industrial products are derived from the use of fossil fuels, and some of the manufacturing processes require energy-intensive synthetic procedures, it results in a substantial carbon footprint. In Europe, the production and use of 26 chemical raw materials alone account for 75% of total energy consumption in the chemical industry and over 90% of its GHG emissions (150 million metric tons or 150 Mt). If the growth trajectory continues, these compounds are projected to generate 200 million metric tons (200 Mt) of CO₂eq emissions by 2050⁶⁷⁴.

⁶⁷³ Environmental Protection Administration, Executive Yuan (2021). *National GHG inventory report, Republic of China (2021 Version)*. https://unfccc.saveoursky.org.tw/nir/tw_nir_2021.php

⁶⁷⁴ Boulamanti, A., & Moya, J. A. (2017). *Energy efficiency and GHG emissions: Prospective scenarios for the chemical and petrochemical industry*. EUR 28471 EN, doi:10.2760/20486

In 2017, the extraction and processing of fossil fuels consumed a total of 1.2 billion tonnes (1,200 Mt) of oil equivalent and emitted 1.5 billion tonnes (1,500 Mt) of carbon dioxide^{675,676}. Carbon dioxide must first be reduced before utilization. Reduction methods include biological, chemical, and electrochemical approaches. These methods require long-term investment to improve reaction efficiency and energy consumption so as to become effective carbon reduction tools in the future. Relevant explanations are provided as follows in this section.

6.3.2 Future Technologies for CO₂ Utilization

1. Biological CO₂ Utilization Technology

At present, CO₂ in the atmosphere is converted through photosynthesis by plants or microorganisms into organic compounds. This is the most effective method of carbon capture from the air. During photosynthesis, carbon fixation occurs when plants or microorganisms absorb and use sunlight as energy, along with carbon-fixing enzymes (such as Ribulose-1,5-bisphosphate carboxylase/oxygenase, RuBisCO) to fix and convert CO₂ into organic carbon stored in plant bodies.

Biological carbon fixation technologies are characterized by their mild reaction conditions, product specificity, and the diversity of long-chain carbon products they generate. Combined with the emerging metabolic engineering and synthetic biology in recent years, carbon dioxide can be converted into a variety of metabolites, which can then be transformed into various chemical raw materials or plastic monomers. The successful industrial examples currently include the production of ethanol, butanol, isobutanol, lactic acid, 1,3-propanediol (1,3 PDO), 1,4-butanediol (1,4 BDO), and succinic acid. Numerous other examples have been demonstrated in laboratory and pilot plant settings. In theory, biological methods could convert CO₂ or bio-based raw materials into a wide range of chemicals.

The limitations of current bio-based CO₂ utilization technologies mainly lie in rate, efficiency, and scalability. Rate limitations primarily stem from the characteristics of biological growth. Nevertheless, in theory, microorganisms can be modified to enhance the rate, or the process can be scaled up linearly using enzymes in a cell-free

⁶⁷⁵ IEA (2018). The future of petrochemicals: Towards more sustainable plastics and fertilisers. <https://webstore.iea.org/the-future-of-petrochemicals>

⁶⁷⁶ Luna, P. D., Hahn, C., Higgins, D., Jaffer, S. A., Jaramillo, T. F., & Sargent, E. H. (2019). What would it take for renewably powered electrosynthesis to displace petrochemical processes? *Science* 364, 350. doi: 10.1126/science.aav3506

environment. Nonetheless, several technical hurdles remain to be overcome. Efficiency limitations arise because RuBisCO, the primary carbon-fixing enzyme, is affected by oxygen in the environment, leading to photorespiration that reduces carbon fixation efficiency. Moreover, plants and microorganisms exhibit significant carbon fixation effects only during daytime photosynthesis, while nighttime respiration releases carbon dioxide, further limiting the overall efficiency⁶⁷⁷. To address these limitations, two different artificial carbon fixation cycles have been created and published recently^{678, 679}. Both employ oxygen-insensitive carbon-fixing enzymes, combined with enzymes from other microorganisms, to eliminate the interference of respiration. Furthermore, these pathways utilize only biological enzymes instead of entire microorganisms, thereby circumventing the limitations imposed by plant cell growth periods and achieving high carbon fixation efficiency. One of the two published artificial carbon fixation cycles was designed and published by the Academia Sinica in Taiwan. This cycle surpasses the efficiency of photosynthesis in plants and can convert CO₂ into reusable chemicals, not only reducing carbon emissions but also increasing carbon sinks. However, the operating costs in the use of artificial carbon fixation pathways remain high. To realize the goal of large-scale application, it is necessary to reduce enzyme purification costs, increase enzyme stability, extend the effective period, and improve coenzyme regeneration cycles.

2. Chemical CO₂ Utilization Technologies

Chemical methods can also be used to reduce CO₂, primarily by utilizing hydrogen to reduce carbon dioxide into single-carbon organic molecules such as methane, methanol, formic acid, or carbon monoxide (Figure 6.3.1), before used to produce chemical raw materials. The main limitations of this method are the source of zero-carbon hydrogen and the bottlenecks in chemical conversion technology. The current technological developments allow for the production of acetic acid from carbon monoxide and methanol. However, the current acetic acid production in Taiwan is 0.75 million tonnes (Mt), accounting for only a small portion of CO₂ emissions. If CO₂ is

⁶⁷⁷ See also the related news report: Hsieh, P.-H. (2022). President of Academia Sinica, James Liao, successfully creates artificial carbon fixation cycle technology, published in international journal. *Economic Daily News*. https://money.udn.com/money/story/5612/6146486?from=edn_next_story

⁶⁷⁸ Schwander, T., Schada von Borzyskowski, L., Burgener, S., Cortina, N.S., Erb, T. J. (2016). A synthetic pathway for the fixation of carbon dioxide *in Vitro*. *Science*, 354(6314): 900-904. doi: 10.1126/science.aah5237

⁶⁷⁹ Luo, S., Lin, P. P., Nieh, L. Y., Liao, G. B., Tang, P. W., Chen, C. & Liao, J. C. (2022). A cell-free self-replenishing CO₂-fixing system. *Nature Catalysis*, 5, 154–162.

reduced to methane and then converted to ethylene using oxidative coupling of methane (OCM) technology (see 4.4 Petrochemical Industry), it can potentially become the largest source of raw materials for petrochemicals. However, the current conversion rate of OCM technology is only 20-40%, and further research and development is needed. In addition, 4 moles of hydrogen are required to reduce 1 mole of CO_2 to methane. Annual ethylene production is 4 Mt, requiring at least 2.28 Mt of hydrogen, which in turn demands 114 billion kWh of electricity for the production. Therefore, under the current circumstances of insufficient green electricity supply in Taiwan, it is still difficult to reduce CO_2 chemically. The method will only be feasible if low-cost green hydrogen can be imported in the future.

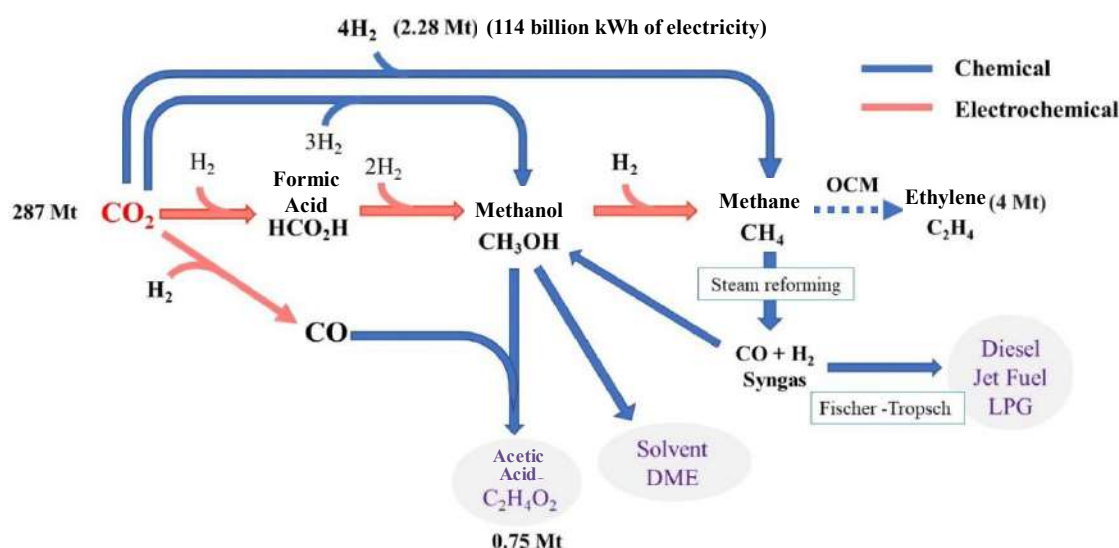


Figure 6.3.1 Possible Pathways for Chemical and Electrochemical CO_2 Utilization

Regarding the innovative cases of CO_2 utilization through chemical processes, a research team at RMIT University in Melbourne, Australia, has recently captured carbon dioxide using gallium-indium liquid metal alloy (EGaIn) and converted it directly into solid carbon. The team leverages the alloy's low melting point to facilitate the reduction reaction of CO_2 at low temperatures. As gas passes through the liquid metal, the gas molecules split, forming flakes of solid carbon, as shown in Figure 6.3.2. At 200 degrees Celsius, this process can generate 319 μmol of carbon per hour. The method achieves CO_2 activation and carbon generation at room temperature without the use of additional reducing agents (e.g., hydrogen). This novel technology allows for an immediate conversion of CO_2 into stable, solid carbon, offering a new decarbonization tool for high-emission industries such as cement, petrochemicals, and steel industries.

The research team has signed a cooperation agreement with an Australian environmental technology company (ABR) to verify the concept and scale up into a modular prototype. Commercialization of this technology could assist the cement and steel industries in their decarbonization efforts. The potential applications of solid carbon, including the uses in building materials and as a cement additive, will be explored in the future⁶⁸⁰. Nonetheless, the biggest challenges are energy consumption and handling of the resulting metal oxides.

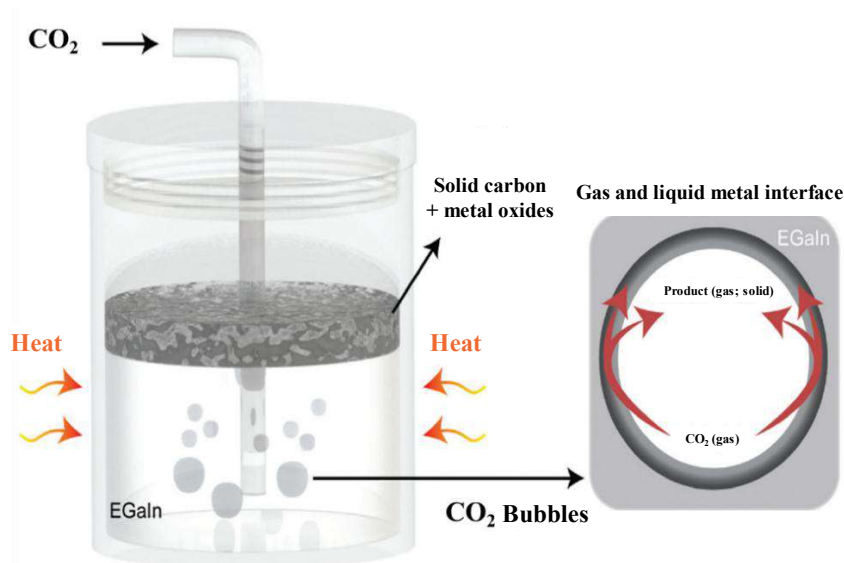


Figure 6.3.2 The Reaction Process of EGaln Liquid Metal with CO₂⁶⁸¹

3. Electrochemical CO₂ Utilization Technologies

Compared to the traditional chemical synthesis methods for producing chemical precursors (such as ethylene, methanol, ethanol, and carbon monoxide), the electrocatalytic conversion of carbon dioxide into the aforementioned compounds has recently emerged as a highly promising technology. The method directly reduces CO₂ using electricity, bypassing the hydrogen production process. The most significant difference from the traditional synthesis methods is that electrocatalytic CO₂ conversion does not require high temperatures and pressures⁶⁸². Therefore, it offers a new pathway to reducing CO₂ emissions. The optimal strategy for utilizing electrochemical CO₂

⁶⁸⁰ Zuraiqi, K., Zavabeti, A., Clarke-Hannaford, J., Murdoch, B. J., Shah, K., Spencer, M. J. S., McConville, C. F., Daeneke, T. & Chiang K. (2022). Direct conversion of CO₂ to solid carbon by Ga-based liquid metals. *Energy Environ. Sci.* 15, 595– 600. <https://pubs.rsc.org/en/content/articlelanding/2022/ee/d1ee03283f>

⁶⁸¹ *Ibid.*, note 680.

⁶⁸² Dry, M. E. (2002). The Fischer-Tropsch process: 1950-2000. *Catal. Today* 71(3-4), 227-241. doi: 10.1016/S0920-5861(01)00453-9

conversion technology involves: integrating zero-carbon energy sources (solar, wind, hydro, geothermal, and tidal power) with electrochemical CO₂ reduction. It allows energy to be stored in chemical bonds and converted into chemical precursors, replacing petroleum-derived raw materials. Moreover, the electrochemical reactions occur at normal temperature and pressure, offering greater flexibility in terms of setup scale and location selection.

As a promising new synthetic pathway, there are still many key factors to overcome with electrocatalytic CO₂ conversion, mainly due to its excessive demands for energy, such as high catalytic overpotential, low Faradaic efficiency of the catalytic reaction⁶⁸³, low selectivity of the catalytic reaction, and low utilization rate of CO₂. The low utilization rate of CO₂ is due to its low solubility in aqueous solutions, which can be solved by engineering methods, such as the use of gas diffusion electrodes. The reaction current density can be increased to more than 100 mA/cm², reaching the preliminary practical stage⁶⁸⁴. As for the first three key factors, they are determined by the characteristics of the catalytic material. Electrode materials currently include copper, silver, gold, tin, lead, bismuth, and their alloys or compounds. The catalytic overpotential of most of them is higher than 300 mV. A few of them have a Faraday efficiency that can reach or exceed 90%, but the energy conversion efficiency is generally around 35%^{685,686}. Since the CO₂ conversion reaction may be accompanied by a hydrogen evolution reaction, it causes reaction competition and reduces the CO₂ conversion rate. Electrocatalysis is currently limited to the production of C1 (single carbon) to C3 (three carbon) chemicals, with poor product selectivity. The generation of high-value carbon (> C3) chemicals involves more proton-coupled electron transfers (PCET). The C-C coupling is more difficult. The reaction pathway is extremely complex and difficult to achieve. Also, with the increase in the number of carbons, the energy efficiency of each electron transfer decreases⁶⁸⁷.

⁶⁸³ Faradaic efficiency is the percentage of the actual products to the theoretical products.

⁶⁸⁴ Weekes, D.M., Salvatore, D.A., Reyes, A., Huang, A., & Berlinguette, C. P. (2018). Electrolytic CO₂ reduction in a flow cell. *Acc. Chem. Res.*, 51(4), 910–918. doi: 10.1021/acs.accounts.8b00010

⁶⁸⁵ De Luna, P., Quintero-Bermudez, R., Dinh, C. T., Ross, M. B., Bushuyev, O. S., Todorović, P., ... & Sargent, E. H. (2018). Catalyst electro-redeposition controls morphology and oxidation state for selective carbon dioxide reduction. *Nature Catalysis*, 1(2), 103-110.

⁶⁸⁶ Jhong, H.-R. M., Ma, S., Kenis, P. J. A. (2013). Electrochemical conversion of CO₂ to useful chemicals: Current status, remaining challenges, and future opportunities. *Curr. Opin. Chem. Eng.*, 2(2), 191–199. doi: 10.1016/j.coche.2013.03.005

⁶⁸⁷ Zhuang, T. T., Liang, Z. Q., Seifitokaldani, A., Li, Y., De Luna, P., Burdyny, T., ... & Sargent, E. H. (2018). Steering post-C–C coupling selectivity enables high efficiency electroreduction of carbon dioxide to multi-carbon alcohols. *Nature Catalysis*, 1(6), 421-428. doi: 10.1038/s41929-018-0084-

When considering the competitiveness of electrocatalytic CO₂ conversion technologies, the price of electricity has the greatest impact on the production costs. In addition, the Faraday efficiency and energy efficiency of the catalysis affects the feasibility of the technology as well. Since the prices of chemicals vary greatly depending on the region and raw materials, if we assume the specifications of an industrially mature polymer electrolyte membrane (PEM) water electrolyzer, electrocatalytic products can only compete with the current market prices of fossil fuel products when the electricity cost is lower than 4 cents per kWh (0.04 USD/kWh or 40 USD/MWh) and that the energy efficiency is at a minimum of 60%⁶⁸⁸. Although this is a rather difficult target, it is not impossible to achieve, especially taking into account the positive substantial impact of using CO₂ as a raw material on carbon emission reduction. Take ethylene as an example. Compared with carbon monoxide, ethanol, and formic acid, ethylene has the largest global market size, reaching 230 billion USD. Electrocatalytic preparation of ethylene can reduce CO₂ emissions by 862 Mt per year⁶⁸⁹. In terms of carbon monoxide, ethanol, and formic acid, the related CO₂ emission reductions can reach 3.6, 546, and 1 million tonnes (Mt), respectively. Considering a power plant with a generating capacity of 500 MW, when the grid carbon emission intensity is 0.11 kg CO₂/kWh and the energy conversion efficiency reaches 70%, the electrocatalytically produced products will all achieve net-zero (ethylene) or net-negative (ethanol, carbon monoxide, and formic acid) emissions⁶⁹⁰. When renewable energy is used as the power source, during peak power generation, excess power often leads to negative market prices of electricity, which is more economically advantageous for the electrochemical synthesis of chemicals.

4. Photochemical CO₂ Utilization Technologies

Reducing CO₂ requires energy input. Zero-carbon hydrogen is used as an energy source in chemical methods, while zero-carbon electricity is used in electrochemical methods. Since both zero-carbon hydrogen and zero-carbon electricity can be derived from light energy, it is possible to directly reduce CO₂ with light energy through photocatalysis, also known as artificial photosynthesis. Seemingly simple, this approach also faces significant challenges. It is limited by factors such as the location

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⁶⁸⁸ *Ibid.*, note 676.

⁶⁸⁹ *Ibid.*, note 676.

⁶⁹⁰ *Ibid.*, note 676.

and intermittency of light, the design and efficiency of the photocatalyst, and the collection and purification of products. Only when these limitations are improved will its applicability be possible.

5. Combination of Chemical Methods, Electrocatalytic Methods, and Biological Systems such as Enzymes or Bacteria

With CO₂ as a carbon source and green energy as an energy source, theoretically, it is possible to produce all the chemicals needed to replace petroleum-based raw materials in the petrochemical industry. However, given the magnitude of the required carbon source and energy is much larger than the energy used in the feasibility analysis in the laboratory, it will also be necessary to combine various other possible approaches in the future, including chemical methods, electrocatalytic methods, enzymes or biological systems.

Although the current electrocatalytic CO₂ conversion technologies can only produce C1-C3 products, when combined with biological systems such as enzymes or bacteria, these small molecules with few carbon atoms can be further converted and upgraded into more complex and valuable chemicals^{691,692,693}. In particular, the primary chemicals produced, such as formic acid, can serve as the sole carbon source for microorganisms or enzymes, while also providing reducing power for microbial or enzymatic carbon fixation. Furthermore, if microorganisms are modified to have a higher tolerance to various product molecules^{694,695}, the engineered microorganisms can be used to process the mixture from electrocatalytic CO₂ conversion and upgrade the mixed materials into high-value chemicals. In this case, electrocatalytic selectivity and separation processes will no longer be a limitation.

To achieve the goal of Net-Zero Emissions in 2050, Taiwan needs to develop CO₂

⁶⁹¹ Li, H., Opgenorth, P.H., Wernick, D.G., Rogers, S., Wu, T.Y., Higashide, W., Malati, P., Huo, Y.X., Cho, K.M., Liao, J.C. (2012). Integrated electromicrobial conversion of CO₂ to higher alcohols. *Science*, 335(6076):1596. doi: 10.1126/science.1217643. PMID: 22461604.

⁶⁹² Nangle, S. N., Sakimoto, K. K., Silver, P. A., & Nocera, D. G. (2017). Biological-inorganic hybrid systems as a generalized platform for chemical production. *Current Opinion in Chemical Biology*, 41, 107-113. doi: 10.1016/j.cbpa.2017.10.023

⁶⁹³ Yishai, O., Lindner, S. N., Gonzalez de la Cruz, J., Tenenboim, H., & Bar-Even, A. (2016). The formate bio-economy. *Current Opinion in Chemical Biology*, 35, 1-9. doi:10.1016/j.cbpa.2016.07.005

⁶⁹⁴ Chen, X., Cao, Y., Li, F., Tian, Y., & Song, H. (2018). Enzyme-assisted microbial electrosynthesis of poly (3-hydroxybutyrate) via CO₂ bioreduction by engineered *Ralstonia eutropha*. *ACS Catal.* 8, 4429-4437. doi: 10.1021/acscatal.8b00226

⁶⁹⁵ Qiao, K., Wasylenko, T. M., Zhou, K., Xu, P., & Stephanopoulos, G. (2017). Lipid production in *Yarrowia lipolytica* is maximized by engineering cytosolic redox metabolism. *Nature Biotechnology*, 35(2), 173-177. doi: 10.1038/nbt.3763

conversion technologies to address the carbon emissions challenges faced by the petrochemical industry. By utilizing solar, wind, and other zero-carbon energy sources, coupled with optimized biological and chemical catalytic processes, the traditional petrochemical industry can be transformed into a low-carbon or zero-carbon industry, or an industry that synthesizes high-value fine chemicals.

6.3.3 Policy Recommendations

Whether the goal is carbon neutrality or even negative carbon emissions, it is necessary to have appropriate destinations for the CO₂ captured directly from the atmosphere or from flue gas. In addition to sequestration, CO₂ utilization is an important direction. Biological methods (with plants or algae) are the most effective means at present to capture carbon from the air. Yet, there are still technical challenges to overcome in terms of rate, efficiency, and scaling up. With chemical methods, hydrogen can also be used to reduce carbon dioxide to methane, methanol, formic acid, or carbon monoxide, but hydrogen production must be coupled with a sufficient supply of zero-carbon electricity, and the related supporting technologies, such as the conversion rate of OCM technology, need to be improved. Electrochemical conversion reactions present the advantage of not requiring high-temperature and high-pressure conditions. Together with renewable energy, energy can be stored in chemical bonds, and CO₂ can be converted into chemical raw materials. Nonetheless, challenges such as high catalytic voltage, low Faraday efficiency of catalytic reactions, insufficient selectivity of catalytic reactions, and a low CO₂ utilization rate need to be addressed. In addition, the combination of chemical methods, electrocatalytic methods, and biological systems such as enzymes or bacteria can further transform and upgrade small molecules with few carbon atoms into more complex and valuable chemicals. Hence, it is recommended that Taiwan should continue to promote the development of CO₂ utilization technologies in the long term, including biological, chemical, and electrochemical (photoelectrochemical) methods, as well as conversion technologies that combine different methods to produce more complex and valuable chemicals, in order to solve relevant technical challenges and realize the possibility of boosting the value of CO₂ utilization. Only in this way can we find effective ways to convert the successfully captured CO₂ into other usable materials.

6.4 Future Nuclear Technology

Summary

From Taiwan's First Nuclear Power Plant to the construction of the Fourth Nuclear Power Plant, nuclear technology has made significant advancements over the past decades. Newer Generation III⁺ and Generation IV nuclear technologies come with higher safety coefficients, significantly reducing the risk of nuclear disasters. Furthermore, Generation IV nuclear technology requires considerably less nuclear fuel per unit of electricity generated. The primary obstacle for nuclear power in the future lies in the final disposal sites for radioactive waste, presenting substantial challenges both technically and in terms of public perception.

On another front, once nuclear fusion technology become feasible and achieves a favorable energy output-to-input ratio, it could potentially provide a nearly limitless and abundant energy supply. The United Kingdom has set a target to operate a pilot nuclear fusion power plant by 2040.

This proposal outlines the following policy recommendations for the application of nuclear power generation technology:

1. Carefully evaluate various Generation IV nuclear technologies. If new nuclear technologies demonstrate clear improvements in nuclear safety as well as in the production and disposal of waste, it would be advisable to engage in comprehensive public communication before further exploring their implementation.
2. Closely monitor developments in the commercialization of nuclear fusion. At an appropriate time, initiate the establishment of relevant regulations to align with global efforts in adopting nuclear fusion technology, thereby supporting the goal of achieving net-zero emissions by 2050.

6.4.1 Introduction

In human history, three major nuclear power plant accidents have occurred: the 1979 Three Mile Island accident, the 1986 Chernobyl disaster, and the 2011 Fukushima nuclear disaster. The severe accident at the Fukushima Nuclear Power Plant on March 11, 2011, triggered by the Great East Japan Earthquake, rekindled global anti-nuclear sentiment, leading to another surge in public fear surrounding nuclear energy. As the goal of achieving net-zero emissions by 2050 becomes a global focus, concerns are

rising over the potential inadequacy of renewable energy to meet domestic and worldwide electricity demands by that time. Consequently, the continuous development of nuclear power technology has reintroduced it as a viable candidate for net-zero emissions power generation.

