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Commentary

Perspectives on Taiwan's Pathway to Net-Zero Emissions

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Abstract: For achieving net-zero emissions by 2050, countries worldwide are committed to setting ambitious carbon reduction targets. In 2022, the officially published report, "Taiwan's Pathway to Net-Zero Emissions in 2050", sets out a comprehensive transition plan based on four fundamental strategies: energy, industrial, lifestyle, and social. This transition will likely entail an infrastructure transformation in all sectors of the economy, embracing renewable energy, electricity, and low-carbon fuels. While the Taiwan government is rolling up its sleeves to accelerate the pace of carbon-emission reduction, it is risky to set targets without considering the full implications of net-zero emission and how it will be achieved. This paper provides four insights into Taiwan's net-zero-emission plan from a perspective of the current understanding of decarbonization and the techniques urgently needed. Although many uncertainties and outstanding questions exist in our net-zero energy systems, and the required granular information for decision makers to track progress has not been clearly identified, this paper points out the characteristics that have been neglected and provides guidance for all stakeholders—governments, businesses, investors, and citizens—to work together on a coordinated plan to tackle climate change.

Keywords: policy for net-zero CO_2 emissions; renewable energy; decarbonization; carbon capture; virtual power plant

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1. Introduction

The concept of achieving net-zero emissions dates back to the 26th UN Climate Change Conference (COP26) held in Glasgow, UK on 31 October 2021. While previous COP conferences focused on reducing carbon emissions [1], COP26 marked the first meeting where countries reached a consensus on phasing out coal-power use [2]. Furthermore, COP26 reaffirmed the goal of limiting global temperature increase to 1.5 °C, and finalized the Paris Agreement [2]. To achieve this goal, governments must take active steps towards "net-zero" climate action. So far, more than 130 countries have committed to achieving net-zero emissions by 2050 [3].

Meanwhile, the European Parliament has approved the Carbon Border Adjustment Mechanism (CBAM) as part of a comprehensive legislative effort to reduce net greenhouse gas (GHG) emissions in Europe. The CBAM puts a carbon price on specific imported products while phasing out the free allocation of emissions allowances to European industry [4]. In addition, several global corporations have joined the RE100 initiative, which aims to source 100% of electricity consumption from renewable sources by a specified year [5]. Achieving this ambitious target will require supply chains to accelerate their transition towards zero-carbon grids and to develop techniques to strengthen carbon-reduction efforts. Meanwhile, several research groups have been focusing on developing techniques to strengthen carbon reduction and achieve zero-carbon grids. These efforts involve studying various aspects of energy systems, such as renewable energy generation [6], energy storage [7], and grid infrastructure [7,8]. The research aims to identify the effective strategies to reduce carbon emissions from energy systems and create sustainable energy solutions for the future.

As a country heavily reliant on export economies, Taiwan is bound to face the challenge of more rigorous international carbon action in the future. Therefore, it is urgent to accelerate the deployment of a net-zero transition to comply with the growing trend of carbon-emission reduction in international trade. By doing so, Taiwan can continue to expand its market and secure orders, while meeting international climate goals.

Taiwan's Key Milestones in the Global Fight against Climate Change

In 2009, Taiwan enacted the "Renewable Energy Development Regulations" to encourage the use of renewable energy, promote energy diversification and resilience, reduce GHG emissions, and enhance sustainable development in the country [9]. In 2015, the Greenhouse Gas Reduction and Management Act officially became effective, establishing strategies to reduce and manage GHG emissions, strengthen environmental justice, and promote shared responsibility for environmental protection and national development [10]. The Act set a five-year phase control target, with the first two phases aimed at reducing GHG emissions by 2% and 10% by 2020 and 2025, respectively. The third phase was initially set to achieve a 20% reduction by 2030, but in 2017 it was revised to a more ambitious 50% reduction, in line with global climate goals to limit temperature increases below 2 °C [10,11].