Nuclear fuel has an energy density millions of times higher than fossil fuels, making it highly efficient for electricity generation and suitable as a baseload power source. For instance, the fuel needed for one unit at Taiwan's Third Nuclear Power Plant can be transported on a single flight, contrasting with the continuous monthly imports required for fossil fuels, underscoring nuclear fuel's advantage in supply stability. Furthermore, nuclear power generation essentially produces no carbon dioxide, making it a cleaner option compared to fossil fuels such as coal or natural gas. Unlike wind and solar power, it is also unaffected by weather conditions. If nuclear waste disposal and other social costs are disregarded, the unit cost of nuclear-generated electricity remains relatively low compared to other methods.

However, the main drawback of nuclear power is the potential risk of nuclear disasters. In the event of such an incident, large-scale, or even global, radiation contamination could occur, leading to genetic mutations in humans and other organisms, developmental abnormalities in future generations, and long-term pollution of affected lands that may require multiple generations to recover. Nuclear plants require large quantities of water for cooling; while seawater is a cost-effective solution, it can raise the surrounding seawater temperature, which has previously caused environmental issues, such as coral bleaching.

Beyond the risk of nuclear disasters, another significant challenge lies in the absence of a universally accepted method for effectively managing high-level radioactive waste. Radioactive waste is categorized into high-level and low-level types. High-level waste primarily includes raw spent fuel or extracted residues from reprocessing, which require up to a million years to decay to safe radiation levels. Low-level waste comes from radioactive-contaminated instruments, materials, or waste from power plants and from the medical, research, industrial, and agricultural sectors; it typically decays to natural background radiation levels within several hundred years. Domestically, only low-level radioactive waste equivalent to radioactive medical waste is stored on Orchid Island (*Lanyu*), yet it has already attracted criticism and opposition.

The most internationally accepted method for disposing of high-level radioactive

waste is deep geological disposal⁶⁹⁶, which involves burying waste deep underground in geologically stable regions. However, geological disposal poses unresolved issues, as it requires isolation from the biosphere for hundreds of thousands of years. This method must consider factors such as the durability of disposal containers, the stability of engineered and natural barriers, potential degradation due to unforeseen seismic activity or tectonic shifts, and acceptance by local residents and governments.

In recent years, nuclear power technology has advanced to Generation IV. In 2021, China announced the completion of the world's first grid-connected Generation IV reactor, the very-high-temperature gas-cooled reactor at Shidao Bay in Rongcheng, Shandong. Generation IV nuclear technology generates more power per unit of fuel and is progressing toward small modular reactors (SMRs), which offer advantages such as lower construction costs, greater flexibility, enhanced safety, the ability to generate power from nuclear waste, and the recyclability of its own nuclear waste. However, managing the high-level radioactive waste generated by these reactors remains a challenge.

Although nuclear fusion technology is still in the research and development phase, it is regarded as a promising future technology for net-zero emission power generation. Fusion generates almost no high-level radioactive waste, and its hydrogen isotopic fuel is virtually inexhaustible. However, technical barriers still need to be overcome before nuclear fusion can become a viable, cost-effective, zero-carbon power source.

6.4.2 International Trends

Table 6.4.1 compares the nuclear installed capacity in 2020 for the top 15 countries worldwide, along with Taiwan, which ranks 16th globally. The United States leads the world in the number of nuclear power plants, with 56 plants and 96 reactors as of the end of 2020⁶⁹⁷. The average age of these reactors is 39 years, with the newest, Watts Bar Unit 2, connected to the grid in 2016. The ongoing construction of Vogtle Units 3 and 4 is expected to be completed within the next two years. The U.S. reached its peak nuclear installed capacity in 2012 with 104 reactors, totaling 102,000 MW. By 2020, its capacity was 98,152 MW, producing 790 billion kWh annually, which supplies

⁶⁹⁶ Ramana, M. V. (2018). Technical and social problems of nuclear waste. *Wiley Interdisciplinary Reviews: Energy and Environment*, 7(4), e289. <https://wires.onlinelibrary.wiley.com/doi/abs/10.1002/wene.289>

⁶⁹⁷ The U.S. Energy Information Administration (2021). What is the status of the U.S. nuclear industry? <https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php>

approximately 20% of the nation's electricity.

France holds the second-largest nuclear installed capacity globally, with 58 reactors in 2020 and a nuclear power contribution of 70.6% of its total electricity⁶⁹⁸. Over the next decade, France plans to build six more reactors. China, with 50 reactors, ranks third in terms of the number of reactors and total nuclear capacity⁶⁹⁹. Recently, China has made significant progress in localizing nuclear equipment production.

Table 6.4.1 Comparison of 2020 Nuclear Installed Capacity: Top 15 Countries and Taiwan⁷⁰⁰

Country	Number of Reactors	Total Installed Capacity (MW)	Electricity Generation (million kWh)	Nuclear Share (%)
United States	96	98,152	789,918.61	19.7
France	58	63,130	338,735.78	70.6
China	50	47,528	344,747.50	4.9
Japan	33	31,679	43,098.63	5.1
Russia	39	29,503	201,821.27	20.6
South Korea	24	23,150	152,583.25	29.6
Canada	19	13,624	92,166.11	14.6
Ukraine	15	13,107	71,549.60	51.2
United Kingdom	15	8,923	45,668.04	14.5
Germany	6	8,113	60,918.11	11.3
Sweden	7	7,763	47,361.83	29.8
Spain	7	7,121	55,825.26	22.2
India	22	6,255	40,374.37	3.3
Belgium	7	5,942	32,792.85	39.1
Czech Republic	6	3,934	28,371.87	37.3
Taiwan	4	3,844	30,341.92	12.7

⁶⁹⁸ Mei, Y.-Y. (2022). Macron announces “revitalization of the nuclear industry” with plans to construct 14 nuclear reactors, sparking debate on energy self-sufficiency. <https://www.thenewsline.com/article/162659>

⁶⁹⁹ People's Daily Online (2021). China nuclear energy development report 2021: China maintains world's largest installed capacity of nuclear units under construction for consecutive years. <http://finance.people.com.cn/BIG5/n1/2021/0418/c1004-32080738.html>

⁷⁰⁰ International Atomic Energy Agency (2022). Nuclear share of electricity generation in 2021. <https://pris.iaea.org/PRIS/WorldStatistics/NuclearShareofElectricityGeneration.aspx>

Nuclear fission reactors are categorized by their generation, including Generations I, II, III, III+, and IV (refer to Figure 6.4.1). Generation I reactors were experimental, while commercial reactors began with Generation II, producing about 700 million kWh of electricity per ton of fuel. Notable accidents, including Chernobyl, Three Mile Island, and Fukushima, involved reactors from this generation. Taiwan's Second and Third Nuclear Power Plants also belong to Generation II. The originally planned Fourth Nuclear Power Plant in Taiwan is Generation III, capable of generating approximately 1.4 billion kWh per ton of fuel. Compared to Generation II, Generation III nuclear technology features digitalized control systems and improvements in both reactor structures and shutdown mechanisms. Compared to Generation III, the newer Generation III+ features passive safety shutdown (requiring no human intervention) and has an accident probability two orders of magnitude lower than Generation II. It also introduces new designs that enable rapid load increases.

Generation IV reactors, mostly in the research and development stage, include six design types, producing between 900 million and 12 billion kWh per ton of fuel, depending on the design. This generation significantly increases the power generated per ton of fuel compared to Generation III+. Some Generation IV designs enable the reuse of spent nuclear fuel, alleviating the burden of nuclear waste disposal. These reactors have been developed to be smaller and modular, theoretically allowing for significantly reduced construction and maintenance times. They are also adaptable for deployment in remote areas, oil exploration sites, and military bases. Furthermore, they incorporate passive safety mechanisms, further enhancing safety shutdown processes that require no human intervention, and they eliminate the need for large concrete structures to shield nuclear fuel rods.

Unlike fission, nuclear fusion is expected to produce no high-level radioactive waste and poses no risk of uncontrollable chain reactions, making it a safer nuclear energy option. Fusion reactors use hydrogen isotopes, deuterium and tritium, as fuel. Deuterium can be extracted from seawater, while tritium can be generated by neutron collisions with lithium-6, ensuring an abundant and stable fuel supply.

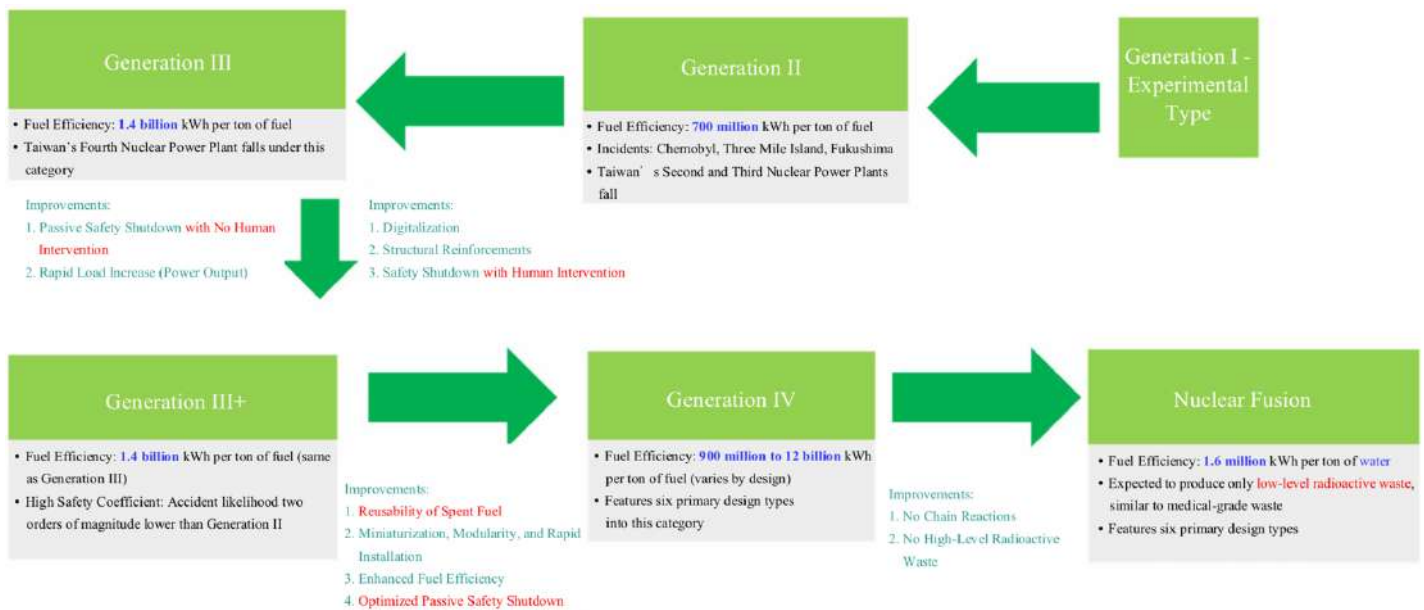


Figure 6.4.1 Evolution of Nuclear Technology

Generation IV nuclear reactors can be categorized into six main types (refer to Table 6.4.2): (1) the very-high-temperature reactor (VHTR), (2) the sodium-cooled fast reactor (SFR), (3) the supercritical water reactor (SCWR), (4) the gas-cooled fast reactor (GFR), (5) the lead-cooled fast reactor (LFR), and (6) the molten salt reactor (MSR).

The very-high-temperature reactor (VHTR) uses uranium compounds as fuel and can theoretically generate approximately 12 billion kWh of electricity per ton of fuel, the highest efficiency among Generation IV reactors. However, its spent fuel cannot be reused. On December 20, 2021, the Shidao Bay VHTR in Rongcheng, Shandong, China, developed by Huaneng Nuclear Power Development Co., was connected to the grid, making it the world's first operational Generation IV reactor⁷⁰¹.

The sodium-cooled fast reactor (SFR) uses uranium/plutonium carbide as fuel and liquid sodium as a coolant. It can theoretically generate 1.2–4.8 billion kWh of electricity per ton of fuel and supports the reuse of spent nuclear fuel, with a single fuel replenishment lasting several decades. A project in Wyoming, backed by Bill Gates, plans to begin operation of an SFR named Natrium by 2030⁷⁰².

The supercritical water reactor (SCWR) is categorized into two types based on

⁷⁰¹ udn.com (2021). Generation IV High-Temperature Gas-Cooled Reactor Connected to the Grid. <https://udn.com/news/story/7333/5976423>

⁷⁰² Chuang, D. (2021). Bill Gates' next-generation sodium reactor expected to be completed by 2030, with Kemmerer, Wyoming, as the preferred site. <https://technews.tw/2021/11/17/terrapower-wyoming-kemmerer/>

neutron states: heavy-water thermal neutron SCWRs, which use thorium as fuel, and fast neutron SCWRs, which use uranium and plutonium oxide mixtures. These reactors can theoretically generate about 900 million kWh of electricity per ton of fuel. Depending on the design, spent fuel may or may not be reused⁷⁰³. The International Atomic Energy Agency (IAEA) continues to refine SCWR designs.

The gas-cooled fast reactor (GFR) uses uranium and actinide elements as fuel, producing about 1.2 billion kWh of electricity per ton of fuel. It also supports the reuse of spent nuclear fuel. Radiant, a startup founded by former SpaceX engineers, is developing helium-cooled fast reactors. These affordable 1 MW microreactors are designed for mass production, with each microreactor capable of providing electricity for approximately 1,000 households⁷⁰⁴.

The lead-cooled fast reactor (LFR) uses uranium compounds as fuel and can produce approximately 1.6 billion kWh of electricity per ton of fuel. It also supports the reuse of spent fuel. Recently, experimental LFR projects have received government funding in Italy, through Ansaldo Nucleare, and in Romania, through Reinvent Energy⁷⁰⁵.

Molten salt reactors (MSR) include two types: molten salt fuel reactors, which use uranium waste, plutonium waste and thorium salts as fuel, and solid-fuel reactors, which rely on uranium waste and plutonium waste. These reactors can theoretically generate 2.8–7.9 billion kWh of electricity per ton of fuel. On November 18, 2021, Southern Company signed an agreement with the U.S. Department of Energy to design, construct, and operate an experimental molten salt reactor in Idaho, based on TerraPower's original design⁷⁰⁶.

⁷⁰³ GEN IV International Forum (2022). Supercritical-water-cooled reactor (SCWR). https://www.gen-4.org/gif/jcms/c_42151/supercritical-water-cooled-reactor-scwr

⁷⁰⁴ Blain, L. (2021). Radiant aims to replace diesel generators with small nuclear reactors. <https://newatlas.com/energy/radiant-portable-advanced-nuclear/>

⁷⁰⁵ Todorović, I. (2022). US startup last energy plans to install small modular nuclear reactor in Romania. <https://balkangreenenergynews.com/us-startup-last-energy-plans-to-install-small-modular-nuclear-reactor-in-romania/>

⁷⁰⁶ Nuclear Engineering International (2021). Southern company, DOE to lead demonstration of molten-salt reactor. <https://www.neimagazine.com/news/newssouthern-company-doe-to-lead-demonstration-of-molten-salt-reactor-9267269>

Table 6.4.2 Comparison of Six Generation IV Nuclear Reactor Types

Type	Features	Progress
Very-High-Temperature Reactor (VHTR) Fuel: Uranium compounds	• Fuel Efficiency: 12 billion kWh/ton of fuel (highest among Generation IV types) • Open (spent fuel not reused)	December 2021: The pebble-bed very-high-temperature reactor (VHTR) in Shidao Bay, Shandong, China, successfully began operation.
Sodium-Cooled Fast Reactor (SFR) Fuel: Uranium and plutonium oxide mixtures	• Fuel Efficiency: 1.2–4.8 billion kWh/ton of fuel • Closed (spent fuel reused)	November 2021: The sodium nuclear power plant in Kemmerer, Wyoming, backed by Bill Gates, is scheduled for completion by 2030.
Supercritical Water Reactor (SCWR) Fuel: Heavy-water SCWR: Thorium Fuel: Fast SCWR: Uranium and plutonium oxide mixtures	• Fuel Efficiency: 900 million kWh/ton of fuel • Open and closed cycles exist	May 2021: The International Atomic Energy Agency (IAEA) continues to refine the design of a supercritical water reactor (SCWR) prototype.
Gas-Cooled Fast Reactor (GFR) Fuel: Uranium and actinide elements	• Fuel Efficiency: 1.2 billion kWh/ton of fuel • Closed (spent fuel reused)	November 2021: Radiant, a startup founded by former SpaceX engineers, is developing a helium-cooled fast reactor.
Lead-Cooled Fast Reactor (LFR) Fuel: Uranium compounds	• Fuel Efficiency: 1.6 billion kWh/ton of fuel • Closed (spent fuel reused)	November 2021: Italy's Ansaldo Nucleare and Romania's Reinvent Energy have invested in an experimental lead-cooled fast reactor (LCFR), supported by government funding.
Molten Salt Reactor (MSR) Molten salt fuel type: Uranium waste, plutonium waste and thorium salts Solid fuel type: Uranium waste and plutonium waste	• Fuel Efficiency: 2.8–7.9 billion kWh/ton of fuel • Fast neutron: Closed (spent fuel reused) • Thermal neutron: Open (spent fuel not reused)	November 2021: Southern Company plans to establish an experimental molten chloride fast reactor in Idaho.

Nuclear fusion technology is not yet mature enough for practical use. Two key indicators are used to evaluate its readiness: (1) the ability to sustain uninterrupted nuclear fusion in plasma at 150 million degrees Celsius for 30 minutes, or (2) achieving an energy output-to-input ratio (Q-value) greater than 10 (e.g., producing 500 MW of power with 50 MW of thermal energy input). The conditions required for nuclear fusion are extremely stringent, and any instability leads to an immediate shutdown, thus eliminating the risk of uncontrollable chain reactions associated with nuclear fission. Nuclear fusion, in principle, does not produce high-level radioactive waste⁷⁰⁷. However, the most promising fusion technology for commercial application is deuterium-tritium fusion, where tritium—a byproduct of fission reactors—is required. As a result, nuclear fusion may indirectly generate high-level radioactive waste due to its reliance on tritium. The United Kingdom anticipates that nuclear fusion technology will enter the commercial stage after 2040 and has already begun drafting relevant regulations⁷⁰⁸. Taiwan should also start monitoring international developments and establishing its own regulatory frameworks.

Nuclear fusion technology can be categorized into six main types: (1) tokamak, (2) stellarator, (3) reversed field pinch⁷⁰⁹, (4) inertial confinement fusion⁷¹⁰ (ICF), (5) magnetized target fusion, and (6) hybrid fusion (a combination of fusion and fission).

The tokamak reactor utilizes a large helical magnetic field to confine and heat deuterium-tritium plasma, enabling nuclear fusion at a plasma density of 10^{14} cm^{-3} . The induced plasma current initially heats the plasma to $1 \times 10^7 \text{ K}$. Examples of tokamak-based systems include the Joint European Torus (JET) and the Korea Superconducting Tokamak Advanced Research (KSTAR), a member of the International Thermonuclear Experimental Reactor (ITER) initiative. In October 2021, JET achieved a Q-value of 2/3 (16 MW output from 24 MW input) for 0.1 seconds, while KSTAR achieved the milestone of maintaining a temperature of 100 million degrees Celsius for 30 seconds and is expected to generate approximately 500 MW of power in the future. On

⁷⁰⁷ Willis, C. & Liou, J. (2021). Safety in fusion: An inherently safe process. <https://www.iaea.org/bulletin/safety-in-fusion>

⁷⁰⁸ Department for Business, Energy & Industrial Strategy, UK (2021). *Towards fusion energy: The UK government's fusion strategy*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1022540/towards-fusion-energy-uk-government-fusion-strategy.pdf

⁷⁰⁹ Sarff, J. (2020). *Reversed field pinch research in MST (Final technical report)*. <https://www.osti.gov/biblio/1638828-reversed-field-pinch-research-mst-final-technical-report>

⁷¹⁰ Peeva, A. (2021). Exploring alternatives to magnetic confinement: Laser fusion, linear devices and advanced fuels. <https://www.iaea.org/bulletin/exploring-alternatives-to-magnetic-confinement>

September 8, 2021, Commonwealth Fusion Systems, a startup jointly supported by MIT and the National Ignition Facility (NIF) at Lawrence Livermore Laboratory, announced the development of the world's strongest high-temperature superconducting magnet⁷¹¹, designed for use in magnetic confinement fusion.

The stellarator reactor employs complex magnetic coils to simulate the conditions of a star, maintaining high plasma stability without inducing plasma current. It offers continuous energy output.

Reversed field pinch reactor operates similarly to the tokamak but allows fine-tuning of the magnetic field configuration. It potentially eliminates the need for superconducting magnets by using neutron-shielding copper shells as magnetic coils. TAE Technologies' design, based on aneutronic fusion, is a notable example, with a prototype expected by 2030⁷¹².

Unlike the previously mentioned technologies that use magnetic fields to confine deuterium-tritium plasma, the fourth type, inertial confinement fusion (ICF), utilizes lasers to compress the distance between hydrogen isotopes, ultimately triggering nuclear fusion. This approach allows fusion fuel to be heated in a more controlled manner over a longer period. The National Ignition Facility (NIF) employs inertial confinement fusion and, in August 2021, achieved an energy output of 1.3 MJ, which corresponds to 70% of the input energy of 1.9 MJ.

The fifth type, magnetized target fusion reactors, combines magnetic fields and mechanical constraining forces to confine hydrogen isotopes. This approach offers a wider range of operating parameters, requires shorter confinement times while providing greater stability compared to purely magnetic confinement, and demands plasma particle densities several orders of magnitude lower than inertial confinement. It also requires lower implosion velocities, reduced laser specifications and costs, and features a simpler design. The United Kingdom Atomic Energy Authority (UKAEA) and Canadian developer General Fusion are collaborating to build a demonstration plant for magnetized target fusion reactors, expected to be completed by 2025.

The sixth type, hybrid fusion-fission reactors, uses neutrons produced by nuclear

⁷¹¹ Commonwealth Fusion Systems (2021). Commonwealth Fusion Systems creates viable path to commercial fusion power with world's strongest magnet. <https://cfs.energy/news-and-media/cfs-commercial-fusion-power-with-hts-magnet>

⁷¹² Delbert, C. (2022). This Google-Backed Fusion Reactor Must Run 8 Times Hotter Than the World's Largest Tokamak. <https://31vid02ja3oz1qdp991dz9z7-wpengine.netdna-ssl.com/wp-content/uploads/081122-PopMech.pdf>

fusion to drive nuclear fission reactions. This design eliminates the need for neutron shielding and requires much less fusion to generate electricity compared to pure fusion reactors, making it easier to achieve practical implementation.

In addition to the six previously mentioned nuclear fusion methods, Alpha Ring⁷¹³ has developed another fusion technology that utilizes the electron screening effect to lower the Coulomb barrier, facilitating ignition conditions⁷¹⁴. This approach employs hydrogen-boron fusion to achieve aneutronic fusion with net energy output. The system uses Lorentz forces to drive weakly ionized hydrogen gas within a cylindrical chamber to high rotational speeds, generating strong centrifugal forces and creating high-density gas. Increasing the density of reactants effectively boosts the fusion reaction rate.

Table 6.4.3 provides a comparison of the advantages, disadvantages, and unresolved issues between Generation IV nuclear power and nuclear fusion. Generation IV nuclear power produces spent fuel at only 1/10 to 1/2 the volume of Generation III reactors. The modular design of these advanced reactors supports a business model in which the entire reactor, along with its spent fuel, can be returned to the manufacturer for processing. Additionally, many Generation IV designs enable spent fuel to be reprocessed and reused as fuel. However, most Generation IV technologies remain in the design phase. Despite the reactors themselves being extremely safe, the challenge of managing high-level radioactive waste persists. Moreover, while certain technologies allow spent fuel to be reprocessed into new fuel, there is still a lack of convincing data regarding the economic efficiency and safety of the entire reprocessing cycle.

Nuclear fusion has the distinct advantage of producing virtually no high-level radioactive waste, and its fuel—hydrogen isotopes—is almost inexhaustible. However, a major drawback of current nuclear fusion technology is that tritium, one of its key fuels, may need to be mass-produced in fission reactors. Additionally, public opposition in Taiwan to storing even low-level radioactive waste domestically (e.g., on Orchid Island (*Lanyu*)) poses another challenge. As nuclear fusion technology remains in the experimental stage, it is still uncertain whether it can achieve cost-effectiveness that meets practical and economic requirements.

⁷¹³ Lin, S.-H. (2020). Power generation on your desk! Chinese team Alpha Ring develops “artificial sun,” aiming to become the next TSMC? <https://www.gvm.com.tw/article/74211>

⁷¹⁴ U.S. Patent: US10515726B2.