Although both laws were proposed and passed in accordance with the international consensus on climate change, Taiwan's processes on carbon reduction and energy transition have been limited over the years [12]. Simply integrating with international standards may not have sufficiently prepared Taiwan to respond to the rapidly changing market driven by climate change. Taiwan also needs to develop a climate adaptation framework that can address the negative impacts of extreme weather events and other climate-related challenges.

In March 2022, Taiwan published its official blueprint for the "2050 Net Zero Emission Pathway Plan", which aims to achieve virtually net-zero GHG emissions by 2050. The plan focuses on four major strategies and two major foundations: technology development and climate legislation [13]. Later in the year, the Climate Change Office of the Environmental Protection Administration Executive, Yuan, proposed amendments to the Greenhouse Gas Reduction and Management Act, renaming it the "Climate Change Response Law", and enshrining Taiwan's net-zero target for 2050 into law. Other proposed amendments included strengthening emission management, promoting reduction, pricing carbon, and aligning the carbon content of specified products with environmental objectives [14]. The proposed amendments were officially published in January 2023 [10].

2. Net-Zero Policy in Taiwan: A Low-Carbon Transition

Although the 2050 Net-Zero Emissions Pathway Plan, which has legislative effect to meet the net-zero target was officially announced in 2022, Taiwan's efforts to reduce emissions date back to 2020, when short-term targets were first set, and, according to the 2021 Taiwan EPA Environmental Statistics Yearbook [15], Taiwan was able to meet its short-term target in 2020 by achieving a 2.12% reduction in emissions compared to 2005 levels.

In 2019, net GHGs emissions in Taiwan were 265.62 million metric tons of carbon dioxide equivalent ($MtCO_2e$), with 21.44 $MtCO_2e$ removed through carbon absorption by forests [13]. Emissions by sector were as follows: manufacturing (51.4%, 147.46 $MtCO_2e$), residential and commercial (19.38%, 55.34 $MtCO_2e$), energy (self-use) (13.20%, 37.88 $MtCO_2e$), transportation (12.89%, 36.99 $MtCO_2e$), agricultural (2.22%, 6.37 $MtCO_2e$), and environmental (0.94%, 2.70 $MtCO_2e$) [13].

According to the Announced Pledges Scenario (APS) modeled by the International Energy Agency (IEA) [16], the power sector's fossil fuel consumption is projected to rapidly decline, due to the increasing use of low-carbon-emission power sources such as renewable energy, hydrogen energy, and low-carbon technologies, as well as improved fuel efficiency. Conversely, with the rapid growth of electricity demand in various industrial sectors and household appliances (e.g., fuel vehicles being replaced by electric vehicles), the electricity consumption in various countries is expected to show an increasing trend [17]. As a result, the global energy demand will plateau after 2030 [16]. Referring to the same net-zero scenario, Taiwan's mean annual electricity-consumption growth is 2.0 ± 0.5% [13] (Figure 1).

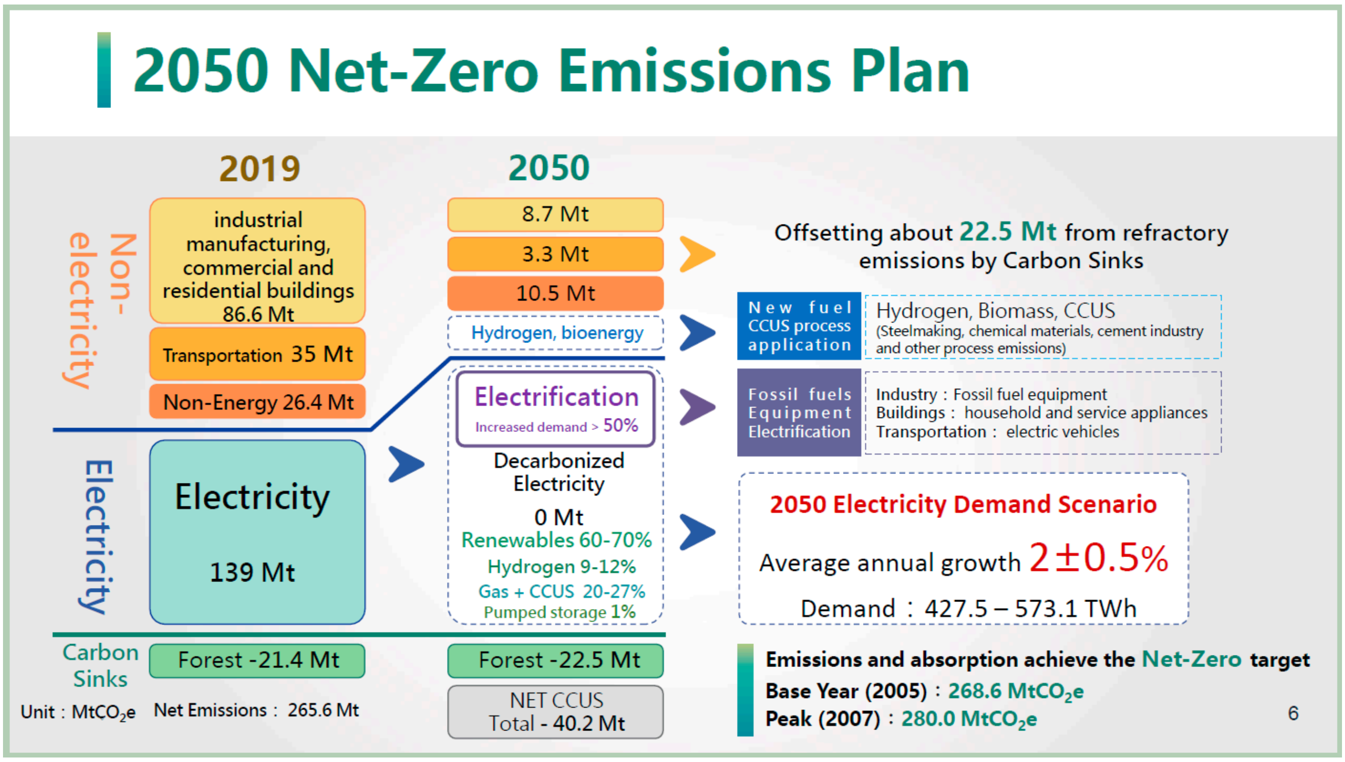

Figure 1. Taiwan's 2050 net-zero emissions plan (Reprinted/adapted with permission from Ref. [13]. Copyright 2022, National Development Council).

Taiwan's net-zero emission plan (Figure 1) is expected to be implemented in two stages [13]. The Net Zero Plan Stage 1: 2020–2030, aims to implement existing carbon reduction measures to achieve low-carbon emissions, stop building new coal power plants, and increase renewable electricity capacity and its share in the power sector to mitigate the climate change impact by reducing greenhouse gas emissions [13]. The Net Zero Plan Stage 2: 2030–2050, deploys a long-term net-zero plan by actively investing in various innovative low-carbon technologies (e.g., Carbon Capture, Utilization, and Storage, CCUS) so that the developing net-zero technologies can be well laced to accelerate the last mile of carbon-emission reduction [13].

Through Stage 1 and 2, the preliminary blueprint for net-zero emissions by 2050 (see Figure 1), shows that renewable energy accounts for 60–70% of total electricity supply, hydrogen energy accounts for 9–12%, and 20–27% of total electricity is generated by thermal power plants equipped with carbon capture technologies [13].

Regarding other GHG emissions that are difficult to eliminate, such as fluorinated greenhouse gases from manufacturing [18], as well as methane and nitrous oxide emissions from agricultural and livestock production [19] and waste and wastewater treatment [20], offsetting through carbon sinks will be implemented using optimal land-management practices, including afforestation (the conversion of non-forested land to forest), revegetation, improved agricultural practices, and wetlands conservation [13].