Table 6.4.3 Comparison of Generation IV Nuclear Power and Nuclear Fusion

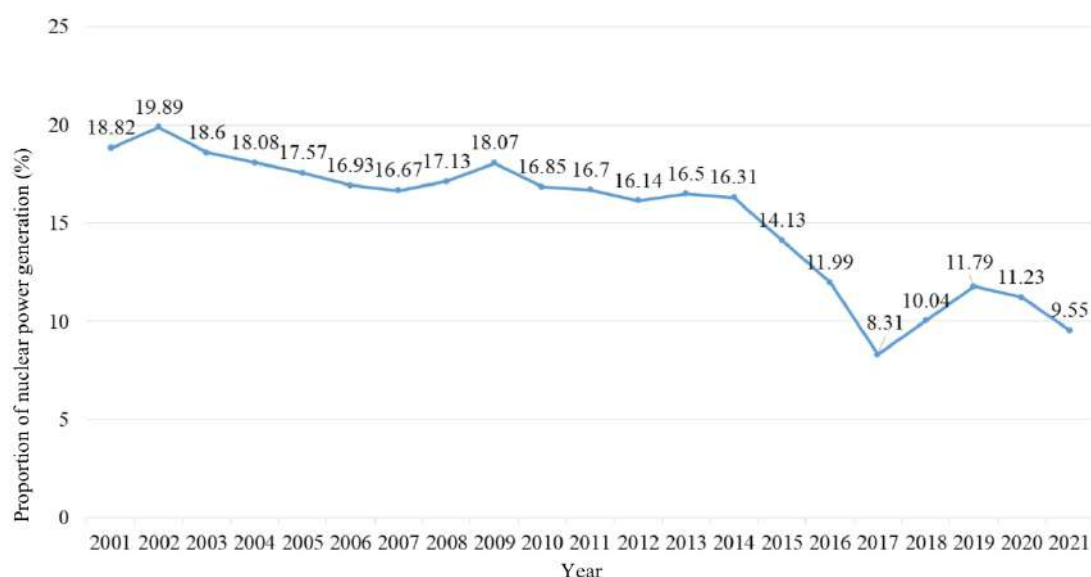
Aspect	Generation IV	Nuclear Fusion
Advantages	• Produces 1/10 to 1/2 the spent fuel of Generation III reactors • Entire reactor units, including spent fuel, are container-sized and can be returned to the manufacturer • Spent fuel can be reprocessed into usable fuel	• Produces almost no high-level radioactive waste, generating only low-level waste comparable to medical radioactive waste • Fuel (hydrogen isotopes) is abundant
Disadvantages	• Challenges remain in disposing of high-level radioactive waste	• Tritium may need to be mass-produced in fission reactors • Public opposition to storing low-level radioactive waste in Taiwan (e.g., on Orchid Island (Lanyu))
Unresolved Issues	• Economic efficiency of spent fuel reutilization is uncertain • Most technologies are still in the design or testing phase	• Still in the design or experimental phase; cost-effectiveness is uncertain

6.4.3 Current Situation in Taiwan

In 2020, nuclear power accounted for 11.22% of Taiwan's total electricity generation. The share of nuclear power over the years (2001–2021) is shown in Figure 6.4.2. Taiwan's First, Second, and Third Nuclear Power Plants were commissioned in 1978, 1981, and 1984, respectively. The First Nuclear Power Plant was decommissioned in 2019, while the Second and Third Nuclear Power Plants are scheduled for decommissioning in 2023 and 2025. The First and Second Nuclear Power Plants use boiling water reactors, while the Third uses a pressurized water reactor; all three are Generation II nuclear plants. The Fourth Nuclear Power Plant, which is currently mothballed, is an advanced boiling water reactor of Generation III nuclear technology. During its construction, the project faced delays due to the 1986 Chernobyl disaster, after which then-President Chiang Ching-Kuo ordered a construction slowdown. Between 1992 and 2006, the plant experienced several halts and resumptions in construction, and following the 2011 Fukushima disaster in Japan, public opinion swayed toward halting the project. Consequently, in 2014, the Executive Yuan announced its suspension and began returning purchased fuel rods to the

manufacturer. Currently, Taiwan has no plans for Generation IV nuclear technology or nuclear fusion research and application.

Figure 6.4.2 Nuclear Power’s Proportion of Electricity Generation in Taiwan⁷¹⁵



Taiwan has also experienced nuclear power plant incidents, the most severe of which occurred on March 17, 2001, at the Third Nuclear Power Plant’s Unit 1, where a 345-kilovolt ultra-high-voltage line failure caused the reactor to shut down. At 12:46 a.m. on March 18, both the 161-kilovolt and 345-kilovolt power supplies were lost simultaneously, and two emergency diesel generators failed to integrate into the power system. The Atomic Energy Council, Executive Yuan, was notified and subsequently declared a 2A “Alert” category incident under the Nuclear Emergency Response Plan⁷¹⁶. Fortunately, the incident concluded without further escalation. In addition, insiders have disclosed multiple high-risk events that never reached the public eye⁷¹⁷, including inadequate protective measures and radiation water leaks. Currently, low-level radioactive waste is stored on Orchid Island (*Lanyu*), within nuclear power plants, and at the Institute of Nuclear Energy Research. According to Taiwan Power Company’s “Low-Level Radioactive Waste Final Disposal Plan” the final disposal site for low-level waste should be located in tunnels or beneath the seabed, requiring a series of rigorous steps, including a local referendum, detailed site design, and safety analysis review

⁷¹⁵ Bureau of Energy, Ministry of Economic Affairs (2022). 2021 energy statistics handbook.

⁷¹⁶ Atomic Energy Council, Executive Yuan (2001). Explanation of the Ultra-High-Voltage Line Failure and Reactor Shutdown at Unit 1 of the Third Nuclear Power Plant. <https://www.aec.gov.tw/newsdetail/news/157.html>

⁷¹⁷ Chang, C.-W. (2012). Uncovering 8 secrets of Taiwan’s nuclear power plants. <https://www.businesstoday.com.tw/article/category/80392/post/201203220011/>

before construction. However, site selection has not yet been completed⁷¹⁸.

According to Taiwan Power Company's "Final Disposal Plan for Spent Nuclear Fuel"⁷¹⁹, the disposal process for high-level radioactive waste includes 10 years of wet storage cooling, several decades of dry storage cooling through air circulation, and final deep geological disposal. However, both wet and dry storage are currently conducted on-site at the power plants, and a location for deep geological disposal has not yet been identified. Should Taiwan introduce Generation IV nuclear technology in the future, its passive safety shutdown mechanism, which operates without human intervention, would significantly reduce the likelihood of severe accidents. Nonetheless, careful attention would still be required for personnel protection and radiation water management. The use of nuclear power inherently involves the challenge of final waste disposal, and to date, no nuclear-powered country has found a solution universally accepted by the public.

6.4.4 Policy Recommendations

Past major nuclear disasters have left a lasting impression on the public; however, Taiwan's Fourth Nuclear Power Plant, currently mothballed, is based on Generation III technology. Since its initial design, several decades have passed, and nuclear technology has made significant advancements. With the dual pressures of electricity shortages and the 2050 net-zero emissions goal, the government can help the public understand the advantages and disadvantages of new nuclear technologies, allowing citizens to make informed decisions on whether to restart or phase out nuclear energy as the best course for national development. Generation IV nuclear power generation is inherently very safe, requiring significantly less nuclear fuel per unit of power, generating no carbon dioxide, and offering a capacity factor far greater than that of green energy sources like solar or wind. It provides stable power unaffected by weather, and its fuel costs are less volatile than fossil fuels like natural gas. The challenge lies in the safe disposal of radioactive waste and gaining public acceptance, both of which require thorough research and communication.

Regarding nuclear fusion, while Taiwan lacks the experience or economic

⁷¹⁸ Science Media Center Taiwan (2021). Expert opinions on "nuclear waste disposal". <https://smctw.tw/11574/>

⁷¹⁹ Taiwan Power Company (2019). Final disposal plan for spent nuclear fuel (2018 revised edition). https://www.aec.gov.tw/share/file/fcma/629CrD95ZefdhJqIeU9qrQ_.pdf

foundation to independently develop fusion technology, breakthroughs in this field could revolutionize energy usage. The UK, for example, has begun to support the development of a domestic nuclear fusion supply chain, with a pilot fusion power plant slated for completion by 2040. The Environment Agency and the Health and Safety Executive are preparing the necessary regulations⁷²⁰. Taiwan should take early steps to monitor international nuclear fusion developments, explore participation in related supply chains, and begin planning the regulatory framework required for future commercial deployment of fusion technology. This will enable Taiwan to acquire and effectively utilize relevant technology in a timely manner, alleviating its power supply challenges. This proposal's policy recommendations are as follows:

1. Conduct a careful evaluation of various Generation IV nuclear technologies. If these new nuclear technologies can clearly address public concerns about nuclear safety and waste production and disposal, consider implementing them after thorough communication with the public.
2. Closely monitor developments in the commercialization of nuclear fusion. At an appropriate time, initiate the establishment of relevant regulations to align with global efforts in adopting nuclear fusion technology, thereby supporting the goal of achieving net-zero emissions by 2050.

⁷²⁰ *Ibid.*, note 715.

6.5 Conclusion

This chapter discusses three categories of breakthrough technologies: (1) direct air capture, (2) carbon dioxide utilization technologies through biological, chemical, and electrochemical methods, and (3) future nuclear technology.

Direct air capture (DAC) involves removing carbon dioxide (CO₂) directly from the atmosphere. Currently, only a few pilot plants are testing DAC abroad. Traditionally, the cost of capturing high-concentration CO₂ (such as from natural gas processing emissions) is approximately 25 USD/tCO₂eq, while capturing low-concentration CO₂ (such as emissions from the power generation and cement industries) costs around 50 USD/tCO₂eq. However, the current cost of DAC exceeds 300 USD/tCO₂eq. Furthermore, the energy consumption in manufacturing capture agents and operating the DAC process still needs careful assessment to evaluate the overall carbon fixation effectiveness.

Beyond sequestration, CO₂ reutilization is an important pathway. Reutilization first requires reducing CO₂. For biological CO₂ utilization, current limitations include reaction rate, efficiency, and scaling challenges. In chemical and electrochemical processes, higher efficiency reactions are needed, but if these processes use electricity or hydrogen production, additional CO₂ emissions may be generated. Consequently, the use of renewable electricity is essential for future applications of these methods. Given Taiwan's current limited green energy supply, reducing CO₂ through chemical methods remains challenging. If low-cost green hydrogen imports or surplus renewable electricity become available in the future, these methods could become viable. Overall, to achieve the 2050 net-zero emissions target, Taiwan will need to develop CO₂ conversion technologies to mitigate emissions from petrochemical industry. Harnessing solar, wind, and other zero-carbon energy sources, combined with optimized biological and chemical catalytic processes, may enable the transformation of the traditional petrochemical industry into a low- or zero-carbon industry or even into one that synthesizes high-value fine chemicals.

In terms of advanced nuclear technology, Generation IV nuclear power has improved safety in the power generation process, significantly reduces the nuclear fuel required per unit of power, and does not produce CO₂. Its capacity factor is far greater than current green energy sources like solar or wind. However, nuclear power still faces challenges related to the safety of radioactive waste disposal sites and public acceptance.

Regarding emerging nuclear fusion technology, while Taiwan currently lacks the capability for independent development, it is essential to monitor international progress. If technological breakthroughs make nuclear fusion practical, Taiwan can promptly integrate into the international supply chain and adopt relevant power generation facilities, supporting Taiwan's goal of net-zero emissions.

Chapter 7 Economic and Social Enabling Factors

Sections

7.1 Introduction

7.2 Economic Aspects

7.3 Social Dimensions

7.4 Conclusion

7.1 Introduction

Our recommendations focus on scientific and technological research and development (R&D), but one cannot ignore the influence of social, economic, governance and other factors. Despite the fact that these aspects have been discussed in many reports and publications, this chapter will elaborate on some of the key points. For a detailed discussion, please refer to the original papers or publications.

The Global Risks Report 2022 of the World Economic Forum (WEF) lists the top 10 global risks over the next 10 years.⁷²¹ “Climate Action Failure” is identified in the report as the number 1 risk and the most severe threat facing mankind. The COVID-19 pandemic triggered a global economic crisis and many governments chose to prioritize short-term measures to restore economic growth and ignore possible long-term impacts of climate change. Generally speaking, if the world does not take the impact of increased global carbon emissions on global warming seriously, and if the world fails to take effective action to deal with the potential impacts and problems of climate change, we won’t be able to achieve a net-zero carbon transition.

At the same time, over the years, declarations of the UN Climate Change Conferences (COP) have repeatedly asked people to reflect on their past actions and actively make changes. Governments around the world have also increased their investment in the R&D of various carbon reduction and clean energy technologies to promote the transition to net zero and find a way for economic development and environmental protection to coexist. However, at this critical moment, apart from accelerating scientific R&D, the public sector also needs to take economic measures to facilitate the promotion of net-zero emissions in order to change the behaviors of individuals and businesses. For example, by paying fees for carbon emissions, businesses will be forced to include costs related to carbon emissions in their production costs. Fostering green finance can help businesses make the transition to net zero, respond to changes in Taiwan’s electricity prices and the introduction of international carbon border adjustment taxes, and gradually improve the resilience of individuals, businesses and society. Meanwhile, the public sector must take social enabling measures to shape the prospect of a net-zero transition and carbon reduction. For example, measures should be taken to improve the governance framework, promote

⁷²¹ World Economic Forum (2022). *Global risks report 2022*. <https://www.weforum.org/reports/global-risks-report-2022>

public-private partnerships, encourage civil society participation and establish communication channels to talk to the public. This is because the transition to net zero means the transition of all sectors and thus requires public support, participation and action. At the same time, we also need to ensure that the rights and interests of all stakeholders can be protected during the transition period. Thus, the public sector should promote the concept of net-zero emission via education and guide a just social transition with long-term and systematic thinking. To promote net-zero emission strategies that are just and sustainable for all generations, localized adaptations will be needed so we can gradually achieve Taiwan's goal to reach net zero by 2050.

To sum up, this chapter will focus on socio-economic policies and strategies needed to support the net zero technologies discussed in previous chapters.

7.2 Economic Aspects

Summary

As an export-oriented country, Taiwan has to establish a suitable carbon pricing system corresponding to our goals to reach net-zero emissions. By implementing fees for carbon emissions, businesses will include the cost of carbon emissions in their production costs. Only then can we help businesses make the transition to net-zero emissions, stimulate the growth of a low-carbon economy and help Taiwan achieve net zero. Such measures can also help exporters respond to future international carbon border adjustment taxes. On the other hand, improving green finance can help businesses minimize the impacts they may face during the transition. In addition, it is necessary to continue promoting a circular economy and ensure that electricity prices can reasonably reflect external environmental costs, while promoting a comprehensive transformation of the socio-economic system to help achieve Taiwan's goal of net-zero emissions. Considering Taiwan's situation, our recommendations are as follows:

1. Charge carbon taxes and establish a carbon pricing scheme as soon as possible to promote the concept that one should pay for carbon emissions. In the short term, carbon taxes should be imposed, and the operation mechanisms required for carbon trading should be improved to facilitate the long-term operation of the carbon trading system.
2. Improve the mechanisms to allocate funds collected from carbon taxes to ensure effective use.
3. Optimize regulations on Taiwan's green finance to encourage financial institutions to give priority to small and medium-sized enterprises (SMEs), investments related to green and sustainable start-ups, and companies with less-than-ideal ESG performance but are willing to make changes.
4. Improve Taiwan's regulatory environment and promote policy incentives related to circular economy.
5. Redesign the electricity pricing mechanism to ensure that Taiwan's electricity prices can reasonably reflect external environmental costs and help improve the market competitiveness of zero-carbon electricity. However, appropriate plans should be in place to cope with the adverse impact that electricity price adjustments may have on low- and middle-income households.

7.2.1 Introduction: To Reach Net Emissions by 2050, We Need to Use Economic and Financial Tools

In previous chapters, we have emphasized the importance of gradually deploying and applying tools made available through technology R&D to achieve the vision of net-zero emissions by 2050. In addition, the government can also use macroeconomic incentives and microeconomic policies to guide systematic adjustments in finance, investment and employment so as to increase the driving force for industrial and social transformation toward sustainability, green, and low carbon. This is important for Taiwan to seize the once-in-a-century opportunity to make the economic, industrial, and social shift to net zero emissions.

According to scholarship on the macroeconomic and financial policy tools related to sustainability and a green economy (Heine et al., 2021; Climate Bonds, 2021; Krogstrup et al., 2019), the government's economic tools can be roughly divided into three major categories: macroeconomic policies, financial policies and other economic tools^{722,723,724}.

- Macroeconomic policies include taxation (such as commodity taxes, energy taxes, carbon taxes, and carbon border taxes), tax reductions, carbon trading, electricity prices, economic growth rates, and the development of a circular economy/green economy;
- Financial policies include providing businesses with diversified fund management tools (including bonds, loans, investments, financial products, etc.), along with supporting measures, such as ESG rating systems, Task Force on Climate-related Financial Disclosures (TCFD) or systems like green/sustainable classification standards (green taxonomy);
- Other economic tools include government subsidies for R&D on green energy technologies, investment in green energy technology startups, encouragement of green procurement, rewards and consultation for green employment, etc.

⁷²² World Bank (2021). Toolkits for policymakers to green the financial system. World Bank, Washington, DC. <https://openknowledge.worldbank.org/handle/10986/35705> License: CC BY 3.0 IGO.

⁷²³ Climate Bonds (2021). Carbon pricing for climate action: New countdown to COP policy briefing. <https://www.climatebonds.net/2021/09/carbon-pricing-climate-action-new-countdown-cop-policy-briefing>

⁷²⁴ Krogstrup, S., Oman, W., von Allmen, U. E., Celasun, O. (2019). Macroeconomic and financial policies for climate change mitigation: A review of the literature. *IMF Working Papers*, 2019(185) A001. <https://www.elibrary.imf.org/view/journals/001/2019/185/article-A001-en.xml>

See Figure 7.2.1 for details. In particular, the encouragement of innovative R&D of carbon reduction green energy technologies and the incubation of startup companies for these technologies will not only help Taiwan achieve the goal of net zero but also promote industrial transition and technology upgrading.

Many economic tools of the government have already been used in the existing energy reduction framework and will not be analyzed in detail here. This section will focus on tools that have been used in recent years to promote net-zero emissions in the international community, such as carbon pricing and green finance. Major international initiatives suggest that appropriate carbon pricing can motivate businesses and countries to invest in low-carbon technologies or reduce carbon emissions. Hence, to ensure that carbon pricing can effectively drive substantial changes, other financial policy tools should also be used. According to the World Bank, rather than relying only on carbon pricing for green transition, a combination of green bonds and carbon pricing can lead to better performance⁷²⁵. Moreover, promoting a circular economy is considered to be an important carbon reduction strategy in addition to renewable energy and better energy efficiency. The adjustment of electricity prices can also encourage people and businesses to reduce carbon emissions. Hence, this section will focus on carbon pricing, green finance, circular economy and electricity prices and offer suggestions on how to achieve net zero with economic tools.

⁷²⁵ Heine, D., Semmler, W., Mazzucato, M., Braga, J. P., Flaherty, M., Gevorkyan, A., Hayde, E., Radpour, S. (2019). *Financing low-carbon transitions through carbon pricing and green bonds*. Policy Research Working Paper No. 8991. World Bank, Washington, DC. © World Bank. <https://openknowledge.worldbank.org/handle/10986/32316> License: CC BY 3.0 IGO.

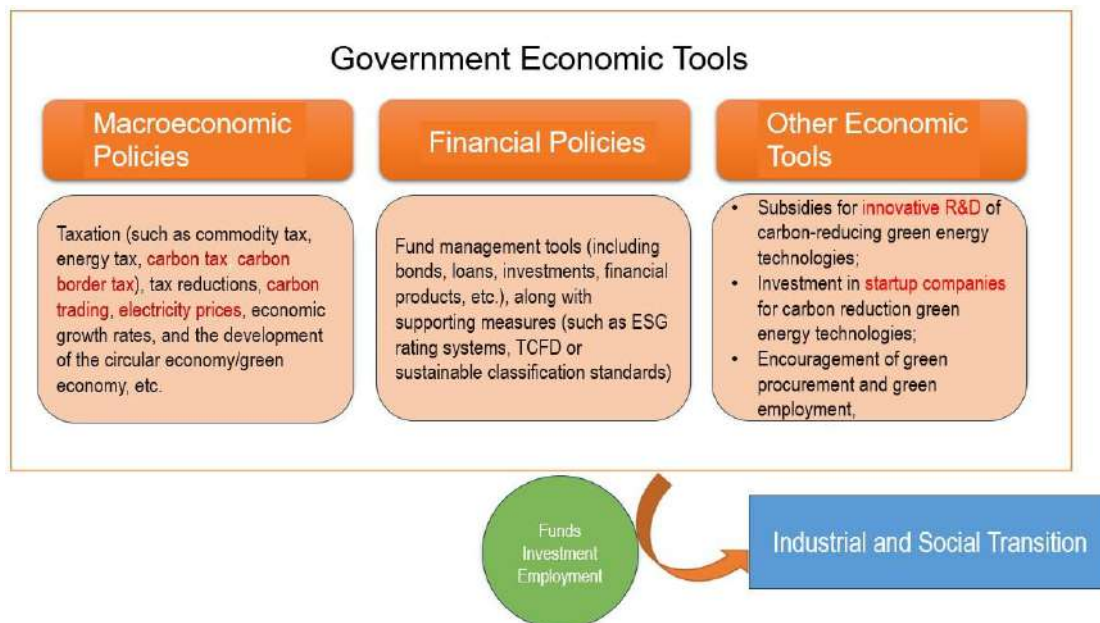


Figure 7.2.1 Economic Tools, Financial Policies and Other Tools Related to Sustainability and Green Economy^{726,727,728}

7.2.2 International Trends: Carbon Pricing, Green New Deal Programs and Economic Tools

1. Carbon Pricing

Carbon pricing tools aim to internalize the costs of emitting carbon; in other words, the impact of carbon emissions on the environment can be converted into costs that need to be paid by polluters. At the same time, carbon pricing creates incentives for consumers, producers and investors to change their behaviors to control carbon emissions and ultimately achieve the result of climate change mitigation⁷²⁹. Generally speaking, carbon pricing can include government programs as well as voluntary pricing by private companies.

(1) Government Carbon Pricing

Government carbon pricing is a tool to guide businesses to reduce their greenhouse gas emissions. Government carbon pricing includes explicit carbon pricing and implicit carbon pricing. Explicit carbon pricing includes Emission Trading Systems (ETS), carbon taxes and energy taxes. According to the Organization for Economic Cooperation and Development (OECD), compared with other policy approaches,

⁷²⁶ *Ibid.*, note 722

⁷²⁷ *Ibid.*, note 錯誤! 尚未定義書籤。.

⁷²⁸ *Ibid.*, note 錯誤! 尚未定義書籤。.

⁷²⁹ Daigee Shaw (2021). Carbon pricing mechanism. How should Taiwan choose? Lecture, The Risk Society and Policy Research Center, National Taiwan University.

explicit carbon pricing is considered the most cost-effective method to create incentives to make the transition towards a zero-carbon economy⁷³⁰. The scope of implicit carbon pricing includes Feed-in Tariffs (FiT) and voluntary action plans under energy-saving laws (such as subsidies, tax reductions, etc.) to provide policy incentives for emission reductions. However, some scholars believe that although emission reductions can lower external costs, it does not necessarily lead to external benefits. Hence, the effect of carbon reduction through subsidies like FiT is not obvious⁷³¹.

(2) Private Company Voluntary Carbon Pricing

Companies can estimate their own carbon prices to promote low-carbon investments and decide strategic actions to reduce their own carbon intensity. According to research by Nomura⁷³², the objective of private company voluntary carbon pricing includes driving low carbon investment or energy efficiency, changing internal behaviors, identifying and seizing low-carbon opportunities, and navigating GHG regulations. At present, nearly 50% of the world's renowned companies have implemented or planned to implement internal carbon pricing⁷³³. In Taiwan, companies like Formosa Plastics Corp., Delta Electronics Inc., and Yuanta Financial Holding Co., Ltd. have internal carbon pricing systems in place. Delta Electronics, for example, set a consistent internal carbon price of USD 300/tCO₂eq in 2021⁷³⁴.

According to World Bank statistics in 2021, 64 governments around the world have used carbon pricing tools (ie: carbon taxes, Emission Trading Systems) (see Figure 7.2.2 for details), covering 21.5% of global carbon emissions, and carbon pricing in 2020 has generated a total of 530 billion USD in revenue⁷³⁵. Carbon prices ranged between 40 to 80 USD/tCO₂eq in 2020. By 2030, carbon prices could reach 50-100

⁷³⁰ Nomura (2021). Carbon pricing and financial markets: The cheapest most expensive commodity. <https://www.nomuraconnects.com/focused-thinking-posts/carbon-pricing-and-financial-markets-the-cheapest-most-expensive-commodity/>

⁷³¹ Daigee Shaw, Wen-Hsiu Huang, Shih-Mo Lin, Yu-Hsuan Fu (2020). Carbon mitigation policy in Taiwan: Subsidies or taxes? *Green Economy*, 6 (Special Issue), pp. 1-23.

⁷³² *Ibid.*, note 730.