2.1. Four Strategies of Taiwan's Net-Zero Emissions

In order to achieve net-zero emissions by 2050, Taiwan has developed a comprehensive transition plan based on four fundamental strategies: energy, industrial, lifestyle, and social, as outlined in the officially published report "Taiwan's Pathway to Net-Zero

Emissions in 2050" [13]. This transition will likely involve a significant overhaul of the infrastructure across all sectors of the economy, to adopt renewable energy, electricity, and low-carbon fuels.

2.1.1. Energy Transition

Thermal-power generation currently accounts for the largest share of electricity production in Taiwan, making up 79.6% of the total [21], and it is also the largest source of GHG emissions in Taiwan. Increasing the renewable energy capacity is viewed as an urgent measure to address GHG emissions. Solar photovoltaic and offshore wind energy are mature and competitive renewable sources in Taiwan [13]. The Ministry of Economic Affairs (Taiwan) aims to achieve a combined installed capacity of 27 GW by 2025, with 20 GW of solar, 5.6 GW of offshore wind, and 1.4 of other sources, which will account for 20% of the electricity generation [13]. Efforts towards promoting renewable energy date back to 2012, when the Energy Bureau of the Ministry of Economic Affairs initiated the "Million Rooftop PVs" and "Thousand Wind Turbines" programs. The "Million Rooftop PVs" encourages the installation and use of residential PV systems by providing a guaranteed purchase agreement for 20 years, and selling electricity from renewable sources at government set rates [22]. The "Thousand Wind Turbines" program aims to expand small-scale installations from onshore to offshore, and from shallow sea to deep sea [23]. With offshore wind energy now considered a mature market with a growing global following, the installed offshore capacity is expected to reach 5.6 GW by 2025, up from 0.23 GW in July 2022 [15,21].

In addition, there are ongoing efforts to (i) promote other renewable energy sources such as geothermal, wave power, and ocean-power generation, (ii) maximize the use of natural gas, projected to reach 50% of electricity generation by 2050, (iii) encourage private gasification plants to use materials such as bio-fuel and solid recovered fuel (SRF) for a more sustainable energy production, (iv) build a low-carbon and high-efficiency electricity power system, and (v) reduce energy consumption through the Demand Load Response program [13].

2.1.2. Industrial Transition

The industrial transformation focuses on four major sectors: manufacturing, commerce, construction, and transportation. A step-by-step plan is outlined to achieve promotion based on the principles of moving from the public to private sector and from large to small enterprises [13]. The manufacturing sector aims to improve process and convert to energy-efficient practices, while the commerce sector focuses on modifying business models. The construction sector aims to achieve a circular economy by introducing the use of recycled building materials and energy-efficient building design [13]. In the transportation sector, the Ministry of Economic Affairs has put forward a vision of achieving a 100% price-to-sales ratio for electric vehicles by 2040, to enhance the electrification [13].

2.1.3. Lifestyle Transition

The key concept of lifestyle transition is people-oriented thinking [24]. By increasing awareness and consensus on climate change and net-zero transformation, behavioral changes can be brought about in various aspects of life such as food, clothing, housing, and transportation. Practical advice and guidance can be given on how to live a low-carbon life, such as choosing locally sourced, organic, and seasonal food to reduce the use of fertilizers, pesticides, and energy spent on transportation and preservation. In terms of transportation, people can consider options such as walking or biking for short distances, using public transport such as trains and buses, or choosing environment-friendly vehicles such as electric or hybrid cars, if necessary. By implementing low-carbon lifestyles, the public can encourage manufacturers to create a low-carbon business model and green-life industry supply chains.

2.1.4. Social Transition

Social transformation comprises two key components: just transformation and civic engagement [13]. The net-zero transition is expected to create various challenges related to labor employment, industrial transformation, regional development, and people's livelihood consumption [25]. For instance, to achieve the goal of net-zero emission by 2050, companies will be required to adopt renewable and green energy sources, invest in innovation and the circular economy, and promote clean-energy supply chains. However, the transformation of high-carbon-emission industries may adversely impact local tax revenues, regional development and residents' income stability, and even result in labor emigration [26]. Additionally, the transformation process may increase the production cost of enterprises, which could lead to higher living costs for consumers, especially low-income families [25,26]. Therefore, the Taiwan government is championing the "leaving no one behind" initiative by enhancing the support system, fostering public–private collaboration, implementing compensatory mechanisms to mitigate socioeconomic impacts, and transforming conflicts into sustainable opportunities [15,26].

The initiative includes five aspects: (i) Promote a multi-party participation mechanism and establish a responsible organization and advisory committee. (ii) Expand social participation to assist the government in communicating with stakeholders. (iii) Extend the scope of just transition beyond labor issues to include compensation mechanisms for electricity prices and investment in advanced technology research and innovation. (iv) Expand the object of just transformation beyond labor to include industrial transformation and regional activation. (v) Propose a just transition roadmap, report, and legislation, and allocate sufficient funds to ensure that all vulnerable groups affected by the transition are taken care of [26].

3. Insights into Taiwan's Net-Zero Emission Plan

As the Taiwan government accelerates the pace of carbon-emission reduction, setting targets without fully understanding the implications of the net-zero emissions and how they will be achieved is risky. There are many uncertainties and outstanding questions that exist in our net-zero energy systems, and the granular information required for decision makers to track progress has not been clearly identified. In this context, we discuss several uncertainties and provide four insights based on key findings.

3.1. Will the Renewable Energy Boom Lead to More Blakouts?

Taiwan's energy transition is focused on significantly increasing the proportion of renewable energy in the electricity system, with solar and offshore wind energy playing a key role [13]. However, their intermittent and unpredictable nature as intermittent renewable energy sources (IRES) or variable renewable energy (VRE) poses significant challenges for grid operators, who must ensure a balance between supply and demand [27]. It is worth noting that a detailed and comprehensive discussion on the ways to best exploit renewable energy sources can be found in the following Section 3.2.

The electricity supply cannot be increased or decreased arbitrarily, and the storage cost is too high to meet short-term changes in demand through inventory. As is the case with other commodities [27]. As a result, the power companies must dispatch generator sets flexibly to meet fluctuations in power demand in real time and maintain a dynamic balance between supply and demand [28]. If the power company fails to balance the power flows in the electricity grid, the supply will become unstable, causing power outages [28].

The electricity generation of renewable energy is classified as "non-dispatchable" or "variable" energy, due to the uncertainty of factors such as weather, season, region, and equipment performance, which makes power generation intermittent and unpredictable [27]. Renewable energy cannot generate stable electricity in the same way as coal-based thermal power and nuclear energy, which are suitable for long-term continuous operations to obtain better power-generation efficiency and are widely designed for baseload supply [27]. They differ from gas, oil fuel, and hydraulic power, including pumped-storage hydroelectricity, in that their generator sets can rapidly start up to meet spikes in demand, often supplying energy for peak load [28]. Additionally, renewable energy cannot flexibly control the electricity output following instructions from power companies to respond to demand load in the same way as a conventional power plant [27]. With the rapid growth of renewable energy connected to the grid, its uncertainty factors will increase the probability and frequency of blackouts [27].

The reason for power outages in recent years in Taiwan was discussed, and speculated to be due to a variety of factors, including the shutdown of nuclear power reactors to achieve a non-nuclear policy [29], the reduction in bituminous coal usage in coal-fired power plants to comply with the Air Pollution Control Act [30], limitations on the operation of gas-fired power plants due to noise and environmental concern [30], and the addition of new power grid lines causing instability, due to the return of Taiwanese businessmen to set up production facilities. As energy shifts to renewables, the grid needs more reliable generation, not more intermittent supplies.