⁷³³ Industrial Sustainable Development Clearinghouse, Industrial Development Bureau, Ministry of Economic Affairs (2021). Nearly 50% of world-renowned companies have implemented or planned to implement internal carbon pricing. <https://proj.ftis.org.tw/isdn/Message/MessageView/1502?mid=59&page=1>

⁷³⁴ Delta Electronics, Inc. (2021). Recent milestones (Q1 2021). https://www.deltaww.com/services/csr/corporate_citizen/recent_milestones_ch.htm

⁷³⁵ World Bank (2020). *State and trends of carbon pricing 2020*. Washington, DC. <https://openknowledge.worldbank.org/handle/10986/33809> License: CC BY 3.0 IGO.

USD/tCO₂eq⁷³⁶. Nevertheless, this level is not enough to achieve the targets set in the Paris Agreement to limit temperature rise to less than 2 degrees Celsius. According to World Bank statistics, most advanced countries, including those in the European Union, set their carbon prices at 25 USD/tCO₂eq. South Korea in Asia sets the price at 16 USD/tCO₂eq, and Singapore at 4 USD/tCO₂eq. Differences in carbon prices are quite obvious among countries at different stages of development⁷³⁷. The report from the National Academy of Sciences (NAS) recommends that the U.S. government set their carbon prices at 40 USD/tCO₂eq and increase the prices by 5% every year. NAS also suggests the US set carbon prices for all sectors (including electricity, transportation, industry, and buildings) and establish a carbon emission trading system (ETS) to influence the public and private sectors in their decision-making processes⁷³⁸ and encourage innovative approaches of carbon reduction.

⁷³⁶ Carbon Pricing Leadership Coalition (2017). Report of the high-level commission on carbon prices. <https://www.carbonpricingleadership.org/report-of-the-highlevel-commission-oncarbon-prices>

⁷³⁷ World Bank (2021). *State and trends of carbon pricing 2021*. Washington, DC. <https://openknowledge.worldbank.org/handle/10986/35620> License: CC BY 3.0 IGO.

⁷³⁸ National Academy of Sciences (2021). *Accelerating decarbonization of the U.S. energy system*. <https://nap.nationalacademies.org/catalog/25932/accelerating-decarbonization-of-the-us-energy-system>

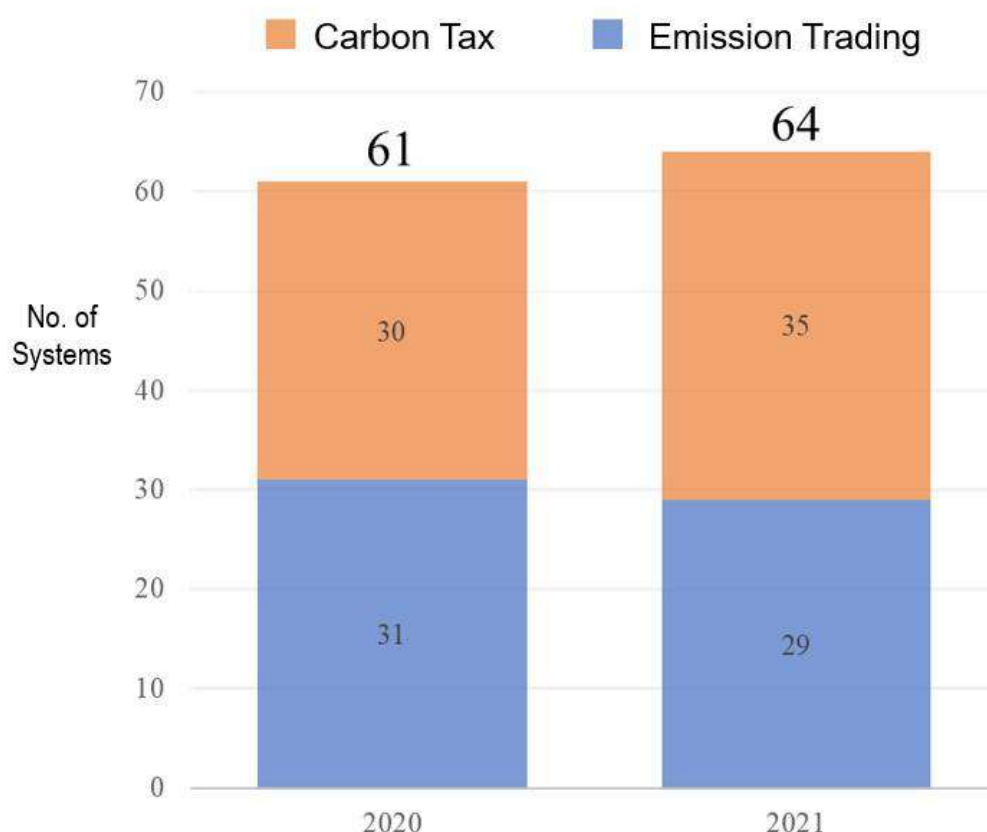


Figure 7.2.2 Global Carbon Pricing in the Past Two Years^{739,740}

We can also examine the potential of using carbon pricing to promote the development of green energy technology. Research findings show that removing subsidies for traditional fossil fuel power generation and using appropriate carbon pricing (such as 20 or 40 USD/tCO₂eq shown in Table 7.2.1), can reveal the true cost of traditional fossil fuel power generation and allow green energy (bottom half of Table 7.2.1) to compete with traditional fossil fuel power generation (top half of Table 7.2.1). For example, the levelized cost of a combined-cycle gas turbine (at a carbon price of 40 USD/tCO₂eq) is 0.093-0.218 USD/kWh. In comparison, solar energy (residential), solar energy (commercial), solar energy plus energy storage, geothermal and wind power are cost competitive.

⁷³⁹ *Ibid.*, note 735.

⁷⁴⁰ *Ibid.*, note 737.

Table 7.2.1 Comparison of the Levelized Cost of Traditional Fossil Fuel Power Generation and Green Energy Power Generation⁷⁴¹

Fossil fuel power generation	Levelized cost (Unit: USD/kWh) (Carbon price 20 USD/tCO₂)	Levelized cost (Unit: USD/kWh) (Carbon price 40 USD/tCO₂)
Coal	0.086	0.165
Combined-cycle gas turbine	0.053-0.164 (peak load)	0.093-0.218 (peak load)
Green energy power generation	Levelized cost (Unit: USD/kWh)	
Solar (residential)	0.147-0.221	
Solar (commercial)	0.067-0.180	
Solar energy plus storage	0.126-0.156	
Geothermal	0.056-0.093	
Wind power	0.026-0.050	

On the other hand, if we compare the total costs of system operation (including transportation) between traditional CCUS and direct air capture (DAC), appropriate carbon pricing (i.e. 100 USD/tCO₂eq or higher) will enable emerging CCUS technologies (like DAC) to compete and thus accelerate the development of such technologies. Current estimates of the comparative cost of negative emission technologies are shown in Table 7.2.2. **

⁷⁴¹ Lazard (2021). Lazard's levelized cost of energy analysis-version 15.0, levelized cost of energy comparison-sensitivity to carbon pricing. <https://www.lazard.com/media/451905/lazards-levelized-cost-of-energy-version-150-vf.pdf>

Table 7.2.2 Cost Estimates of Traditional CCUS and Negative Emissions Technologies
Such as DAC^{742,743,744}

CCUS (Carbon capture, compression and dehydration, transportation, injection, storage, monitoring)	Total cost (USD/tCO₂eq)
Coal carbon capture + pipeline transportation	65-113
Coal carbon capture + ship transportation	85-112
Natural gas carbon capture + pipeline transportation	94-142
Natural gas carbon capture + ship transportation	104-141
DAC capture + pipeline transportation	153-406
DAC capture + ship transportation	153-405

2. Carbon Trading

Carbon trading is a market-oriented tool to implement environmental policies. The government sets the limit of carbon emissions for businesses, so companies with lower emissions (i.e. companies who have successfully reduced their carbon emissions) can sell their emission rights (sellers) to other businesses, especially those whose annual emissions are expected to exceed the permitted emissions (buyers) through the supply and demand market of carbon trading, thereby providing incentives to encourage businesses to reduce their carbon emissions⁷⁴⁵. Among various carbon pricing tools, carbon taxes and carbon fees are easier to implement with low-cost. In comparison, an Emission Trading System requires the establishment of a measurement mechanism, so the trading costs are higher. However, the two tools can be used in parallel. An Emission Trading System can be further divided into a carbon credit trading system and an allowance trading system (Figure 7.2.3).

Carbon credit trading is a baseline-and-credit system that estimates potential

⁷⁴² Global CCS Institute (2021). Technology readiness and costs of CCS. <https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf>

⁷⁴³ Schmelz, W.J., Hochman, G., Miller K.G. (2020). Total cost of carbon capture and storage implemented at a regional scale: Northeastern and midwestern United States. *Interface Focus* 10: 20190065. <http://dx.doi.org/10.1098/rsfs.2019.0065>

⁷⁴⁴ UNECE (2021). UNECE technology brief - Carbon capture, use and storage. https://unece.org/sites/default/files/2021-03/CCUS%20brochure_EN_final.pdf

⁷⁴⁵ Sci-Tech Vista (2018) Mission carbon reduction: The advantages and disadvantages of carbon tax and carbon trading. <https://scitechvista.nat.gov.tw/Article/C000003/detail?ID=88553415-3d1a-4e78-b2f7-493ddfe3da7d>

reductions before carrying out a greenhouse gas reduction plan, and the government sets the limit of emissions. If a company (i.e., the emission source) proposes a specific project and is able to prove that the implementation of the project can reduce its emissions to be lower than the emission limit, then the difference between the actual annual emissions and the annual permitted emissions can be converted into a carbon credit. Trading of such carbon credit requires verification by a third party. This approach allows participants to develop under the premise of limiting their emissions, but the disadvantages are that the verification process is complex, transaction costs are high, and there is uncertainty in the overall effectiveness and reduction estimates⁷⁴⁶.

The allowance trading system focuses on total volume control. The government establishes an allocation system for emissions and sets the reduction targets or emission limits (cap) to be achieved during a specific period. The emission quota is divided among eligible participants in the trading system. Eligible participants can freely trade their allowance with each other, and no government permission is required before trading^{747,748}. However, annual verification is required at the end of the year to show that the actual emissions of each emission source are not higher than the allowance after trading. This approach has lower transaction costs, but the disadvantage is that it is restricted to specific participants, so it is a relatively closed system.

⁷⁴⁶ Ching-hua Pan (2007). Lesson of CO₂ emission trading to Taiwan financial industry. <https://www.twse.com.tw/ch/products/publication/download/0001000319.pdf>

⁷⁴⁷ *Ibid.*, note 746.

⁷⁴⁸ *Ibid.*, note 729.

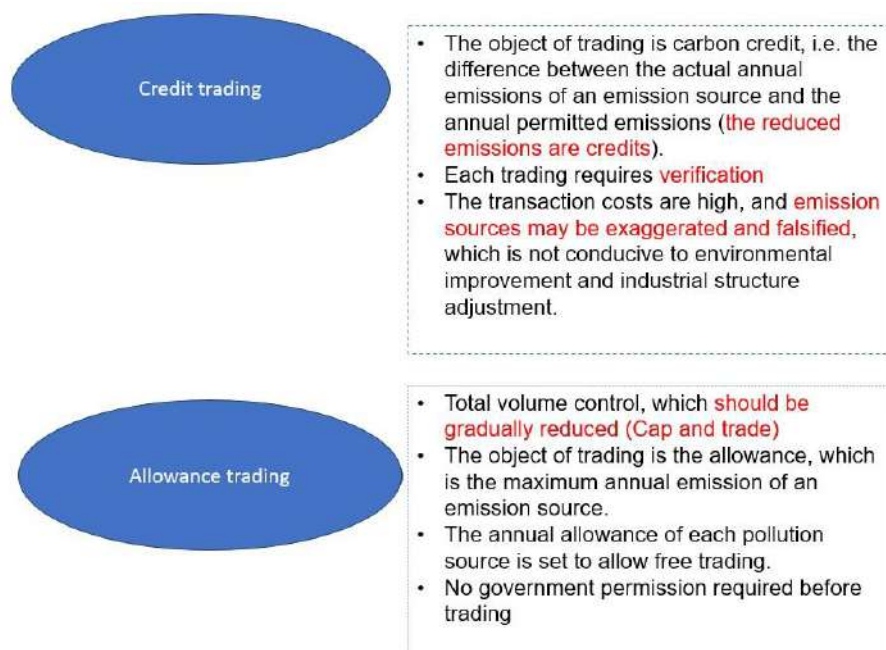


Figure 7.2.3 Carbon Credit Trading and Allowance Trading System⁷⁴⁹

3. Green New Deals and Economic Tools Recommended in Think Tank Reports

At present, many countries have adopted various economic tools in the promotion framework of their post-pandemic Green New Deals, including:

(1) Government Budget for Investment (Along with Funds from the Private Sector)

The European Green Deal Investment Plan aims to invest 260 billion euros every year for ten years, with a total of 1 trillion euros in funds. The funds come from both the public sector (EU budget) and loans from the private sector. It is hoped that the funds can be used for climate action, infrastructure, R&D and innovation, small and medium-sized enterprises, social investment and skill development⁷⁵⁰. The total budget of the American Jobs Plan is US\$2 trillion. Part of the funds will be used to improve infrastructure such as transportation, power supply systems, and building renewal. Some will be also used to invest in clean energy technologies^{751,752}. Based on its 2050 Green Development Strategy, Japan launched the Green Innovation Fund Project with

⁷⁴⁹ *Ibid.*, note 729.

⁷⁵⁰ Yingting Guo (2020). Key points of the “European green deal” action roadmap: Carbon tariffs, energy tax reform, green transition financing, and climate covenant. (Repost) Environmental Information Center. <https://rsprc.ntu.edu.tw/zh-tw/m01-3/climate-change/1408-1090508-1-enviro-center.html>

⁷⁵¹ White House (2021). FACT SHEET: The American jobs plan. <https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/31/fact-sheet-the-american-jobs-plan/>

⁷⁵² iKnow, Science & Technology Policy Research and Information Center NAR Labs (2021). In the U.S., Biden promotes a 2 trillion infrastructure plan to revive the U.S. economy. <https://iknow.stpi.narl.org.tw/Post/Read.aspx?PostID=17661>

a 2 trillion yen fund to support businesses by investing about 15 trillion yen for R&D in equipment and bold initiatives. The funds are managed by the New Energy and Industrial Technology Development Organization (NEDO)⁷⁵³.

(2) Tax Adjustment

Japan believes that it is not easy to achieve the goal of carbon neutrality by 2050. So, in addition to long-term R&D investment, it is necessary to encourage companies to invest in high-efficiency equipment. It is thus necessary to adjust the tax system to ensure that businesses receive strong support from the government as they make zero-carbon investments. Japan thus promotes (1) tax systems (tax deductions or special depreciation) to promote carbon-neutral investments; (2) for companies that work on business restructuring or reorganizing, a special exception is set up to raise the upper limit of tax deduction for loss carried forward; (3) expand the tax system to support businesses who are willing to increase their R&D even though the turnover decreases by more than 2% compared with turnover before COVID-19. The upper limit of tax deductions can be increased from the existing maximum of 25% to 30%⁷⁵⁴. The American Jobs Plan also proposed the Made in America corporate tax plan to eliminate federal tax reductions for the traditional petrochemical energy industry⁷⁵⁵.

(3) Green Finance Systems or Instruments

Following its Climate Innovation Finance Strategy 2020 (September 2020), Japan believes that investment from the private sector is needed for environmental protection, transition, and innovation. Hence, Japan uses Climate Transition Finance to encourage investment in low-carbon technologies during the transition period. For example, if a project lasting more than 10 years has been recognized by the government, the Finance offers a performance-linked interest subsidy program (with 1 trillion yen in financing within three years) so businesses can have a longer period to make the transition⁷⁵⁶. The National Academy of Sciences (NAS) recommends that the U.S. federal government should establish a green bank to provide loans for low-carbon or zero-carbon

⁷⁵³ International Cooperation Department, Ministry of Economic Affairs (2021). Japan's actions to achieve net-zero by 2050 (Economic Division, Taipei Economic and Cultural Representative Office in Japan). https://mnscdn.moea.gov.tw/MNS/ietc/bulletin/Bulletin.aspx?kind=54&html=1&menu_id=33779&bull_id=8838

⁷⁵⁴ Cabinet Office of Japan (2021). Green growth strategy through achieving carbon neutrality in 2050. <https://www.cas.go.jp/jp/seisaku/seicho/seichosenryakukaigi/dai11/siryou2-2.pdf>

⁷⁵⁵ Cathay Pacific Bank (2021). Biden's build back better plan is about to be launched. A complete analysis of US finances! (Part 1). <https://www.cathayrobo.com/welcome/trends/articles/050069>

⁷⁵⁶ *Ibid.*, note 754.

technologies, business models and infrastructure⁷⁵⁷.

As mentioned earlier, the issue of net-zero emissions is an international issue. As an export-oriented country, Taiwan should plan to set up an appropriate carbon pricing system that corresponds to net-zero emissions goals. By promoting the concept that emitters should pay for carbon emissions, the external cost of carbon emissions can be included in the production cost to stimulate a low-carbon economy and support companies to make the transition to net-zero emissions. At the same time, this approach can help companies respond early to the risk of high international carbon border taxes when they export in the future. There are four reasons why Taiwan should urgently develop carbon pricing: (1) To reflect the market: At present, carbon emitters (ie: the energy and manufacturing industries) have not included their carbon emission costs in their production costs. Carbon pricing can ensure that these external costs can be included to reflect the true market costs; (2) Use of funds: The government can charge carbon emission taxes and fees to control the emission by price, forcing emitters to reduce their emissions. The funds collected can be used for climate actions in the net-zero emission transition; (3) Promoting R&D: Carbon pricing can provide price information to enable energy and negative emission technologies to compete with fossil fuels and accelerate the transition to net zero; (4) Economic/industrial transformation: It can encourage businesses to be innovative with existing R&D as well as the emergence of new businesses for economic growth.

7.2.3 Development Needs, Current Status, and Challenges of Economic Tools for Carbon Reduction in Taiwan

1. Carbon Taxes/Fees

The domestic regulations related to carbon taxes and fees at present include the Commodity Tax Act, the Energy Tax Act (Draft), and the Climate Change Response Act⁷⁵⁸, the breakdown of which is as follows:

- Oil/Gas in the Commodity Tax Act: Gasoline, diesel, kerosene, aviation fuel, fuel oil, solvent oil, liquefied petroleum gas, etc. are taxed on a specific basis.
- Energy Tax Act (Draft): The Ministry of Finance, in consultation with the National Development Council, the Ministry of Economic Affairs, and other

⁷⁵⁷ *Ibid.*, note 錯誤! 尚未定義書籤。.

⁷⁵⁸ *Ibid.*, note 729.

pertaining agencies, all believe that the imposition of an energy tax will impact domestic oil and electricity prices, cost of living, and economic growth, which should be implemented when the economy is in better shape.

- Climate Change Response Act: On October 21, 2021, the Environmental Protection Administration of the Executive Yuan announced the draft amendment to the “Greenhouse Gas Reduction and Management Act” and changed the name to the “Climate Change Response Act.” The collection of carbon fees was also added as an economic incentive tool. In addition to being included in the fund, carbon fee revenue may be used to subsidize or incentivize the development of low-carbon and negative emission technologies and industries, as well as invest in GHG reduction technologies. In response to the international Carbon Border Adjustment Mechanism (CBAM), Article 27 was introduced, which includes authorization regulations on the calculation and verification methods of carbon content of specific products, the collection of carbon fees on imported products, and the basis for authorizing the competent authority to formulate fee collection measures⁷⁵⁹.

The difference between the carbon fee currently promoted in Taiwan and other proposed approaches, such as a carbon tax, lies in the collecting authority and restrictions on the use of funds (see Table 7.2.3). The current plan in Taiwan focuses on a carbon fee to be collected by the Environmental Protection Administration of the Executive Yuan, and included in a dedicated fund, with relatively significant limitations on the use of the funds, making it less flexible for purposes like a just transition. In contrast, a carbon tax, similar to other taxes, would be part of government revenue with no particular restrictions on the use thereof, allowing for a more flexible allocation and utilization of funds.

⁷⁵⁹ Environmental Protection Administration, Executive Yuan (2021). General explanation of the draft amendment to the Greenhouse Gas Reduction and Management Act. <https://enews.epa.gov.tw/DisplayFile.aspx?FileID=26E59EF644F21D93>

Therefore, if the carbon fee system is adjusted and changed to a carbon tax system led by the Ministry of Finance, the funds collected by the government can be used more broadly for climate action options for a net-zero transition, such as:

- To offset new burdens on consumers, producers, communities, and the broader socio-economic system brought by carbon taxation. [Examples: rebates to citizens (with a focus on low-income individuals), support for skill and talent cultivation for impacted groups (e.g., indigenous peoples)].
- To support various efforts that further reduce GHG emissions, such as investment in research and development of renewable energy and other infrastructure related to innovation and net-zero emissions, conducting social communication about net-zero emissions [for targeting groups impacted economically (low-income individuals) and geographically (indigenous peoples)], saving and accumulating funds for carbon removal and purchasing carbon removal services, and so forth.
- To mitigate the hazards introduced by climate change (including investment in coastal protection and infrastructure that can reduce impacts of extreme weather events). In addition, a carbon tax can also be allocated like other general taxes to fund other public priorities, effectively optimizing the use of funds^{760,761,762}.

⁷⁶⁰ Man, D. B. and Morris, A. C. (2016). How to use carbon tax revenues. <https://www.brookings.edu/wp-content/uploads/2016/07/howtousecarbontaxrevenueamarronmorris.pdf>

⁷⁶¹ Liao, T.S. (2020). Constructing a carbon tax system: A study of carbon tax legislation in British Columbia, Canada. *Public Finance Review*, 49(5). <https://www.mof.gov.tw/download/4501e59f440947cf84f146f409737a5f>

⁷⁶² *Ibid.*, note 729.

Table 7.2.3 Carbon Fee vs. Carbon Tax⁷⁶³

Item	Carbon Fee (Current Domestic Direction)	Carbon Tax (Other Proposed Direction)
Levy Objective	To promote voluntary emissions reduction from emitters	To promote voluntary emissions reduction from emitters
Levy Target	Carbon dioxide (or greenhouse gases) emissions from fossil energy, goods, or services (based on respective embedded emissions)	Carbon dioxide (or greenhouse gases) emissions from fossil energy, goods, or services (based on respective embedded emissions)
Levy Authority	Environmental Protection Administration, Executive Yuan (Fund)	Ministry of Finance (National Tax Revenue)
Use Restrictions	The revenue is incorporated into a closed fiscal circulation system (special fund account), earmarked for the prevention and control of the specified pollution. *	Same with other tax revenues, it becomes part of government revenue, with no specific restrictions on its use.

* Limited by the Justices' interpretation regarding the dispute over the implementation of the Air Pollution Control Act and the collection of air pollution fees by the Environmental Protection Administration, Executive Yuan.

As for recommendations for the scope of the carbon fee, domestic surveys by *Business Weekly* and Greenpeace suggest that over 80% of businesses expect a minimum carbon fee set at 10 USD by the government, gradually rising to match international standards⁷⁶⁴. The “Carbon Pricing Options for Taiwan Report,” prepared for Taiwan Environmental Protection Administration suggests that we could start with a lower carbon fee to minimize the initial impact on competitiveness and reduce the need for additional support to businesses. However, the report also recommends that in the long run, it is necessary to establish and maintain a clear price trajectory. For instance, our government could make a clear statement that it will gradually increase carbon pricing over time, raising the levy rate by 10% annually, thereby providing a reliable price signal to support investments in low-carbon technologies⁷⁶⁵. As a result, even if the initial carbon fee is lower, it is still necessary to gradually increase the fee

⁷⁶³ *Ibid.*, note 729.

⁷⁶⁴ Kuan, W.Y. (2021). How high Should Taiwan's carbon fee be? Companies' desired prices are far lower than those of South Korea and the EU. *Business Weekly*. https://www.businessweekly.com.tw/magazine/Article_mag_page.aspx?id=7004746

⁷⁶⁵ Environmental Protection Administration, Executive Yuan (2020). Carbon pricing options for Taiwan report – Prepared for Taiwan Environmental Protection Administration. <https://enews.epa.gov.tw/DisplayFile.aspx?FileID=3B2E3FFF2ACE0E80>

in response to international trends. Otherwise, industries relying on export will ultimately be impacted by CBAM and suffer losses. Furthermore, after reaching a high price saturation point, the system should transition to an emissions trading scheme (detailed later), ultimately forming a carbon trading market.