3.2. Virtual Power Plant (VPP), a New Form of Energy Management

Due to the variability of wind- and solar-energy generation, traditional load forecasting methods are no longer effective [31]. To address the rapid growth of renewable energy, a new strategy has emerged: the virtual power plant (VPP), which centers around the concept of "demand management"—controlling electricity consumption and supply in real-time [31]. A VPP integrates small-scale, distributed energy resources (such as wind farms, solar PV, and combined heat and power units) and load management schemes (such as dynamic electricity prices and demand response), and centrally controls them through information and communication technology (ICP), networking across different levels of power grids to meet various requirements [31,32]. The VPP is referred to as "virtual" because it can improve the resilience of the power system, and adapt to fluctuating changes in demand and load. This emerging power plant can coordinate various distributed power sources to achieve a stable power supply, increase the proportion of overall renewable energy generation, reduce total losses in power distribution and transmission lines, and improve overall energy efficiency.

3.3. A Nuclear-Free Taiwan by 2025?

Taiwan has three nuclear power plants, each equipped with two nuclear reactors, and a fourth plant that was stopped by referendum. The government has scheduled the decommissioning of these nuclear power plants for 2019, 2023, and 2025, respectively, in line with the "Non-nuclear Homeland" policy [29]. This policy is similar to Germany's phase-out of nuclear power, which saw the permanent shutdown of eight out of its seventeen reactors after the 2011 Fukushima nuclear disaster [33]. Some in Taiwan believe that, with the rapid growth of renewable energies, nuclear power, which currently accounts for 10% of electricity generation, will no longer be needed [21,34]. However, due to Taiwan's location at the junction of the Eurasian Plate and the Philippine Sea Plate, the island is prone to frequent moderate-to-strong earthquakes [35]. A report by the Community Research and Development Information Service (CORDIS) identified Taiwan as one of the geographic zones at the highest risk of large tsunamis [36]. Two of Taiwan's nuclear reactors are cited in this report, raising concerns about the potential risks of nuclear reactor damage from tsunamis [36].

Moreover, Taiwan's independent power grid cannot follow Germany's strategy of equipping electricity interconnectors that connect neighboring countries' electricity systems to solve the intermittent renewable energy problem [37]. Furthermore, unlike nuclear-power or thermal-power generation that runs all day, renewable energy, whether wind or solar energy, is subject to variability. Currently, nuclear power in Taiwan accounts for 10% of electricity generation through three reactors in the two active plants [21]. However, the implementation of the non-nuclear policy, while ensuring a stable electricity supply, may lead to a significant increase in the use of coal and natural gas to compensate for the variability introduced by renewable energy, contradicting the current trend of achieving net-zero carbon emissions. In fact, Germany has announced plans to temporarily halt the phase-out of the last two nuclear power plants, due to the Russian invasion of Ukraine, which has cut natural gas supply to European countries [38]. The Japan government has been pushing for a return to idled nuclear plants and developing next-generation reactors for safety concerns, due to a fuel shortage following the Russo-Ukrainian War and climate commitment to carbon-free energy [39]. Meanwhile, the European Commission has proposed the Complementary Climate Delegated Act (CCDA), which lists specific gas and nuclear activities in the taxonomy of sustainable sources of energy [40]. Only new nuclear plants applying the most advanced technologies or modifications to existing plants may be recognized until 2040 or 2045, depending on the specific situation [40]. Reports have acknowledged that nuclear power is a low-carbon energy source, and its CO_2 emissions over the life cycle are comparable to those from renewable energies.