2. Carbon Allowance Trading

The development of a carbon trading system in Taiwan has gone through several stages, including the implementation of a pilot credit project in 2010; the establishment of a carbon trading information platform in 2012-2014; the implementation of Regulations for Gas Emission Inventory and Registration Management in 2016; the launch of the performance standard reward and micro-credit project in 2018; and finally the promulgation of the Climate Change Response Act (Draft) in 2021, marking a significant step forward for carbon pricing policy. The planned greenhouse gas cap-and-trade system currently includes both credit trading and allowance trading (Table 7.2.3). A carbon fee will be implemented first, but a detailed system needs to be designed first. The main considerations are that the emission sources in Taiwan are concentrated, the market size is small, and the development mechanism is not yet mature. The transaction cost of implementing a carbon fee is relatively low. If an allowance trading mechanism is adopted, it will face challenges such as insufficient market liquidity and competitiveness, which will require further development of trading mechanisms. In addition, transaction costs will gradually increase due to the need for business to create carbon evaluation with help from consulting firms, as well as the cost of the review, verification, and inspection of credit projects by the Environmental Protection Administration, Executive Yuan. Therefore, in the short term, carbon taxes (or fees) should be employed as the reduction tool in Taiwan. In the long term, in order to achieve the goal of Net Zero by 2050, it is necessary to combine allowance trading with carbon taxes (fees) to reduce economic efficiency losses. Furthermore, carbon taxes (fees) have a broad and direct impact, first by fostering awareness among the public and industries that carbon emissions come with a price, while simultaneously obtaining emissions data through tax (fee) collection. They can also help reduce the costs of creating an allowance trading system, as well as the high costs of conducting carbon inventories⁷⁶⁶. Hence, a carbon allowance trading system should still be

⁷⁶⁶ Shaw, Daigee; Chien, Yu-lan; Tsai, Li-hsueh; Shaw, D., Hung, C. M., & Lo, S. F. (2010). A comparison of carbon tax and carbon trading and an examination of their compatibility. *Monthly Journal of Taipower's Engineering*, 747, 59-66.

established step by step and have its measurement standards continuously refined. It is especially important to note that numerous domestic companies, in order to meet customer requirements, intend to purchase carbon credits from abroad. However, there have been instances in the past where companies exploited loopholes in the United Nations Clean Development Mechanism (CDM) to develop “garbage” carbon credits without actual additionality, and these credits are still circulating in the international market^{767,768}. Moreover, there have been cases of fraud domestically in the name of carbon trading⁷⁶⁹. Therefore, if we do not establish a carbon trading market of our own, our companies will be forced to purchase carbon credits from abroad, and the relevant funds will eventually flow overseas. As a result, we will lack incentives to encourage our companies to invest in sustainable industries and fail to form a positive cycle for our national carbon reduction effort as a whole⁷⁷⁰. Consequently, to promote substantial carbon reduction in Taiwan, we need to eventually establish a domestic carbon trading market. In the meantime, we can also consider participating in international carbon trading markets (such as that of the EU) or a regional carbon trading market formed by the East Asian countries. A larger number of buyers and sellers will lead to lead to greater transaction opportunities, which can increase market liquidity and provide domestic enterprises with more options for participating in the international markets⁷⁷¹.

3. Green Finance

Green finance and investing aim to spur a corporate transformation using capital. Green financing mainly focuses on environmental protection, sustainable development, and energy decarbonization. It involves banks providing loans to businesses or raising funds through public bond issuance. Currently, there are multiple syndicated loans involving large enterprises and organizations in Taiwan. Nevertheless, most of them are more aimed at enhancing corporate image (for related domestic and foreign instruments, please refer to Table 7.2.4).

⁷⁶⁷ The Epoch Times (2022). With concerns over insufficient carbon inventory capacity, carbon credit scholars call for Taiwan first. <https://www.epochtimes.com/b5/22/1/21/n13520632.htm>

⁷⁶⁸ Liu, C.-E. (2022). What kind of carbon credit market does Taiwan need? *CSR@CommonWealth*. <https://csr.cw.com.tw/article/42368>

⁷⁶⁹ Central News Agency (2021). Fake carbon credit investments defraud over 100 people of NT\$ 160 million, Hsinchu prosecutors arrest 2 suspects. <https://www.cna.com.tw/news/asoc/202108110250.aspx>

⁷⁷⁰ *Ibid.*, note 768.

⁷⁷¹ Chen, P. (2011). Preliminary discussion on the east Asian carbon trading common market. *Circular economy and energy conservation and carbon reduction*, CTCI Foundation. <https://www.ctci.org.tw/media/3847/東亞碳交易共同市場芻議論文-陳筆-991221.pdf>

Green investing on the other hand primarily involves investors allocating capital to enterprises that focus on economic, environmental, and social goals⁷⁷², as well as funds that manage sustainable (or green) indices. The goals of green investment are to reduce greenhouse gas emissions, enhance natural resource efficiency, protect the natural environment, preserve biodiversity, and promote environmental sustainability. For effective promotion in these regards, relevant investment metrics and information disclosures (such as the Task Force on Climate-related Financial Disclosures, TCFD) are necessary. Green investment targets include stocks and bonds of companies emphasizing environmental and sustainable development; stocks and shares of companies in renewable or new energy sectors; green infrastructure for transportation and water resources; green real estate investment (green finance and green buildings); sustainable farms/forestry farms/ranches/aquaculture farms⁷⁷³.

⁷⁷² Green Investment Group (2016). *Green investment handbook - A guide to assessing, monitoring and reporting green impact*. <https://www.greeninvestmentgroup.com/assets/gig/who-we-are/our-impact-and-measurement/A-Guide-to-the-Green-Investment-Handbook-Simplified-Chinese.pdf>

⁷⁷³ Green Impact (2019). Green investment. <https://greenimpact.cc/en/article/kx3rk/green-investment>

Table 7.2.4 Types of Green Financing Products^{774,775,776,777}

Category	Type	Cases
Loans	e.g., • Green Loans • Sustainability-linked Loans	Kreditanstalt für Wiederaufbau (KfW) offers three project-based financing plans, funding 10 offshore wind power projects on behalf of the German government to accelerate the expansion of offshore wind power development in Germany.
Bonds	e.g., • Green Bonds • Sustainability Bonds • Sustainability-linked Bonds	The European Commission issued NextGenerationEU green bonds to provide funding for green policies. O-Bank issued its first green bond (NT\$500 million) to support renewable energy and energy technology development. Enel, an Italian power company, set a predefined Sustainability Performance Target (SPT) of 55% renewable energy capacity by December 31, 2021.

At present, the government and the private sector in Taiwan have planned and created various financial tools such as green investment/financing and green procurement⁷⁷⁸. Coupled with the Green Finance Action Plan of the Financial Supervisory Commission (FSC), these tools strengthen the support for green and sustainable industries. For example, since 2017, the FSC has implemented its Green Finance Action Plan 1.0, encouraging financial institutions to engage in four strategies: i.e., invest in and finance green energy industries, promote the development of relevant

⁷⁷⁴ World Bank (2021). What you need to know about green loans. <https://www.worldbank.org/en/news/feature/2021/10/04/what-you-need-to-know-about-green-loans>

⁷⁷⁵ Taiwan Institute for Sustainable Energy (2021). How green are Wall Street banks? Major banks accelerate green investment. <https://taise.org.tw/post-view.php?ID=235>

⁷⁷⁶ Loan Syndications & Trading Association (2021). Sustainability linked loan principles (SLLP). <https://www.lsta.org/content/sustainability-linked-loan-principles-sllp/>

⁷⁷⁷ CTCI Foundation (2017). *Promoting green finance to facilitate the development of green energy industries*. https://www.ctci.org.tw/media/4684/2017-10_專題報告-推動綠色金融以促進綠能產業發展.pdf

⁷⁷⁸ This refers to market-oriented mechanisms and financial products to control pollution and emissions, maintaining ecosystems, and preventing environmental damage from industry. Reference from Toxic and Chemical Substances Bureau, Environmental Protection Administration, Executive Yuan. (2019). *Financial instruments for green finance*. <https://topic.epa.gov.tw/greenchem/cp-374-8072-a055c-1.html>

markets like a green bond market in Taiwan, facilitate the development of green financial products or services, and require disclosures of significant ESG information in their Corporate Social Responsibility (CSR) reports.

Moreover, the Green Finance Action Plan 2.0 promulgated in August 2020 covers eight additional aspects⁷⁷⁹. Please refer to Figure 7.2.4 for details of the vision, goals, core strategies, and aspects.



Figure 7.2.4 Green Finance Action Plan 2.0⁷⁸⁰

Recent development has centered around investments in the green energy sector by insurance funds, financing for green technology, financing for offshore wind, the green bond market and the launch of green financial products. Additional effort has focused on developing ESG information and climate-related financial disclosures (TCFD). On the one hand, these steps strengthen the quality and content of public information disclosed by TWSE/TPEX listed companies. On the other hand, they encourage financial institutions to invest in sustainable development.

There are still areas for improvement in our promotion of green finance. For instance, the majority of investment and financing schemes at present are concentrated on large enterprises. Small and medium-sized enterprises (SMEs) have limited resources and face greater challenges in accessing information, funding, and talent

⁷⁷⁹ Financial Supervisory Commission (2020). Green finance action plan 2.0. <https://www.fsc.gov.tw/websitedownload?file=chfsc/202012241329020.pdf&filedisplay=綠色金融行動方案 2.0 簡報.pdf>

⁷⁸⁰ *Ibid.*, note 779.

compared to large enterprises. They are also more vulnerable to the impacts of a net-zero transition. Hence, SMEs that are willing and need to transform, or companies with moderate sustainability performance that still have room for improvement, should be prioritized as green finance targets. Various means and resources, such as preferential interest rates, initial development funds, project guidance, and credit enhancement mechanisms, should be made available, providing funding guarantees and support to SMEs that need to transform and startups that provide green/sustainable products and services. Enterprises and startups will thus be guided toward making progress and accelerating their transformation.

4. Circular Economy

In recent years, the international community has actively promoted the idea of a circular economy, with countries incorporating the concept into their policymaking. The European Union in particular has enacted regulations, hoping to contribute to energy conservation and carbon reduction. Recent discussions on carbon reduction in Taiwan have also frequently mentioned a circular economy, highlighting its growing importance. In fact, circular economy is not a completely new topic, but rather a continuation of the reshaping of existing industrial ecosystems.

The concept of a circular economy emphasizes a restorative industrial system for resources, with cycles of production, consumption, and recycling/reuse. The current economic model extracts materials from the Earth, manufactures products, and finally discards them as waste, which is a linear process. In contrast, the model of a circular economy aims first and foremost to stop producing waste⁷⁸¹. By changing production, consumption, and recycling/reuse patterns, it aims to achieve sustainable development⁷⁸². Therefore, a circular economy reduces waste generation or recycles waste through the use of renewable energy, redesigning materials, products, and processes, and even through innovative business models⁷⁸³.

The government is taking the lead in guiding the private sector towards a circular economy by setting an example, including the Executive Yuan's Circular Economy

⁷⁸¹ Ellen MacArthur Foundation (2021). What is a circular economy? <https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview>

⁷⁸² Executive Yuan (2019). Circular economy promotion plan. <https://www.ey.gov.tw/Page/5A8A0CB5B41DA11E/18ef26a4-5d05-4fb3-963e-6b228e713576>

⁷⁸³ Taiwan Sugar Corporation (2019). What is circular economy? <https://www.taisugar.com.tw/circular/CP2.aspx?n=11216>

Promotion Plan⁷⁸⁴ and the Environmental Protection Administration's 2018-2020 Resource Recycling Promotion Plan⁷⁸⁵. The Environmental Protection Administration enacted a Resource Recycling Act as early as 2002 and formulated a Resource Recycling Promotion Plan in 2003, calling on various ministries and agencies to jointly promote resource recycling. President Tsai also clearly declared in her 2016 inauguration speech that she would lead Taiwan toward an era of circular economy. Subsequently, in 2018, the Environmental Protection Administration approved the 2018-2020 Resource Recycling Promotion Plan, establishing promotion strategies from four angles: production, consumption, waste management, and secondary raw material markets. At the end of 2018, the Executive Yuan also approved a Circular Economy Promotion Plan, establishing four strategies including innovative research and development and industrial symbiosis. It set up the Circular Economy Promotion Office⁷⁸⁶ under the Ministry of Economic Affairs to carry out interagency and interdisciplinary communication and integration.

In line with international trends and government policies, the private sector is also making every effort to promote a circular economy. Private organizations and alliances are springing up, including non-profit organizations such as Circular Taiwan Network, Circular Economy and Innovative Transformation Association, Taiwan Society for Circular Economy, and Sustainable and Circular Economy Development Association, all dedicated to promoting the concept of a circular economy. Furthermore, to promote innovation and implementation across various sectors, the public and private sectors have collaborated to hold an annual Taiwan Circular Economy Week⁷⁸⁷ since 2019. The event brings together different types of activities, showcasing practical achievements to domestic and international audiences and driving the concept of a circular economy. Aside from showcasing achievements, the Taiwan External Trade Development Council (TAITRA) also organizes the Circular Economy Taiwan event, with dedicated zones for environmental technology and new business models,

⁷⁸⁴ *Ibid.*, note 782.

⁷⁸⁵ Environmental Protection Administration, Executive Yuan (2022). Circular economy policy. <https://smmdb.epa.gov.tw/circulation/index>

⁷⁸⁶ The Circular Economy Promotion Office is commissioned by the Industrial Development Bureau, Ministry of Economic Affairs, to the Industrial Technology Research Institute for assistance in its operation. <https://www.cepo.org.tw/Default.aspx>

⁷⁸⁷ Ministry of Economic Affairs, Environmental Protection Administration, Executive Yuan, Council of Agriculture, Executive Yuan, Ministry of the Interior, Public Construction Commission, Executive Yuan. (2021) Taiwan Circular Economy Week. <https://twceweek.tw/>

promoting circular economy products from home and abroad. The Ministry of Economic Affairs has taken the lead in establishing Taiwan Circular Economy 100 (TCE100), which holds a Taiwan Circular Economy Forum from time to time⁷⁸⁸. As a result, we not only allow domestic enterprises to play a key role in the global supply chain, but also endeavor to become a leading nation in the circular economy.

Despite the joint efforts of the public and private sectors in Taiwan to promote a circular economy, there are still areas to be improved, including:

(1) Corporate Accounting and Financial Reporting Systems to Be Reformed in Response to a Circular Economy⁷⁸⁹

Accounting and reporting methods are still based on the linear model. As a result, numerous external costs are not included and many resources are classified as expenses under the past linear economic model. Under a circular economy framework, resources should be capitalized. Therefore, changes in accounting and financial reporting systems will be needed.

(2) Traditional Waste Regulations to Be Reformed

Traditional regulations do not pay attention to issues of external costs and carbon emissions, leading to waste materials being treated simply as something to be disposed of. However, the concept of net-zero emissions emphasizes promoting zero waste and zero emissions from the source. To strengthen the goals of zero waste, zero accidents, and zero emissions, we need to redesign relevant regulations, instead of pondering over solutions after waste has been generated.

(3) Procurement Related to the Circular Economy to Be Strengthened⁷⁹⁰

To promote the development of products and services related to a circular economy, government budgets and resources can be leveraged. With net-zero emission targets as a key criterion in selection, net-zero emission/circular public procurement should be promoted.

(4) Other Policies

Other social and governance strategies for a green transition include emulating the

⁷⁸⁸ Industrial Development Bureau, Ministry of Economic Affairs (2019). 2021 Taiwan Circular Economy Forum. https://www.idbevent.org.tw/Events/event_more?id=d393e378d62f4b1fa2b6344ad64d04dc&AspxAutoDetectCookieSupport=1

⁷⁸⁹ Huang, C. C., Lin, S., & Ti, A. (2019). Future accounting under the trend of circular economy. *Accounting Research Monthly*, 409, 56. <https://www.accounting.org.tw/blktopic.aspx?b=676>

⁷⁹⁰ Circular Taiwan Network (2020). Circular procurement, opening the market for a circular economy. <https://circular-taiwan.org/2020/11/11/20201111-2/>

international practice of introducing the concepts of net-zero emissions and a circular economy from elementary school⁷⁹¹, rather than limiting it to university education; incorporating net-zero emissions awareness into regular public sector training, prompting the public sector to lead the review of KPIs in different departments of state-owned enterprises, and concretizing circular economy issues related to net-zero emissions into performance appraisals. In addition, in line with the international concepts of Corporate Social Responsibility (CSR) and Environment, Social and Governance (ESG), by constructing a comprehensive extended producer responsibility (EPR) system, the responsibility of producers is thus not limited to manufacturing products, but can be extended to the entire product lifecycle of upstream, midstream, and downstream.

5. Electricity Prices

To reflect the ongoing rise in the international fuel prices, electricity prices have been adjusted upwards by an average of 3% for various uses like energy charges and bundled user unit prices since 2018. However, based on the latest statistics from the International Energy Agency (IEA) and Enerdata, compiled by Taiwan Power Co.⁷⁹², an examination of electricity prices in major countries shows that in 2020, the residential electricity price in Taiwan was the 4th lowest in the world, and the industrial electricity prices were the 6th lowest globally (Table 7.2.5). This implies excessive government subsidy, mainly through the national treasury (ie: taxpayers) subsidizing both industrial and residential electricity consumption. Therefore, it is necessary to further review how to implement the user-pays principle, a reasonable electricity pricing structure, and subsidy mechanisms to live up to our sustainable development objectives like international carbon reduction commitments, launch of an energy transition, and electric-industry reforms.

⁷⁹¹ Circular Taiwan Network (2021). Circular campus: Investing in the next generation, never a waste. <https://circular-taiwan.org/event/210831-2/>

⁷⁹² Taiwan Power Company (2021). Comparison of electricity prices across countries. <https://www.taipower.com.tw/tc/page.aspx?mid=213&cid=351&cchk=1b3221ee-37c3-4811-9d4d-a1bb215f33c8>

Table 7.2.5 Average Electricity Prices across Countries in 2020^{793,794}

Residential						Industrial					
Rank	Country	NTD/kWh	Rank	Country	NTD/kWh	Rank	Country	NTD/kWh	Rank	Country	NTD/kWh
1	Malaysia	2.2711	17	Chile	5.3355	1	Sweden	1.8621	17	Poland	3.1791
2	Mexico	2.2775	18	New Zealand	5.6228	2	United States	1.9701	18	Czech	3.2867
3	Mainland China*	2.3231	19	Czech	6.0081	3	Denmark	2.2811	19	Netherlands	3.3032
4	Taiwan	2.5596	20	Finland	6.1362	4	Finland	2.3063	20	Spain	3.4638
5	Turkey	3.0370	21	Australia	6.2049	5	Hungary	2.3150	21	Austria	3.5068
6	South Korea	3.0746	22	France	6.3586	6	Taiwan	2.4461	22	France	3.6865
7	Canada	3.2248	23	Luxembourg	6.4463	7	Malaysia	2.4901	23	Switzerland	3.7312
8	Hungary	3.4150	24	Switzerland	6.6362	8	Luxembourg	2.5094	24	Ireland	3.7453
9	Thailand*	3.6973	25	Austria	7.0010	9	Canada	2.6531	25	Portugal	3.7777
10	United States	3.9031	26	Portugal	7.1666	10	Mainland China*	2.7218	26	Belgium	4.0709
11	The Philippines	4.3776	27	United Kingdom	7.2157	11	South Korea	2.7902	27	Singapore	4.3776
12	Lithuania	4.5833	28	Japan	7.5488	12	Mexico	2.8099	28	United Kingdom	4.6495
13	The Netherlands	4.7992	29	Ireland	7.7292	13	New Zealand	2.9367	29	Japan	4.7875
14	Poland	5.0124	30	Spain	8.1280	14	Thailand*	2.9874	30	Chile	4.8675
15	Singapore	5.0283	31	Italy	8.5014	15	Turkey	3.0351	31	Italy	5.0771
16	Sweden	5.1479	32	Denmark	9.0707	16	Lithuania	3.1056	32	Germany	5.1284

* Data in 2019.

In March 2022, the outbreak of the Russo-Ukrainian War led to a surge in the international natural gas prices. At present, natural gas power generation accounts for 37% of the energy mix in Taiwan, second only to coal (44%). According to the current energy transition policy, the share of natural gas power generation is expected to rise to 50% by 2025. This will surely increase the power generation costs, which will in turn impact the electricity prices. Electricity prices are currently set using a formula⁷⁹⁵

⁷⁹³ *Ibid.*, note 792.

⁷⁹⁴ The values in the table were originally denominated in US dollars. The exchange rate used for conversion to New Taiwan Dollars (NTD) is 1 USD = 29.578 NTD (at the average exchange rate of 2020).

⁷⁹⁵ Bureau of Energy, Ministry of Economic Affairs (2018). Meeting slides for the public briefing on the calculation formula for transmission and distribution line installation fees. Electricity Tariff. <https://www3.moeaboe.gov.tw/ele102/Content/Messages/contents.aspx?MmmID=654246034164516120#>

where “power purchase expenditures” (including profit) cover the cost of power purchased by Taiwan Power Company itself, as well as from private power plants and self-use power generation equipment; transmission and distribution expenditure, including ancillary services, transmission losses, dispatching services, power wheeling, and other expenses; electricity sales service fees, including taxes and fees, depreciation and interest, personnel expenses, maintenance fees, other operating expenses, other power business operating expenses, and other operating income; and the reasonable profit of electricity retailing utility corporations, which is estimated as the rate base $\times$ a 3-5% ROI $\times$ the proportion of employees.

Average electricity price per kWh of electricity retailing utility corporations = (Electricity purchase expenditure + Transmission and distribution expenditure + Electricity sales service expenses + Reasonable profit of electricity retailing utility corporations) $\div$ Electricity sales by kWh

From the electricity price formula above, we can observe that although the current domestic electricity price takes into account the economy and cost of living, it does not reasonably reflect these additional costs: (1) the internalization of the external costs of power generation, including the external costs to health and the environment (such as the harm to health caused by pollution and the external costs resulting in climate change); and (2) the cost of stable power supply. The work of internalizing the external costs of power generation mainly depends on government carbon pricing, including carbon taxes/fees or carbon trading, and prompting Taiwan Power Co. to include it in electricity price adjustments. In addition to revising the electricity price formula, the governance system must be amended as well, including liberalization of the power sector and the establishment of an “independent regulator” for the power sector (ie: public utilities), such as the Public Utility Commissions of various U.S. states, to eliminate the influence of political forces on the power market and electricity prices and truly solve the problem of excessively low electricity prices. Regarding the cost of stable power supply, because Taiwan has an independent but fragile power grid, it is even more necessary to prepare for power outages or blackouts caused by weather or unexpected factors (such as the major power outages on May 13, 2021, and March 3, 2022). Otherwise, the target of 30% renewable energy by 2025 in line with a net-zero emissions pathway may not be achieved. Aside from the two missing costs above, electricity prices in general are low, hindering domestic industrial restructuring,

creating a lack of public awareness and wastefulness, and resulting in inefficient electricity use. Hence, in addition to considering the carbon reduction effect of increased electricity prices, complementary energy efficiency tools should also be provided. Otherwise, the desired effect of reducing consumption through pricing mechanisms cannot be achieved.

The implementation of the aforementioned energy or carbon tax/fee systems will be reflected in electricity and gasoline prices. Nevertheless, since these carbon or energy taxes, levied for the purpose of carbon reduction, are regressive in nature, they will result in a higher burden on lower-income earners. During large-scale carbon reduction efforts, this can negatively impact income redistribution for low-income households⁷⁹⁶. Therefore, a greater portion of tax revenue in the public sector must be allocated to assist the impacted populations, especially the low- and middle-income households.

Finally, if we observe the European countries' net-zero pathways under high electricity prices, they overcame difficulties by means of technical advancements and technological innovation. Although the cost of net-zero emissions is high, from an economic perspective, it is recommended that the government not rely solely on a single economic tool to achieve carbon reductions. Economic tools should be a supporting means for carbon reduction. Therefore, domestically, we should focus on innovative technologies development and make good use of "Intelligentization Enabling Technology" and tools that change the lifestyles of humanity. Through various information and communication technology applications, we can derive different business models and lifestyles, thereby achieving our long-term goal of net-zero emissions step by step.

⁷⁹⁶ Chen, P. (2017). The costs of carbon reduction and the choices of carbon reduction (1): Why are people "insensitive" to carbon reduction? <http://ddpp.ntu.edu.tw/publish-and-video/newsletter/248-2017-08-02-10-43-30.html>

7.2.4 Policy Recommendations

1. Promptly implement carbon taxation and clarify carbon pricing to establish the concept of paying for emissions. In the short term, prioritize carbon tax mechanisms while simultaneously enhancing the operational mechanisms and tools required for carbon emissions trading to support long-term integration into a carbon trading system

Carbon pricing will be necessary to internalize the external costs of climate change, transforming them into payable costs. This creates incentives for consumers, producers, and investors in Taiwan to alter behaviors and reduce carbon dioxide (CO₂) emissions. To achieve net-zero emissions, implementing carbon pricing is necessary. The Climate Change Act already includes provisions for carbon fees, and the transaction costs for implementing a carbon tax are relatively low, warranting swift action. However, Taiwan's emission sources are relatively concentrated, and its market size is small. Adopting an emissions trading mechanism at this stage would face challenges such as insufficient market liquidity, low competitiveness, and higher transaction costs due to the lack of development of the system. In the long term, controlling carbon emissions will require both carbon taxation and carbon trading. A carbon trading system should be gradually established and supported with robust mechanisms and tools, such as measurement standards. Once carbon taxes are operating smoothly and approach international market levels, reducing the marginal effectiveness of emissions reduction, offsetting mechanisms or emissions trading systems can be added to help achieve the nation's overall net-zero emissions goals.

2. Enhance the effective utilization and allocation of funds collected from carbon taxes

The Climate Change Act draft proposes allocating carbon fee revenues to a dedicated fund for specific uses, such as subsidizing and incentivizing the development of low-carbon and negative-emission technologies and industries, as well as investing in greenhouse gas reduction technologies. To better utilize these funds for climate action, it is recommended to expand the scope beyond the planned subsidies and incentives for technology and industry development. The funds should also be used to offset new burdens on consumers, producers, communities, and the broader socioeconomic systems caused by the carbon tax. This approach would further enhance the effectiveness of greenhouse gas emission reductions and mitigate the adverse impacts

of climate change more effectively.

3. Optimize green finance regulations to encourage financial institutions to fulfill responsible investment and lending obligations, prioritizing SMEs, green sustainable startups, and lagging companies willing to adopt ESG

Currently, green finance in Taiwan primarily targets large enterprises with strong branding and sustainability. However, during the net-zero transition, the additional financial resources provided by green finance hold limited practical significance for such enterprises. Conversely, small and medium-sized enterprises (SMEs), with fewer resources, are more vulnerable to the impacts of the net-zero transition. Therefore, it is recommended that the government prioritize green finance investment and lending to SMEs and green sustainable startups that are willing and need support for transition, as well as mid-performing enterprises with room for improvement on sustainability. These businesses should be provided with greater financial guarantees and support, while being monitored to ensure tangible improvements, thereby accelerating a comprehensive transition across sectors.

4. Refine legal frameworks and incentives for the circular economy

Achieving net-zero emissions will require not only renewable energy and energy efficiency strategies but also a circular economy. However, currently, Taiwan's framework for corporate accounting, financial reporting, waste management regulations, and public procurement do not fully incorporate external environmental cost calculations. These frameworks require redesign or adjustments to promote zero waste and net-zero carbon emissions from the source. It is necessary to refine the relevant legal and policy frameworks and promote incentives that make net-zero emissions and the circular economy core components of Taiwan's governance. This will help align government policies with net-zero targets and mainstream circular economy practices to achieve emission reduction goals.

5. Redesign electricity pricing formulas to reflect external environmental costs and enhance the competitiveness of zero-carbon electricity, while mitigating adverse impacts on low-income households

Taiwan's current electricity pricing considers economic and market factors but does not adequately reflect the external costs of traditional fossil fuel use, such as the health impact of environmental pollution, the cost of climate change, and power supply stability. This results in relatively low electricity prices, making it difficult to incentivize industrial restructuring or reduce electricity waste.

A redesigned electricity pricing formula should reflect external environmental costs, using pricing mechanisms to promote carbon reduction and enhance the competitiveness of zero-carbon electricity compared to fossil fuel-based generation. This can encourage the expansion of zero-carbon power in society. Governance structures should also be reformed, including liberalizing the electricity markets and establishing an independent regulatory body for utilities (e.g., a Public Utility Commission akin to those in U.S. states) to eliminate political interference in electricity markets and pricing, effectively addressing the issue of excessively low electricity prices. Additionally, electricity price adjustments may disproportionately impact vulnerable groups, such as low-income households, exacerbating energy poverty during the energy transition. Adequate plans must be developed, such as utilizing carbon tax revenues for income redistribution, subsidizing energy-efficient appliances for disadvantaged households, or assisting in retrofitting low-carbon, energy-efficient housing, to mitigate the effects on affected groups.

7.3 Social Dimensions

Summary

The net-zero transition encompasses transformations across all social spheres. Achieving the 2050 net-zero emissions target requires societal cooperation, support, and proactive action at every stage of the transition. To enhance public awareness of the importance of individual contributions to carbon reduction, education and policy mechanisms need to be designed to drive changes in personal perceptions and behaviors, thereby integrating carbon reduction technologies into daily life.

Additionally, comprehensive civil engagement and communication mechanisms should be established to enable public and stakeholder participation in decision-making processes. This approach can enhance the societal acceptance of a net-zero transition and sustainability. For the unavoidable negative impacts of the transition, the government should assess the scope and degree of such impacts for each strategy and establish transition mechanisms and allocate necessary resources to achieve social equity and justice. The following measures are suggested:

1. Develop a robust governance framework with clear regulations and well-defined roles for responsible agencies. While strengthening governance systems in the whole of society, embed net-zero principles in education to foster societal recognition of sustainable values.
2. Implement timely localized adaptation behaviors to promote cooperation between the public sector, businesses, and civil society organizations. Establish public-private partnerships to enhance societal resilience and support the deployment and adoption of innovative low-carbon energy solutions.
3. Establish platforms and mechanisms for civil society participation and social communication, incorporating societal needs and stakeholder voices into decision-making processes to facilitate the formulation and promotion of carbon reduction policies.
4. Identify and clarify the groups and areas in Taiwan that are likely to be affected by the low-carbon transition. Allocate corresponding resources to address social equity and justice in a net-zero transition.

7.3.1 Introduction

Beyond changes to energy systems and technologies, the net-zero transition will also require a long-term social transformation to change individual and societal mindsets, behaviors, and values. This is critical for increasing public acceptance of carbon reduction policies and reducing potential social conflict and resistance. Individual behavior plays a significant role in carbon reduction. For example, measures to reduce emissions across industrial, building, transportation, and residential-commercial sectors, from energy supply to consumption, rely heavily on individual actions, such as adopting public transportation, electric vehicles, or energy-efficient appliances. To accelerate behavioral change, the government must use policy tools, such as institutional design, subsidies, and regulations. A net-zero transition will impact not just energy and technology but also transforms the entire society. Gaining societal consensus and willingness to support the transition will require effective communication channels, active civil participation, and collaborative decision-making to establish a shared vision. However, the transition process will inevitably incur additional costs and risks, negatively impacting certain groups. Examples include the construction of renewable energy facilities, the transition of fossil fuel-related industries, job losses for workers in these sectors, and increased energy prices affecting household expenses. To mitigate the unequal distribution of costs and risks and reduce conflicts or resistance, mechanisms must be established to ensure smooth stakeholder participation and dialogue. At the same time, the rights of affected groups must be safeguarded, ensuring fairness and justice in the carbon reduction transition (see Figure 7.3.1).

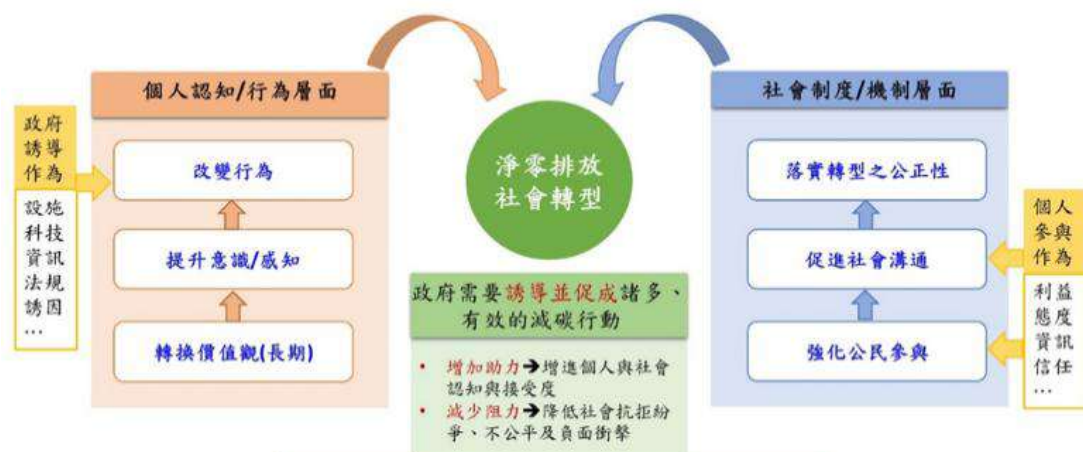


Figure 7.3.1 Social Dimensions of a 2050 Net-Zero Emissions Transition^{797,798}

7.3.2 Personal Perceptions and Behavioral Changes

Personal perceptions and behavioral changes are essential for achieving global net-zero emissions goals. According to the International Energy Agency's (IEA) Net Zero by 2050 report, global carbon dioxide (CO₂) emissions could be reduced by a total of 34 Gt by 2050 (as shown in Figure 7.3.2). Of this, more than 60% of the reductions must rely on changes in public behavior and values. Behavioral changes⁷⁹⁹ and improvements in material efficiency could reduce CO₂ emissions by 2.9 Gt (8%). If consumers actively choose low-carbon and energy-efficient products, such as purchasing electric vehicles and installing solar panels, an additional reduction of approximately 20 Gt (55%) could be achieved. However, low-carbon technology applications that do not directly involve the general public, such as low-carbon power generation and low-carbon manufacturing, would only reduce emissions by about 11 Gt (37%)⁸⁰⁰. This demonstrates that reliance solely on low-carbon power generation and production-side technological investments is insufficient to achieve optimal net-zero emissions goals. Broad public participation is also required, targeting carbon

⁷⁹⁷ Chou, Kuei-Tien (2020). Climate change and national governance: Sustainability, future, and generations in conflict. Straits Exchange Foundation. *Cross-Strait Exchange Magazine*, February 2017, Issue 151. <https://www.sef.org.tw/article-1-129-4869>

⁷⁹⁸ Hsu, Keng-Ming (2012). A preliminary study on the comparison of urban climate governance models in Taiwan: An analysis of the five municipalities. Part of the 2010 research project "A Study on the Construction of Urban Climate Governance Models," funded by the National Science and Technology Council. http://ir.nou.edu.tw/bitstream/987654321/20825/2/E27_047-098.pdf

⁷⁹⁹ Behavioral change: This refers to repetitive actions related to energy use and demand, such as transportation behaviors and temperature settings for heating and cool.

⁸⁰⁰ IEA (2021). *Net zero by 2050: Roadmap for the global energy sector*. <https://www.iea.org/reports/net-zero-by-2050>

reduction from the demand side through changes in individual perceptions and behaviors to effectively meet net-zero emissions targets.

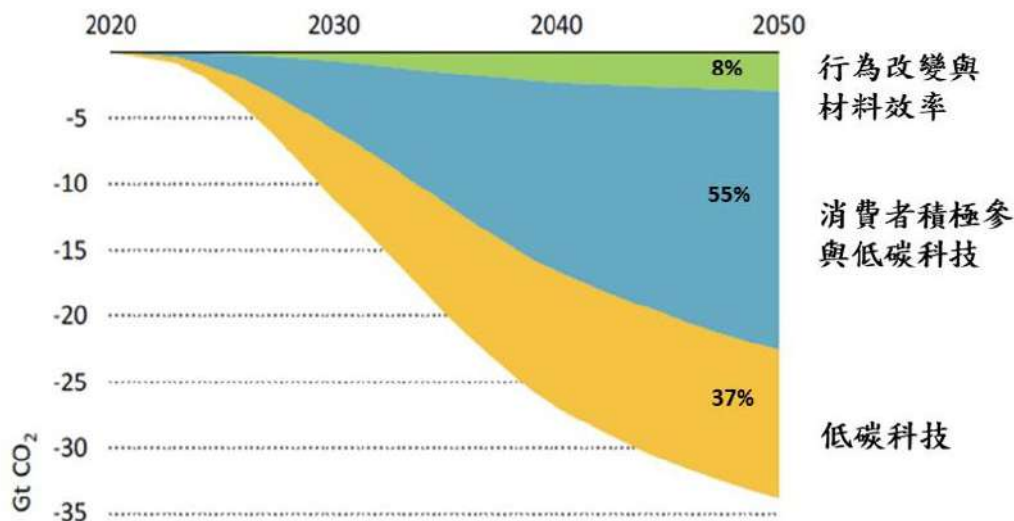


Figure 7.3.2 Carbon Reduction Contributions from Low-Carbon Technologies and Behavioral Change Strategies on the Net-Zero Carbon Pathway⁸⁰¹

1. Current Status and Challenges

Based on analyses from organizations such as the IEA and the UK's Department for Business, Energy, and Industrial Strategy (BEIS), the impact of personal perceptions and behavior changes can be categorized into four major areas: buildings, transportation, waste, and diet^{802,803}. The current status and trends are as follows:

(1) Buildings:

In 2019, carbon emissions from the residential sector in Taiwan amounted to 28.5 Mt CO₂eq, accounting for approximately 10% of total emissions. Over 80% of these emissions were due to the use of air conditioning, lighting, and household appliances⁸⁰⁴.

(2) Transportation:

In 2019, emissions from the transportation sector reached 37 Mt CO₂eq, or about 12.9% of total emissions. Road transport accounted for 96% of this, with approximately 50.5% of road transport emissions coming from passenger cars (6.3% of total emissions) and 12.9% from motorcycles (1.6% of total emissions)⁸⁰⁵.

⁸⁰¹ *Ibid.*, note 807.

⁸⁰² BEIS (2021). *Net zero: Principles for successful behaviour change initiatives*.

⁸⁰³ IEA (2021). *Do we need to change our behaviour to reach net zero by 2050?*

⁸⁰⁴ Ministry of the Interior and Ministry of Economic Affairs (2021). Assessment briefing on the net-zero emissions pathway for the residential and commercial sectors.

⁸⁰⁵ Environmental Protection Administration, Executive Yuan (2020). Energy balance sheet.

(3) Waste:

Greenhouse gas emissions from the waste sector in 2019 were approximately 2.7 Mt CO₂eq, accounting for about 0.9% of total emissions. Although this is lower than emissions from the residential-commercial and transportation sectors, general waste generation in Taiwan has shown an increasing trend. According to statistics from the Environmental Protection Administration (EPA), general waste reached a record high of 986 Mt in 2020, a 0.58% increase from 2019. On average, each person generated 1.1 kg of general waste and 0.06 kg of household food waste daily⁸⁰⁶.

(4) Diet:

Taiwan relies heavily on imported food, with a comprehensive food self-sufficiency rate of only 31.7% in 2020⁸⁰⁷. Greenhouse gas emissions from the agriculture sector have been decreasing annually; in 2018, emissions from agriculture, forestry, fisheries, and livestock totaled 5.8 Mt CO₂eq, accounting for about 2% of total emissions. However, dietary-related carbon emissions are not limited to production, but also include processing, packaging, transportation, sales, storage, and food waste disposal.⁸⁰⁸ Meat products have the highest carbon footprint⁸⁰⁹, and meat consumption in Taiwan has been increasing. In 2020, per capita meat supply reached 86.5 kg annually⁸¹⁰, the highest in the past decade.

Carbon reductions in these four areas can be achieved through changes in personal perceptions and behaviors, such as switching to energy efficient appliances, using electric vehicles and public transportation, reducing plastic packaging, increasing recycling rates, and minimizing food waste (Table 7.3.1).

⁸⁰⁶ Environmental Protection Administration, Executive Yuan (2021). *2021 Statistical Yearbook*.

⁸⁰⁷ Council of Agriculture, Executive Yuan (2021). *2020 Agricultural Statistics Yearbook*.

⁸⁰⁸ FDF (2021). *Achieving net zero: A handbook for the food and drink sector*.

⁸⁰⁹ Ritchie, H. (2020) You want to reduce the carbon footprint of your food? Focus on what you eat, not whether your food is local. <https://ourworldindata.org/food-choice-vs-eating-local>

⁸¹⁰ *Ibid.*, note 814.

Table 7.3.1 Behavior Changes Beneficial for Carbon Reduction^{811,812}

Sectors	Behavior Changes Beneficial for Carbon Reduction
Buildings	Avoid setting air conditioning and heating temperatures too high or too low; choose high-energy-efficiency appliances; select low-carbon buildings or building materials.
Transportation	Use low-carbon transportation or public transit; phase out internal combustion engine vehicles; replace regional flights with high-speed rail; reduce the need for long-haul flights.
Waste	Increase recycling rates; reduce the use of plastic packaging or products.
Diet	Reduce consumption of high-carbon-intensity meats; prioritize local and seasonal ingredients; minimize food waste ⁸¹³ .

The public's awareness and willingness to contribute to reducing emissions can be observed through attitudes toward electricity pricing and taxes. The "Toward a Deep Low-Carbon Society" project conducted by Academia Sinica in 2017, 2019, and 2021 surveyed public willingness to accept tax increases and price hikes for energy-saving and carbon reduction efforts (Figure 7.3.3)⁸¹⁴. The results indicated a growing trend in public willingness to pay for energy-saving and carbon-reducing measures. More than half of the respondents expressed readiness to accept tax increases or price hikes to support these efforts, with the majority favoring increases within the range of 1% to 5%.

Additionally, the Risk Society and Policy Research Center at National Taiwan University, in collaboration with Academia Sinica's Institute of Sociology, conducted a Taiwan Social Change Survey in 2020 to assess public willingness to pay higher electricity prices for renewable energy (Figure 7.3.4). Approximately 60% of respondents were willing to accept slight price increases^{815,816}.

⁸¹¹ *Ibid.*, note 810.

⁸¹² *Ibid.*, note 815.

⁸¹³ *Ibid.*, note 815.

⁸¹⁴ *Ibid.*, note 824.

⁸¹⁵ *Ibid.*, note 825.

⁸¹⁶ *Ibid.*, note 826.

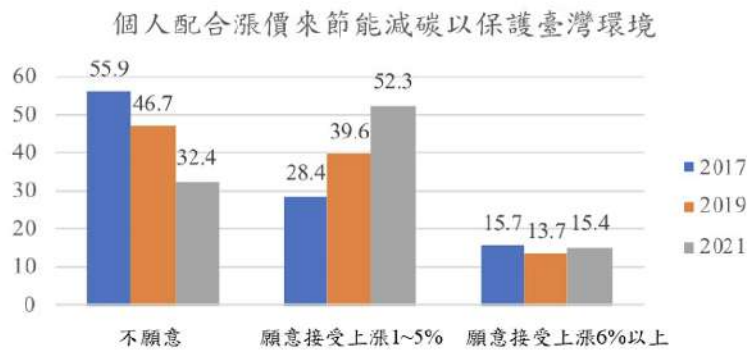
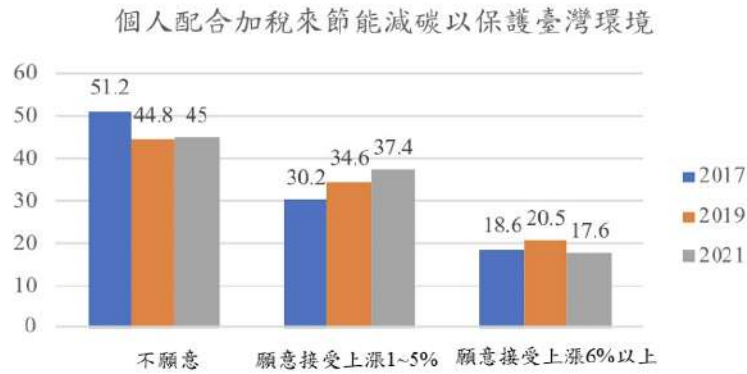


Figure 7.3.3 Public Willingness to Support Tax Increases/Price Hikes for Energy Savings and Carbon Reduction in Taiwan (2017, 2019, 2021)⁸¹⁷

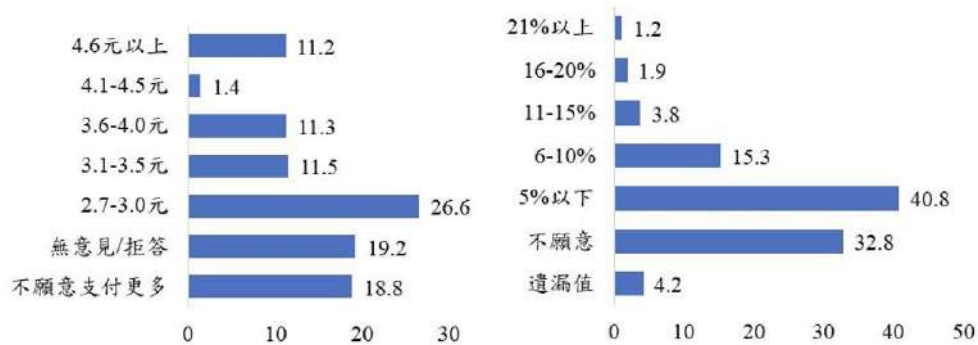


Figure 7.3.4 Percentage of Public Willing to Pay Higher Electricity Prices for Promoting Renewable Energy and Acceptable Price Increase Ranges in Taiwan (2020)^{818,819}

⁸¹⁷ Institute of Sociology, Academia Sinica (2021). *Toward a deep low-carbon society: Action research project on social behavior and institutional transformation - Final report*.

⁸¹⁸ Risk Society and Policy Research Center, National Taiwan University (2020). *2020 public perception survey on energy transition*.

⁸¹⁹ Wu, Chi-Yin (2022). *Taiwan social change survey 2020, phase 8, wave 1: Environment module*. https://srda.sinica.edu.tw/datasearch_detail.php?id=3321

The above surveys indicate that a significant proportion of the Taiwanese public is aware of the importance of energy saving and carbon reduction and is willing to make changes and sacrifices for this cause. Furthermore, in Academia Sinica's Toward a Deep Low-Carbon Society survey, over 80% of respondents believed that businesses should bear greater responsibility for energy saving and carbon reduction compared to individuals. To increase public acceptance of contributions to energy saving and carbon reduction, thereby encouraging more actions and changes, several key challenges must be addressed⁸²⁰:

- **Lack of information connecting personal decision-making to carbon reduction:** Even if individuals want to act, they may not know how or be unable to evaluate the direction and impact of their actions. For instance, they might be uncertain whether a purchased product meets energy-saving standards or about the product's life-cycle carbon footprint.
- **Costs and challenges of change:** While change may be beneficial, the decision-making process requires additional effort, information, and adaptation. Breaking existing habits involves risks and uncertainties, leading to a tendency to maintain the status quo (i.e., status quo bias)^{821,822}. Examples include farming practices for farmers⁸²³ or commuting habits for workers⁸²⁴.
- **High costs or lack of incentives:** If the cost of change is too high or exceeds what individuals perceive as affordable, they are likely to maintain the status quo. For example, in Taiwan, electric vehicles remain significantly more expensive than conventional internal combustion vehicles, and Taiwan is one of the most expensive regions globally for EV purchases⁸²⁵. Additionally, the infrastructure, such as charging stations, is not yet widely available, limiting the willingness to choose electric vehicles.

In summary, promoting changes in individual perceptions and behaviors is a critical success factor for fostering the adoption of innovative low-carbon energy

⁸²⁰ *Ibid.*, note 810.

⁸²¹ Samuelson, W. and Zeckhauser, R. (1988). Status quo bias in decision making, *Journal of Risk and Uncertainty* 1:7-59.

⁸²² Fernandez, R. and Rodrik, D. (1991). Resistance to reform: Status quo bias in the presence of individual- Specific uncertainty. *The American Economic Review* 81 (5): 1146-1155.

⁸²³ Barnes, A.P. (2021). Farmer intentional pathways for net zero carbon: Exploring the lock-in effects of forestry and renewables. *Land Use Policy* 112.

⁸²⁴ BIT (n.a.) *Applying behavioural insights to transportation demand management*.

⁸²⁵ Gibbs (2022). Cost of buying a car around the world. <https://www.confused.com/car-insurance/car-buying-index#4>

technologies and achieving the net-zero emissions target. While actively pursuing zero-carbon power technologies, innovative low-carbon and carbon-negative technologies, and groundbreaking new technologies, efforts should also focus on implementing energy-saving technologies and encouraging public participation in energy conservation to maximize the effectiveness of technological solutions.

This approach will lay the foundation for cross-ministerial and interdisciplinary policy discussions. Therefore, governance frameworks must address both carbon reduction and adaptation while aligning with Taiwan's current social and environmental conditions and trends. Using scientific evidence, localized adaptation measures should be developed, supported by participatory planning mechanisms that integrate and connect practices across ministries, agencies, and societal groups. This approach will help avoid improper adaptation behaviors that shift risks across regions, sectors, or communities. Transparent governance processes can facilitate collaboration between the public sector, businesses, and civil society organizations, ultimately fostering a partnership between public and private sectors.

2. Learning from Others: International Strategies for Promoting Behavioral Change in Line with a Net-Zero Transition

To address the aforementioned three challenges, this section discusses various international and domestic approaches and policy tools (Table 7.3.2). These measures aim to guide systemic value changes, embedding the concept of net-zero emissions into society and laying the groundwork for future transitions and the development of a long-term carbon-neutral society.

(1) Connecting Personal Decision-Making with Carbon Reduction Information

Providing social education and easily accessible information can help improve personal decision-making related to carbon reduction, such as through labeling systems. Since 2001, the Taiwanese government has implemented energy-saving labels for appliances, certifying 52 types of products so far⁸²⁶. Beyond appliances, Foundation Earth in Europe collaborated with major multinational food retailers to introduce food grading labels in November 2021. These labels rate the environmental impact of food production, transportation, and packaging⁸²⁷, helping consumers make informed

⁸²⁶ Bureau of Energy, Ministry of Economic Affairs (2022). Energy saving label. <https://www.energylabel.org.tw/purchasing/psearch/list.aspx>

⁸²⁷ Rating items include: Carbon emissions, water usage, water pollution, and biodiversity.

decisions⁸²⁸. In Taiwan, carbon and carbon-reduction labels were introduced in 2014, but public awareness remains low, with only about 400 products carrying carbon labels and roughly 60 products receiving carbon-reduction labels⁸²⁹.

(2) Overcoming Status Quo Bias

Governments can use status quo nudging to guide behavior, such as comparing electricity consumption among households in a neighborhood. By showing households how their usage compares to others, individuals can gain a concrete understanding of their energy use, motivating them to save energy⁸³⁰.

Some countries adopt green default settings by making renewable energy the default power supply option. Research indicates that most people tend to stick with default options^{831,832}, increasing acceptance and demand for renewable energy.

(3) Addressing Cost Concerns

Price subsidies can alleviate the financial burden of carbon-reducing actions. Examples include California's *On-Bill Financing* (OBF) for energy-efficient equipment and Germany's subsidy policies for replacing fossil fuel-based equipment.

Since 2019, Taiwan has implemented a subsidy program for energy-saving appliances, providing subsidies and tax relief for gas stoves, water heaters, refrigerators, air conditioners, and dehumidifiers⁸³³. Policies can also enforce changes, such as California's 2021 building regulation requiring new construction to install solar panels and switch to electric heating⁸³⁴. Additionally, public investments can increase the feasibility and willingness to adopt behavior changes. For example, the Biden administration in the U.S. plans to invest \$5 billion to install 500,000 electric vehicle charging stations nationwide⁸³⁵. Similarly, Taiwan launched a public charging station

⁸²⁸ Compass Group, UK & Ireland Limited (2021). Compass Group UK & Ireland to roll out eco-labels across business & industry estate. <https://www.compass-group.co.uk/media/news/compass-group-uk-ireland-to-roll-out-eco-labels-across-business-industry-estate/>

⁸²⁹ Environmental Protection Administration, Executive Yuan (2020). *Product carbon footprint information platform*. <https://cfp-calculate.tw/cfpc/WebPage/LoginPage.aspx>

⁸³⁰ 環境省(2017) 日本版ナッジ・ユニット(Behavioral Sciences Team, BEST)

⁸³¹ Liebe, U. et al. (2021). Large and persistent effects of green energy defaults in the household and business sectors. *Nat Hum Behav*, 5, 576–585.

⁸³² Micha Kaiser et al. (2020). The power of green defaults: The impact of regional variation of opt-out tariffs on green energy demand in Germany, *Ecological Economics*, 174.

⁸³³ Ministry of Finance (2021). Refund and reduction of commodity tax for purchasing energy-efficient appliances. <https://www.etax.nat.gov.tw/etwmain/tax-info/purchase-energy-saving-appliance-reduced-commodity-tax-refund-area/consumer-online-apply>

⁸³⁴ *The New York Times* (2021). California's plan to make new buildings greener will also raise costs.

⁸³⁵ The White House (2021). *FACT SHEET: The Biden-Harris electric vehicle charging action plan*.

construction plan in 2021, aiming to build 7,800 charging stations by 2025⁸³⁶.

(4) Long-Term Systemic Value Changes

Education will play a critical role in the long-term success of a net-zero transition. Sustained investment in education across all levels can lead to systemic societal value changes, fostering action from the bottom to the top and cultivating talent to implement net-zero emissions and carbon reduction in the future. During the 26th UN Climate Change Conference of the Parties (COP26) in 2021, countries such as Japan and members of the European Union committed to sustainable and climate education⁸³⁷. In November 2021, the UK Department for Education proposed a new education strategy draft to promote a net-zero transition through climate education, green skills training, sustainable campus infrastructure, green procurement, and competitive events. This strategy spans school and societal education and was planned to be publicized in 2022⁸³⁸.

In Taiwan, climate sustainability education is primarily focused on the school system. The Ministry of Education has incorporated climate change and environmental sustainability into the 12-Year Basic Education Curriculum⁸³⁹ and established a Climate Change Teaching Information Platform to promote education on climate adaptation, greenhouse gas reduction, and talent cultivation within schools⁸⁴⁰.

⁸³⁶ Risk Society and Policy Research Center, National Taiwan University (2021). Can Taiwan do it? A comparative review of electric vehicle policies worldwide.

⁸³⁷ UNESCO (2021/06). Climate education in the spotlight at COP26: Ministers of Education and Environment meet for historic event.

⁸³⁸ Department for Education (2021). Sustainability & climate change: A draft strategy for the education & children's services system.

⁸³⁹ Ministry of Education (2019). Recognizing the new generation's responsibility as global citizens: Comprehensive implementation of climate change education.

⁸⁴⁰ Ministry of Education Climate Change Teaching Resource Network (2022). Climate change teaching information platform.

**Table 7.3.2 Policy Tools and Case Studies Supporting Personal Perceptions
and Behavioral Changes⁸⁴¹**

Policy Tool	Measures and Methods	Examples
Increasing Awareness	Education, promotion, advocacy	Japan (2011–) Summer Energy-Saving Campaign
Providing Information	Label identification, real-time feedback	Taiwan (2001) Energy Efficiency Labels for Appliances, Product Carbon Labels; EU (2021) Food Grading Labels
Status Quo Nudging	Green/climate-friendly default options	Switzerland (2020), Germany (2020) Renewable Energy Default Options
Fiscal/Pricing Tools	Appliance replacement and energy-efficient product subsidies, public transport subsidies, fuel tax	California (2011) On-Bill Financing for Energy-Efficient Equipment; Germany (2020) Fuel-Based Heating Equipment Replacement Subsidy; Taiwan (2019) Appliance Energy Efficiency Subsidies
Regulatory Standards	Emission standards for vehicles, building standards, air quality protection zones	California (2019) Building Codes; UK (2020) Ban on Conventional Fuel Vehicles by 2030
Public Investment	Public transportation infrastructure, electric vehicle infrastructure, public procurement	US, Taiwan (2021) Charging Station Infrastructure Development

⁸⁴¹ *Ibid.*, note 810.

7.3.3 Participation of Civil Society Organizations, Social Communication, and the Justice of Transition

Achieving Taiwan’s net-zero emissions target relies heavily on societal support. The participation of civil society organizations can provide legitimacy and justification to the decision-making process, reducing potential obstacles during policy implementation. Their involvement forms a foundation for net-zero initiatives, increases public trust, and strengthens accountability. Comprehensive participation from civil society organizations and effective social communication help raise societal awareness of relevant issues and foster consensus on the vision for a future society. Additionally, civil society organizations can offer policymakers broader and more in-depth first-hand information, enhancing the quality of policy decisions⁸⁴². At the same time, stakeholders affected by decisions must have opportunities to express their views and influence the policymaking process, thereby reinforcing accountability.

A net-zero transition represents a society-wide transformation. While policies to drive this transformation deliver benefits in reducing carbon emissions, energy transition and carbon reduction measures inevitably impose negative impacts on certain groups, such as low-to-middle-income households, small and medium enterprises, agricultural and fishery workers, and indigenous communities. These measures may also lead to unfair outcomes or other negative issues, affecting the rights and interests of specific groups and stakeholders, potentially resulting in conflicts or protests that force policy changes or cancellations. To further analyze potential inequities associated with current major net-zero transition strategies, Table 7.3.3 organizes the strategies by sector—energy, industry, transportation, and buildings—and compiles the issues for each sector.

Overall, to effectively advance zero-carbon transition policies, it is essential to establish robust mechanisms such as the active participation of civil society organizations and enhanced social communication. These measures will not only help to mitigate conflicts and accelerate the transition but also address potential inequities at an early stage, preventing issues from arising.

⁸⁴² Demski, C. (2021). Net zero public engagement and participation: A research note.

**Table 7.3.3 Overview of Potential Inequities in Zero-Carbon Transition Strategies
by Sector^{843,844,845}**

Zero-Carbon Transition Strategies for Each Sector	Potential Inequities
Energy • Development of renewable energy to replace fossil fuels • Improvement of energy efficiency • Development of clean energy industries	• Increased energy expenses due to electrification, carbon taxes, the removal of fossil fuel subsidies, and the deployment of renewable energy infrastructure affect low-to-middle-income households and SMEs (the International Energy Agency estimates a 75% increase in global energy expenditure by 2050^{846,847}). • Natural environmental resources required for developing renewable energy and power grids may impact specific groups (e.g., farmers, fishers, indigenous communities) and industries (e.g., agriculture, fisheries, forestry). • Workers in fossil fuel industries face job displacement and challenges in transitioning to new roles.
Industry • Electrification and use of green or low-carbon energy • Application of carbon reduction technologies • Implementation of product carbon emission and energy efficiency standards • Promotion of green energy industries	• SMEs face difficulties accessing clean energy and carbon reduction technologies, or their revenues could be impacted by the high costs of implementation⁸⁴⁸. • New green energy jobs may not align with the skills of displaced workers, hindering successful career transitions.
Transportation • Ban on sales of fossil-fueled vehicles and transition to low-carbon vehicles • Reduction of fossil fuel subsidies for transportation	• Transformation and phase-out of traditional fuel vehicle industries. • Transition costs for switching to electric or low-carbon vehicles may increase ticket prices, affecting low-to-middle-income users. • Increased household transportation costs and expenses for adopting electric or low-carbon vehicles.

⁸⁴³ UKGBC (2020). Building the case for net zero.

⁸⁴⁴ *Ibid.*, note 807.

⁸⁴⁵ CTCI Foundation (2016). Challenges and opportunities for Taiwanese SMEs transitioning to a circular economy.

⁸⁴⁶ *Ibid.*, 807.

⁸⁴⁷ The growth figure does not account for population growth and GDP increases between 2020 and 2050.

⁸⁴⁸ *Ibid.*, note 852.

Zero-Carbon Transition Strategies for Each Sector	Potential Inequities
Buildings • New buildings meeting zero-carbon standards; Retrofitting existing buildings to meet zero-carbon standards • Use of high-efficiency appliances • Electrification	• Costs for electrification, retrofitting, or high-efficiency appliances affect low-to-middle-income households. • Rising costs of new construction and increased technical barriers may increase housing prices and rents (e.g., the UK Green Building Council estimates a 5.3% cost increase for zero-carbon residential buildings and 8–17% for zero-carbon office buildings⁸⁴⁹).

1. Current Status and Challenges in Taiwan

To implement the “Guidelines on Energy Development” and actively promote an energy transition⁸⁵⁰, Taiwan’s Bureau of Energy under the Ministry of Economic Affairs initiated the development of the “Energy Transition White Paper” in 2017. Drawing on the experiences of Germany, Japan, and South Korea, the process introduced collaboration across government ministries, local authorities, and civil society organizations, while expanding citizen participation. The White Paper outlined Taiwan’s future energy development goals, concrete measures, and policy tools, establishing a participatory energy governance model for the nation.

The development of the White Paper featured a three-stage participatory approach to enhance public involvement, including preparatory meetings, collaborative workshops, and citizen dialogues. These activities involved diverse stakeholders, including the general public, academia, industry, government, and NGOs. A total of 40 meetings were held, with over 2,000 total attendees⁸⁵¹. The Executive Yuan approved the Energy Transition White Paper in 2020 and subsequently introduced “Key Indicators of Energy Transition” to present trends in a clear and relatable manner⁸⁵². In 2021, the White Paper’s annual implementation report was published, providing the public with insights into the progress of energy transition initiatives while ensuring

⁸⁴⁹ *Ibid.*, note 850.

⁸⁵⁰ Bureau of Energy, Ministry of Economic Affairs (2020). *Energy transition white paper*. https://ghgrule.epa.gov.tw/low/low_tw_doc_page/205

⁸⁵¹ Tsou, M.-H. (2020). The first energy policy with civil consensus: Executive Yuan approves Taiwan’s energy transition white paper. <https://e-info.org.tw/node/228090>

⁸⁵² Bureau of Energy, Ministry of Economic Affairs (2021). Key indicators of energy transition. <https://energywhitepaper.tw/#/>

continued citizen engagement and smooth policy implementation.

In 2018, during the revision of the Air Pollution Control Act, Taiwan's Environmental Protection Administration (EPA) sought to accelerate the retirement of Phase 1 and 2 heavy diesel trucks, triggering protests from freight operators. Although the EPA had consulted several transportation companies and unions prior to announcing the policy, it overlooked independent drivers as a key stakeholder group⁸⁵³. Additionally, market speculation caused the prices of vehicles meeting emissions standards to rise, further reducing drivers' willingness to replace their trucks⁸⁵⁴.

While policies such as raising fuel taxes and phasing out old diesel trucks are effective for reducing carbon emissions, the lack of proper communication and negotiation with stakeholders, coupled with inadequate complementary measures, led to significant public backlash. Ultimately, these policies were reversed, resulting in greater social and economic costs and deepening public distrust in the government, which has further hindered the implementation of subsequent carbon reduction policies. In light of this, the Energy Transition White Paper, developed with the participation of civil society organizations, emphasizes the importance of involving these organizations in social communication during policy formulation and implementation. Such involvement is essential for ensuring better coordination between policy promotion and public oversight mechanisms.

On April 22, 2021, Earth Day, President Tsai Ing-wen publicly announced Taiwan's commitment to achieving net-zero emissions by 2050, emphasizing the need to accelerate transformative actions. During the same event, Vice President Lai Ching-te highlighted sustainable development as the key solution to the transition. He stressed that future sustainable development must balance environmental justice, the fairness of economic transformation, and the inclusivity of social participation, moving toward the goal of inclusive green growth.

The government's declaration, combined with Taiwan's aforementioned existing initiatives, underscores that the zero-carbon transition is an inclusive societal transformation. This requires incorporating all stakeholders into the decision-making

⁸⁵³ Directorate General of Highways, Ministry of Transportation and Communications (2017). Study on the operational and management differences in Taiwan's freight transport industry compared to advanced countries (Case studies: USA and Japan).

⁸⁵⁴ Tseng, H.-W. (2018). The Air Pollution Control Act's lack of clarity in supporting measures creates a cycle of distrust over air pollution issues. <https://www.thenewslens.com/article/101826>

process while addressing the inequalities in resource distribution and risk-sharing. Therefore, strengthening civil society participation, fostering social communication, and achieving a just transition are indispensable components of this holistic transformation.

2. Learning from Others: International Cases of Civil Society Participation, Social Communication, and Transition

Recognizing the importance of civil society participation and social communication, as well as the controversies sparked by issues of unjust transitions, many countries have taken action by either designing participation mechanisms for civil society organizations to address climate change, energy, and carbon reduction, or incorporating stakeholder communication and allocating resources for supporting measures during the policy planning stage. This section examines recent international cases and practices, analyzing their impacts on civil society participation, social communication, and a Just Transition (Box 7.3.1), with a brief overview of their approaches.

Box 7.3.1 Just Transition⁸⁵⁵

The concept of “Just Transition” originally emerged from labor movements and was later adopted in environmental and climate change discussions. It highlights the rights and participation of workers and communities affected by climate change or energy transitions, the affordability of clean energy, and the equitable distribution of the costs and benefits of transitions. An example is the closure of hard coal mines in Germany’s North Rhine-Westphalia region. The hard coal mines in this area faced challenges such as energy transition, pollution, costs, and market competition, prompting the German government to decide to end subsidies for their mining operations. Beginning in 2007, negotiations were conducted between Germany’s central and local governments, mining companies, and workers’ representatives. These discussions focused on supporting affected workers through career transitions and further education, which included establishing vocational training centers, providing on-the-job training, and partnering with local universities to offer courses. Additionally, investments in the region’s renewable energy industry were strengthened, ultimately leading to the closure of the last two hard coal mines in the

⁸⁵⁵ Just Transition Initiative team (2020). Just transition concepts and relevance for climate action.

area in 2018.

The 2018 Yellow Vest Protests in France originated from the government's plan to raise fuel taxes. This policy significantly impacted commuters who could not afford to live in city centers and small self-employed businesspeople reliant on car transport, many of whom were unable to access subsidies. The protests later evolved into a large-scale movement highlighting broader economic and class issues⁸⁵⁶. In response, the Macron administration convened the Climate Citizens' Assembly in 2019 (Box 7.3.2), employing participatory democracy to develop emission reduction measures and provide recommendations to the government. Administrative agencies were required to propose concrete plans and timelines based on the assembly's conclusions. Following France's example, other countries such as the UK, Germany, Denmark, Scotland, and Finland held national-level Climate Citizens' Assemblies between 2020 and 2021 to discuss achieving greenhouse gas reduction targets under fair and just conditions.

Box 7.3.2 Climate Citizens' Assembly⁸⁵⁷

The Climate Citizens' Assembly is a participatory democratic approach increasingly used for environmental, climate, and energy policy decisions at local and national levels. Typically, dozens to hundreds of citizens are randomly selected based on criteria such as geography, age, gender, ethnicity, education level, income, and awareness of relevant issues. Experts, scholars, NGOs, or advocates collaboratively plan the discussion topics and measures, providing participants with relevant materials. The selected citizens engage in learning, discussing, and evaluating the issues and proposed measures. The final conclusions from these meetings, depending on each country's system, serve as references for policymaking or the basis for legislative processes. Notably, the French Climate Citizens' Assembly incorporated a third-party oversight committee to ensure discussions remained free from administrative interference.

Compared to the systemic reforms driven by France's Yellow Vests Protests,

⁸⁵⁶ Chao, W.-T. (2018). Protests ≠ opposition to climate policy: Examining energy taxes and social equity through the “yellow vests protests”. <https://e-info.org.tw/node/215489>

⁸⁵⁷ Lin, H.-C. (2020). France's climate citizens' assembly – A new chapter in participatory democracy: Implementing citizen climate proposals through referendums, legislation, or legal amendments.

Scotland's Orkney Islands zero-carbon transition^{858,859} exemplifies a broader, more impactful systemic transformation. The Orkney Islands once heavily relied on fossil fuels for electricity generation and maritime transport. However, with changes in local residents' behaviors—such as adopting community wind turbines for power generation, transitioning to electric vehicles, and integrating renewable energy facilities into new housing—renewable energy usage has significantly increased, contributing to the decarbonization of the islands. As a result, the Orkney Islands have been voted one of the best places to live in the UK. Additionally, the Orkney Islands Council partnered with government departments to co-invest in establishing the European Marine Energy Center (EMEC) and funded the development of low-carbon technologies like hydrogen-powered vessels. A Transition Training Fund was also established to assist workers in transitioning to the renewable energy sector. In addition to the aforementioned efforts by local government departments and residents to drive the transition, the EU's Smart Islands Energy System project has been introduced. This initiative aims to implement smart grids and energy management systems, not only increasing the share of renewable energy use but also addressing local energy shortages and related challenges.

On the topic of improving social inclusivity, the case of a coal-fired power plant in Poland in 2021⁸⁶⁰ offers valuable insights into empowering disadvantaged groups and enhancing their status. Poland has historically relied on coal-fired power plants for energy production. However, faced with challenges such as pollution, cost, and market competition, the government initiated an energy transition. This move triggered protests from over 7,000 coal miners and power plant workers, who were concerned about unclear management policies threatening their livelihoods. Subsequently, the National Energy Security Agency (NABE) committed to assisting in the transition of coal-fired power plants. Meanwhile, unions formed by coal miners and power plant workers demanded that the government enact legal protections for the industry by 2049. Additionally, Europe's largest coal company, PGE, plans to leverage the EU's Just

⁸⁵⁸ Agulhas (2019). The Orkney Islands are leading the transition towards a renewable energy future - Kate Cerna. <https://agulhas.co.uk/2019/02/04/orkney-islands-leading-transition-towards-renewable-energy-future-kate-cerna/>

⁸⁵⁹ H2020 SMILE (2020). Orkney Islands, United Kingdom. <https://www.h2020smile.eu/the-islands/the-orkneys-united-kingdom/>

⁸⁶⁰ Jo, H. (2021). Polish energy policy protests reflect power struggle. <https://www.dw.com/en/polish-energy-policy-protests-reflect-power-struggle/a-57878428>

Transition Fund to support local transitions. Overall, this case demonstrates how affected individuals empowered themselves through self-organized unions to influence policies, protect their rights, and enhance the accountability of policy formulation.

Taiwan has recently made significant efforts to promote solar and wind energy development. While these initiatives have sparked considerable social debate, they have also given rise to a new model of citizen participation. Box 7.3.3 provides a comparative analysis of three business models for fishery and electricity symbiosis. Among the different models, the citizen power plant model involves establishing solar energy systems through citizen participation, which can take the form of community cooperatives, corporate structures, or crowdfunding initiatives. Compared to traditional self-construction or contractor-based models, the citizen power plant model better balances the interests of community residents, aquaculture farmers, and landowners, achieving the goal of a just transition.

Finally, to achieve net-zero emissions by 2050 and make a fresh start in the post-COVID-19 era, the 26th Conference of the Parties (COP26) to the UN Framework Convention on Climate Change in 2021 actively advocated for the “Just Transition Declaration.” Seventeen countries/regions, including the EU, the UK, Germany, France, the US, and Canada, signed the declaration, aiming to address three core aspects: green growth, decent work, and economic prosperity. The declaration committed to principles such as supporting affected workers in transitioning careers, facilitating social and stakeholder communication, establishing climate-resilient supply chains, providing just transition-related information and reports⁸⁶¹, creating relevant mechanisms, and ensuring adequate funding.

Examining the practices of major nations on this issue, the EU incorporated the Just Transition Mechanism and Fund into its 2019 European Green Deal. In the US, the Build Back Better Act employment plan promotes environmental and energy investments while introducing the Justice 40 Initiative, which aims to channel benefits back to disadvantaged communities. In Canada, 90% of carbon tax revenues are directly returned to households, with most receiving refunds exceeding the amount they paid in taxes. This citizen-focused rebate system has garnered broad support for the carbon tax policy. Additionally, households that adopt more energy-efficient or electric vehicles,

⁸⁶¹ UKCOP26.ORG (2021). Supporting the conditions for a just transition internationally. <https://ukcop26.org/supporting-the-conditions-for-a-just-transition-internationally/>

or improve the energy efficiency of heating systems, are eligible for even larger refunds. This approach not only boosts energy efficiency but also provides significant support for policies promoting transportation electrification and related initiatives⁸⁶².

Box 7.3.3 Business Models for “Fishery and Electricity Symbiosis” in Zero-Carbon Power Technologies

Based on the analyses in Sections 7.2 and 7.3 concerning economic, social, and regulatory aspects, and using the zero-carbon electricity development of “fishery and electricity symbiosis” (discussed in Section 2.2 on solar photovoltaic development) as the research focus, the research project titled “ Targeting Net Zero in 2050: A Study of Carbon Pricing and Industrial Transformation Strategies in Taiwan (2022–2024),” led by Academia Sinica, evaluates three business models for fishery and electricity symbiosis: self-construction, contractor-based operations, and citizen power plants. Through qualitative comparisons of the advantages and disadvantages of these models and assessments of their economic benefits, the project proposes specific incentive mechanisms to enhance public willingness to adopt such systems. This aims to promote better power generation efficiency and water resource conservation^{863,864} through the development of “fishery and electricity symbiosis” zero-carbon electricity models. A comparison of the three business models is presented in Table 7.3.4:

⁸⁶² Parliamentary Budget Officer (2020). Reviewing the fiscal and distributional analysis of the federal carbon pricing system.

⁸⁶³ Sahu, A., Yadav, N., & Sudhakar, K. (2016). Floating photovoltaic power plant: A review. *Renewable and Sustainable Energy Reviews*, 66, 815–824. <https://doi.org/10.1016/j.rser.2016.08.051>

⁸⁶⁴ Ranjbaran, P., Yousefi, H., Gharehpetian, G. B., & Astaraci, F. R. (2019). A review on floating photovoltaic (FPV) power generation units. *Renewable and Sustainable Energy Reviews*, 110, 332–347. <https://doi.org/10.1016/j.rser.2019.05.015>

Table 7.3.4 Comparative Analysis of Advantages and Disadvantages of the Three Business Models for Fishery and Electricity Symbiosis⁸⁶⁵

	Advantages	Disadvantages
Self-Construction	• Landowners and aquaculture farmers are familiar with the layout and operations of aquaculture farms, better understanding their own needs. • Landowners and aquaculture farmers retain autonomy over facilities and revenue. • Landowners and aquaculture farmers can access diverse information and independently evaluate suitable facilities.	• High initial capital investment and difficulty securing financing. • Complex application processes and inconsistent standards among administrative units. • Longer application and setup time. • Limited knowledge of solar power systems among landowners and aquaculture farmers may increase aquaculture risks. • Lack of grid infrastructure in remote areas restricts the system to self-use only, preventing surplus energy sales.
Contractor-Based Operation	• Professional solar experts provide facility planning services. • Landowners and aquaculture farmers do not need to invest significant capital. • Landowners and aquaculture farmers receive a stable income (e.g., rental fees). • Maintenance and servicing of facilities are handled by contractors.	• Lower participation from landowners and aquaculture farmers. • Trust issues between landowners, aquaculture farmers, and contractors or corporations. • Most contractors are unwilling to collaborate with aquaculture farmers in conducting aquaculture activities, resulting in the infringement of the farmers' rights. • Contractors typically retain all revenue except rental fees provided to landowners.

⁸⁶⁵ For detailed research findings, please refer to the final report of the Academia Sinica Sustainable Science Research Program, “Targeting Net Zero in 2050: A Study of Carbon Pricing and Industrial Transformation Strategies in Taiwan (2022–2024)”, conducted by Research Fellow Ching-Cheng Chang and Assistant Research Fellow Zong-Han Yang from the Institute of Economics, Academia Sinica.

Citizen Power Plants	• Supplies electricity to the local community, preventing inconveniences caused by power outages. • Offers a fixed discounted rate for electricity purchase over 20 years, enabling cost recovery and guaranteed reasonable profits. • Increased generation capacity addresses the lack of grid infrastructure and booster stations. • Cooperative-based citizen power plants may receive subsidies from the Council of Agriculture. • For corporate-based citizen power plants, landowners, aquaculture farmers, and contractors can cooperate as shareholders, ensuring equitable rights and status.	• Existing regulations impose limitations. • A comprehensive system (e.g., smart grids and energy storage facilities) is required, leading to high initial capital investment, with ongoing maintenance of grid equipment also dependent on the suppliers. • The collaborative model (e.g., corporate or cooperative) and relevant regulations must be determined at the outset. • Requires consent from local residents to avoid disputes.

7.3.4 Policy Recommendations

The zero-carbon transition is a long-term societal undertaking. To foster sustainable values, it requires not only changes in individual behavior and awareness but also localized carbon reduction and adaptation measures. Moreover, effective mechanisms, such as incorporating participation from individual citizens and civil society organizations and fostering social communication, must be integrated into the social system to achieve a just transition. To ensure the success of zero-carbon transition policies, it is recommended that Taiwan's policy planning include the following principles and approaches:

1. Establishing a Robust Governance Framework and Promoting Rooted Education

The primary task of government governance is to establish a comprehensive framework, including the planning of organizations, platforms, procedures, and roadmaps, to enable other stakeholders or departments to participate collaboratively. In the face of the growing climate crisis and climate emergencies, the governance framework must include clear regulatory structures and well-defined roles for specialized agencies to delineate departmental responsibilities and implementation pathways, thereby progressively strengthening the governance system. While setting zero-carbon transition goals, the government can consider expanding existing climate change education to extend and promote zero-carbon concepts. This effort could broaden from school-based education to include societal education, fostering long-term foundational actions. By driving changes in individual behavior and awareness, this approach can cultivate a collective societal recognition of sustainable values.

2. Implementing Localized Adaptation as a Foundation

In supporting technological advancements to achieve net-zero emissions, the government must implement timely adaptation strategies to enhance societal resilience and amplify the effectiveness of carbon reduction technologies once deployed. While actively seeking low-carbon energy solutions, adaptation measures such as the application of energy-saving technologies and incentives to encourage public energy conservation will be critical to successfully integrating innovative technologies. Therefore, it is necessary to develop localized adaptation measures based on the current state and trends of domestic society. These measures should aim to connect and integrate the approaches of various ministries, agencies, and groups, facilitating

effective collaboration among public sectors, businesses, and civil society organizations, and fostering strong public-private partnerships.

3. Creating Platforms for Participation of Civil Society Organizations and Social Communication

It is essential to establish channels for dialogue among diverse stakeholders, utilizing participatory approaches to design interactive and varied communicative formats. Furthermore, communication should be tailored to meet the needs and preferred participation methods of various stakeholders using multiple channels, such as in-person events and online meetings. Where necessary, specialized contacts can be set up to cater to different stakeholder groups. An example is the EU's "Create Acceptance" initiative, which delves into local communities to understand their context, supporting efforts to enhance social acceptance and communication regarding new energy technologies or climate change projects.

4. Ensuring Fair Resource Allocation for an Equitable Transition

Taiwan should, based on its unique characteristics, identify the groups, individuals, and sectors most affected by the transition, such as determining key impacted industries and employment numbers, analyzing job opportunities created or lost during the transition, and assessing the existing rights and vulnerabilities of affected populations. Secondly, establishing a transition mechanism and planning resource allocation—including compensation measures, education training, job creation and transitions, and support for affected groups—is imperative. These mechanisms must be designed through policy legislation to define accountable departments, secure budgets, and allocate resources effectively, thereby realizing the principles of fairness and justice.

7.4 Conclusion

To successfully achieve Taiwan's 2050 net-zero emissions target, the development and deployment of carbon-free power technologies, innovative zero-carbon and carbon-negative technologies, as well as breakthrough innovations, will be key to the transition. Equally indispensable are the economic and social enablers that support these technologies. On the economic front, adequate resource investment, reasonable cost-benefit ratios, and widespread recognition of environmentally friendly values are essential for fostering the long-term development and deployment of various technologies. These factors will help mitigate potential environmental impacts, enhance industrial resilience, and secure Taiwan's entry into the global green supply chain.

To build national consensus and further encourage society-wide participation in zero-carbon transition efforts, social enablers will play a critical role. These include educational initiatives to strengthen public awareness and the practical implementation of carbon reduction principles in everyday life. The zero-carbon transition is a long-term societal undertaking. During this process, the government must progressively establish a governance framework that aligns with Taiwan's needs and developmental directions, ensuring that it is comprehensive. Robust accountability mechanisms should also be put in place to assign corresponding responsibilities to public-private partnerships, enabling substantive participation. Additionally, communication channels must be established in a timely manner to incorporate the diverse perspectives and voices of stakeholders, including individuals, families, businesses, and government entities. By upholding the fairness of the transition and harnessing collective wisdom, we can collaboratively build a zero-carbon, green, and sustainable homeland.

This chapter explores the economic and social dimensions that will enable net-zero emissions policies, initiatives, and measures. The findings are summarized as follows:

1. Economic enablers primarily involve the government designing economic and financial incentive mechanisms to guide systemic adjustments in funding, investment, and employment directions. These adjustments aim to strengthen the drive of industries and society toward achieving net-zero emissions. Taiwan should focus on key international approaches, such as carbon pricing and green finance, while incorporating additional aspects that align with its unique R&D environment, including the circular economy and electricity pricing. These four

areas should be analyzed and promoted to strengthen mechanisms that drive Taiwan's economic transition toward achieving its net-zero emissions goals.

2. Social enablers aim to shape a sustainable value system throughout society, focusing on establishing a robust governance framework that integrates both carbon reduction and adaptation functions. Zero-carbon principles should be rooted in education to foster changes in individual behavior and awareness. Additionally, as the journey toward net-zero emissions progresses, efforts should be made to expand diverse participation from civil society organizations and develop effective mechanisms for social communication. This process should include identifying the groups, individuals, and sectors affected by the zero-carbon transition and, through policy legislation, defining responsible entities and allocating appropriate resources. These steps are essential to achieving social justice in the zero-carbon transition.

Chapter 8 Conclusion

Sections

8.1 Recommendations on Promoting Net Zero Strategies

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8.3 Conclusion—Looking Toward a Net Zero Taiwan

8.1 Recommendations on Promoting Net Zero Strategies

To cope with the challenges posed by climate change, many countries have pledged to achieve the goal of net-zero emissions by 2050. The global supply chain will also work toward a net-zero transformation. Thus, it is vital for Taiwan to plan transformation strategies consistent with local natural conditions and the socioeconomic development environment. These recommendations explore how to use science and technology to help Taiwan achieve the goal of net-zero emissions by 2050 from the perspective of scientific and technological research and development. Recommended strategies include active promotion of zero-carbon electricity, expansion of carbon sinks, development of forward-looking zero-carbon or negative emissions technologies, promotion of carbon reduction strategies in various sectors, and active exploration of breakthrough technologies. At the same time, it is important to work with economic and social enablers and improve the management framework of scientific research to facilitate national action and achieve Taiwan's goal of net-zero emissions.

To promote zero-carbon electricity, Taiwan should focus on the development of renewable energy (including wind power, solar energy, geothermal energy, ocean energy and biomass energy), MPTP technology, smart grids with digital technology and advanced energy storage. As technologies to develop solar energy are relatively mature, Taiwan should actively develop next-generation solar technology with high conversion efficiency and low production costs, so that less land is needed. At the same time, economic and policy incentives can be used to encourage people to install solar energy systems. The development of wind energy needs to take into account the local natural environment and conditions, improve designs for typhoon and earthquake resistance, and develop floating wind turbines. The development of geothermal energy should focus on exploration and development of deep geothermal energy. As Taiwan has abundant geothermal energy, this renewable energy can be used as base load power to help stabilize the power supply and grid. In short, geothermal energy is a renewable energy that cannot be ignored and must be actively developed in Taiwan. The successful development of geothermal energy depends on precise mapping and drilling technologies. These have seen great progress in recent years, and it is necessary to accelerate their research, development and deployment. Apart from shallow geothermal energy within three kilometers underground, Taiwan should work hard to develop deep geothermal energy. At the same time, the government should pass the Geothermal Act

to provide incentives. High-efficient geothermal feeder systems should be built to use geothermal energy as a net-zero baseload power supply. As for ocean energy, it is important to carry out precise hydrological and geological surveys and exploration to find potential areas of ocean energy as soon as possible and invest in the research and development of ocean thermal energy conversion (OTEC) and grid connection.

In addition, Taiwan should work hard to develop MPTP technology which, when combined with existing natural gas power plants, can become the most important source of green electricity. Related technologies that need to be developed and improved include methane pyrolysis, hydrogen-enriched natural gas (HENG) or hydrogen combustion for power generation, hydrogen gas turbines for electricity, and improvement of hydrogen combustion efficiency. Technologies and business models to use solid-state carbon should also be developed. Although MPTP technology still needs to rely on imported natural gas and only utilizes 55% of the calorific value of natural gas, it is a way to think outside the box by relying on traditional carbon dioxide capture, utilization and storage (CCUS) and develop zero-carbon electricity that is more energy efficient and cost-effective. Emerging biomass conversion technology should also be developed to utilize biomass energy effectively. For instance, biomass pyrolysis can be used to generate hydrogen, and biotechnology can be used to facilitate photosynthesis and improve the efficiency of utilizing C1 carbon sources to increase the production of bio-carbon, bio-chemicals and biofuels (for airplanes). Before we can electrify all modes of transportation, imported ethanol fuel mixed with gasoline can be used as fuel during the transition period. To effectively utilize renewable energy and carbon-free power, measures should be taken to overcome the challenge of intermittent power supply from renewable energy and strengthen the power grid. Apart from using traditional pumped-storage hydroelectricity and electricity generated by private power plants, it is vital to build GW-level energy storage infrastructure so grid-scale energy storage systems can be used to support a high proportion of renewable energy.

In the area of carbon sequestration, net-zero and negative emissions technology, Taiwan should increase the domestic production of timber and carry out well-planned thinning. At the same time, advanced bio-based processing should be developed to promote the development of bioeconomy. Research and development on the pyrolysis of Napier grass (*Pennisetum purpureum* Schumach) should be carried out to enhance the performance of biomass carbon sinks.

Regarding carbon reduction strategies of various sectors, the manufacturing sector

should promote the electrification of manufacturing processes, find alternative fuels, and develop low-carbon and zero-carbon manufacturing technologies. The transportation sector should make more efforts to promote the electrification of vehicles and use electric vehicles. These are more efficient than fuel-powered vehicles, albeit the supply of electricity will need to be increased. The residential and commercial sectors should use energy-saving equipment and green building materials, and the government needs to provide incentives and implement encouraging policies. The agriculture and waste management sector should increase biomass carbon sinks by planting short-rotation biomass crops, such as Napier grass (*Pennisetum purpureum* Schumach), on fallow land or unsuitable land.

Taiwan needs to pay attention to the development of breakthrough technologies and develop technologies that allow us to convert carbon dioxide (CO₂) to reusable chemicals, particularly via bioconversion and eco-friendly conversion, to reduce our dependence on petrochemical raw materials. To facilitate the implementation of these strategies, it is important to redesign electricity pricing mechanisms to rationalize electricity prices and establish a way to effectively use and allocate collected carbon taxes. A comprehensive governance framework should be established to facilitate public-private collaboration and promote the concepts of net-zero and sustainability through education. At the same time, a proper channel should be established to enable citizen participation and social communication for a just transformation. The management of scientific research should focus on bringing together the industry, academia and research institutions to invest in technological research and development with high-risk and high-return. To improve accountability, a systematic platform to monitor scientific research should be established, so the research projects can be properly managed. It is our sincere hope that with forward-looking and localized strategies to promote scientific research, plus effective governance and public participation, we can achieve the goal of net-zero emissions in the future.

After a lot of analysis and discussions, we have proposed the following factors to be considered when conducting research to develop net-zero technologies: First, the current bottlenecks engineering and technology should not be considered as constraints. Rather, researchers need to carry out comprehensive evaluation of future technology and potential feasibility of commercialization by thinking about constraints posed by scientific laws. Second, any research on net-zero technology must focus on carbon reduction and consider the time needed to develop such technology and scale of

potential deployment. Taiwan’s unique situation should also be taken into consideration. For instance, Taiwan has local energy resources in various locations, so it is important to think outside the box and not focus on limited energy options. As shown in Figure 8.1.1, to promote zero-carbon electricity and carbon reduction technologies, Academia Sinica has categorized various projects into four categories: “Critically Urgent”, “Priority for Development”, “Continued Development”, and “Emerging”. Academia Sinica also emphasizes that it is important to cooperate with industry during the research and development stage by, for example, providing research funds, sharing experiment outcomes or looking for opportunities to establish new companies. The goal is to include industry perspectives from an early stage and establish partnerships to ensure that these forward-looking technologies can be commercialized.

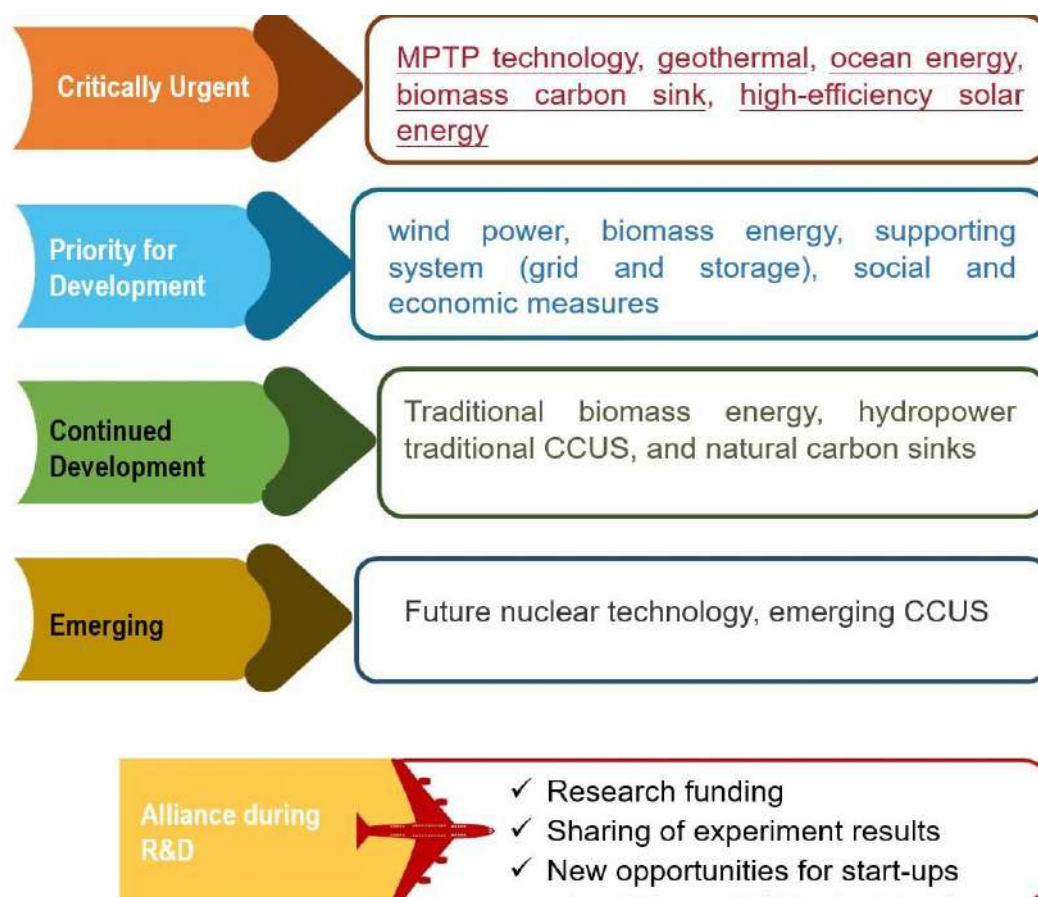


Figure 8.1.1 Academia Sinica’s Prioritization Framework for Zero-Carbon Electricity and Carbon Reduction Technologies

8.2 Suggestions on Prioritization Framework

To respond to the severe challenges posed by global climate change and to achieve the vision of net-zero emissions by 2050, we believe that it is vital to explore net-zero technologies from the perspective of scientific and technological research as well as economic, social, governance and other enabling factors. Our recommendations have proposed three important pillars for policy promotion, which include establishing a national science and technology research and development program, improving the channels to communicate with society and the industry, and promoting an inter-ministerial governance structure. The tasks to promote the pathways to the ultimate goal of net zero by 2050 consist of three aspects: scientific research, socio-economic and governance (Figure 8.2.1).

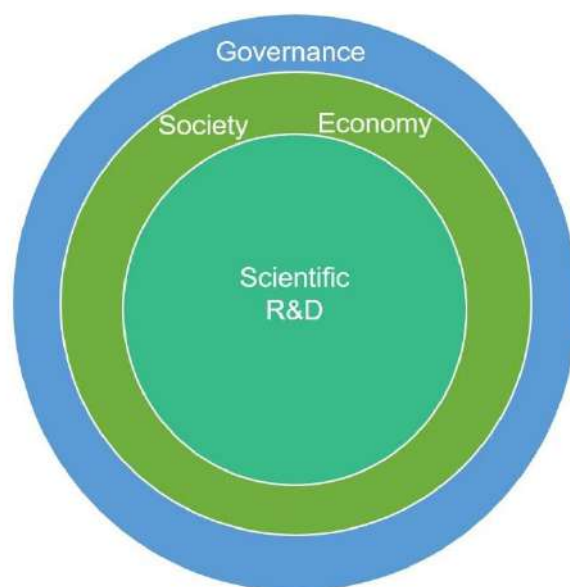


Figure 8.2.1 Policy Pathways to Achieve Net Zero

To begin with, technological research and development is a key driving force in promoting the transition to net-zero. Breakthrough technologies with specific goals can offer opportunities for us to significantly reduce our carbon emissions. Hence, a national science and technology research and development program should be established to support transformative and innovative ideas with high risk and high return to overcome technical barriers and develop low-carbon, carbon-negative and energy-saving technologies. The program can also support the exploration of potentially disruptive technologies with cross-border collaboration and the cultivation of interdisciplinary researchers. We need to use the program to lay a solid foundation

for us to achieve the goal of net-zero transition while meeting the demands for energy security, economic security and sustainable development. Innovative thinking should be incorporated in the process of drafting, implementation, management and assessment of scientific research projects. During the stage of drafting, suggestions from external industry, academia and research institutions should be taken into consideration so the project can be adjusted to overcome technical bottlenecks, to meet the needs and seize opportunities. Then, during the project management stage, the project leader should discuss checkpoints and objectives with the applicant and closely monitor the ongoing project. The project leader is also mandated to intervene or terminate the project. The purpose of the national program is to support technological development in early stages and ensure that the project can reach actual application or commercialization. Typical research outcomes or subsequent developments could include the establishment of a new company, the publication of patents and papers, external sponsorship, collaboration with existing enterprises, or continuing to apply for funding from the public sector for the next stage of technology development. In addition, to attract and retain talent, it is recommended that all sectors set up appropriate reward systems for better and long-term cultivation of key professionals for the development of net-zero technology.

The government should also allocate resources to set up institutions to conduct scientific research on climate change and a net-zero transition for better climate change research, risk assessment and governance, which may include studies on greenhouse gas (GHG) emissions and climate change impacts, simulations and databases on the supply and demand of energy as well as studies on resource recycling. Information technology powered by digital technology and visualization tools, along with interdisciplinary scientific data and evidence, can help to promote open sharing and accessibility of data. Researchers can also bring in discussions exploring how society, the economy and the industry may be influenced during the transition period (such as issues related to COP and the impact of CBAM imposed by the EU.) On the one hand, the government supports researchers, local communities and the public to gain a better understanding of scientific information to facilitate their decision-making; on the other hand, scientific information also supports the government in formulating better policies, coping strategies and better regulation.

Regarding social and economic communication, considering that the use of various economic tools needs to gain support from the industry or the public, it is vital

to ensure participation and dialogue among citizens, businesses, and the government to (1) convey the government's policies and vision on net-zero transformation; (2) to listen to the voices and opinions of the businesses and the general public; (3) to protect the welfare of the general public and workers; (4) to support workers to acquire the skills and competence to make the transition; and (5) to ensure that companies build the capacity to operate sustainably. In other words, as the government promotes the transition to net zero, it is important to ensure a just transition so Taiwan can smoothly go through the process of the socio-economic paradigm shift. In the area of economy, considering international carbon pricing, carbon credits and carbon trading mechanisms, the government should establish mechanisms to charge reasonable carbon fees and carbon taxes. At the same time, the government should explore a carbon trading system that enables the recognition of carbon credits, promotes reductions of emissions and ensures industrial competitiveness. Taiwan should also establish a Just Transition Fund to provide support and compensate economically vulnerable and energy-poor households and affected workers. Therefore, the government should strengthen social and economic communication mechanisms, build consensus through industry-government-citizen dialogue, identify the needs coming out of the transformation process, and provide feedback to guide policy formulation and technological research and development, so that the transformation promotion process can be successfully implemented in different regions.

As for governance structure, the objectives of a net-zero transition can only be achieved through inter-ministerial coordination and governance, leadership of dedicated agencies, and smooth channels of communication and cooperation. It is recommended that the government establish an advisory committee for a net-zero transition at the central government level to announce governance policies on net-zero emissions. The committee should invite experts in various fields, including science, economics, finance, and energy, as well as representatives from industry, government, academia, citizen groups, youth or vulnerable groups to participate. With scientific evidence and risk assessments as the foundation, the committee can help draft climate change adaptation strategies as well as strategies for an energy transition to be provided to the government for formulation of inter-ministerial policies. To implement all the strategies and policies, a dedicated agency should be set up at the Executive Yuan level, led by the Premier of the Executive Yuan who will also supervise inter-ministerial coordination and set short-, midterm- and long-term-goals for net zero emissions for all

ministries and agencies. These goals can then be used to guide businesses and local governments. Regular review and assessment of performance should be carried out to assess the situation and outcomes, and performance reports should be made available to the public in a timely manner for better dissemination of information.

To sum up, we hope that a systematic transition can be made possible by setting up a national research and development platform, by improving communication channels with the society and by enhancing inter-ministerial governance. Facilitated by good policies and scientific research, we can put together the efforts of everyone in Taiwan to meet the goal of net-zero transition.

8.3 Conclusion—Looking Toward a Net Zero Taiwan

Taiwan is an island country known for its strong scientific and technological innovation. It is also a country with a resilient society. However, Taiwan has limited land and energy resources, so we could be severely affected by climate and environmental changes. As the international community works to combat climate change and pursue net-zero emissions, Taiwan, as a member of the global community, cannot remain detached. Instead, Taiwan should follow the trend and seize this opportunity to make the transition to achieve net-zero emissions by 2050 with the rest of the world. We can even work to lead the world in certain technical fields, create business opportunities, and drive industrial transformation. This is a daunting challenge, but we believe that Taiwan can leverage its technological advantages and think outside the box of existing technologies to create opportunities with breakthrough net zero technologies and make substantial contributions to the global common goal of net-zero emissions. It is hoped that Taiwan can reverse the overexploitation of energy to promote the idea of a circular economy and sustainability for all sectors. We also hope that with innovative economic and financial tools, we can boost the net-zero economy, a development model based on the idea of a circular economy, one that Taiwan can make possible. Taiwan can also combine its strengths across all sectors of society to have meaningful dialogue between different ethnic groups and interest groups for mutual understanding and inclusion. Under the premise of justice and fairness, Taiwan can make use of good social communication channels to create a diverse and peaceful society, one that promotes the idea of sustainability and encourages everyone to embrace behavioral changes for a net-zero lifestyle.

We have proposed various options for Taiwan to move toward a net zero goal. Unfortunately, we must admit that even if Taiwan does its best to reduce its own carbon emissions, the existing concentration of GHGs in the atmosphere, the inconsistency of global carbon reduction actions, and the uneven distribution of climate change impacts, Taiwan may still face risks from climate change. This issue is beyond the scope of our recommendations, but is still a key aspect related to Taiwan's response to climate change. We can make our best efforts to mitigate the impact of climate change, but we must not forget the importance of adaptation. We hope that Taiwan can strategically develop both mitigation and adaptation technologies, enhance its capability to respond to climate change, maintain resilience to cope with major challenges and turn research

and development results into practical actions. Ultimately, we can achieve the national goal of a prosperous and resilient Taiwan.