However, radioactive waste is a major challenge associated with nuclear power generation. Nuclear power plants produce spent fuel rods and other types of radioactive waste, which can remain hazardous for thousands of years [41]. The long-term storage and disposal of this waste is a complex and expensive process that requires careful planning and management to prevent any leakage or environmental contamination. One solution for nuclear waste disposal is to store it in a geological repository, which is designed to isolate radioactive waste from the environment for hundreds of thousands of years [42,43]. However, no such repository has been built yet, and the construction and operation of a repository face significant technical, social, and political challenges. Another option is to use advanced nuclear technologies such as fast reactors [44,45] and fusion reactors [46,47], which produce less long-lived radioactive waste or even no radioactive waste at all. However, these technologies are still in the research-and-development stage and have not been deployed commercially.

Despite the planned shutdown of all existing nuclear power plants in Taiwan by 2025, the 2021 white paper from the Chinese National Federation of Industries recommends deferring nuclear retirements and considering retaining nuclear power capacity under specific operational conditions [48]. The paper also suggests that the government should review whether the non-nuclear policy in 2025 is inconsistent with the global goal of carbon neutrality, particularly as nuclear energy is now classified as clean energy and expected to have a significant impact on carbon reduction [48]. Furthermore, the report advocates using zero-carbon nuclear power as a baseload source of electricity and developing a backup power plan to increase the flexibility of power dispatch [48].

3.4. Could Carbon Capture, Utilization and Storage Be the Antidote for Climate Change?

The International Energy Agency (IEA) has identified four strategies to reduce carbon emissions and achieve agreed-upon climate-change goals. These include improving energy efficiency, generating power from renewable energy sources, transitions from high-emitting coal to low-carbon gases, and utilizing carbon capture and storage (CCS) technologies to reduce the CO_2 already produced [49]. CCS has the potential to achieve 9% of the global carbon-reduction effect with continuous development [49]. There are several promising applications of new strategies and technologies for CCS, such as direct air capture (DAC). DAC captures carbon dioxide directly from the air and stores it in geological formations [50–52]. Another application is bioenergy with carbon capture and storage (BECCS), which involves capturing carbon dioxide from biomass energy generation and storing it underground [53–55]. Carbon capture and utilization (CCU) is a related concept that involves converting captured CO_2 into products such as concrete [56,57], plastics [58] or fuels [58,59]. There are numerous innovative CCUS technologies currently in development and undergoing testing, including membrane and chemical-absorption systems. Membrane-based systems use specialized membranes that selectively separate carbon dioxide from other gases, resulting in higher-purity carbon dioxide streams, and are being developed for capturing carbon dioxide from industrial flue gases [50,60,61]. On the other hand, researchers are working on developing more efficient and cost-effective solvents for carbon capture, such as amino acid-based solvents [62], ionic liquids [63–65], and deep eutectic solvents [65,66]. Compared to traditional solvents such as monoethanolamide (MEA) and diethanolamine (DEA), these innovative solvents have lower energy requirements for solvent regeneration, are less corrosive, and have a lower environmental impact. Both CCS and CCU are necessary tools to reduce CO_2 emissions, and are expected to achieve significant emission reductions on a large scale, once commercially viable [67].

Taiwan has been involved in post-combustion CCUS since 1988, with the Bureau of Energy and the Industrial Technology Research Institute (ITRI) conducting various research and evaluation programs. Several large-scale projects have been implemented, such as the calcium-looping CO_2 capture technology in Heping Cement Plant located in Hualien [68], microalgae cultivation to capture emissions from thermal power plants through photosynthesis in Dalin Power Plant located in Taichung [69], and geological surveys on the possibility of CO_2 sequestration in saline aquifers in Miaoli Yonghe Mountain and the Zhangbin Industrial Zone, which were carried out by the China National Petroleum Corporation and the Taiwan Power Company, respectively [70].

However, CCUS projects typically set a baseline target of a 90% capture rate as the minimum threshold to make the investment worthwhile, beyond which mitigation becomes uneconomical [71]. CCUS technologies applied to coal-fired power plants often use scrubbers for carbon dioxide adsorption, desulfurization, denitrification, and fly ash, which can increase power generation costs and energy consumption [72]. For example, the Petra Nova project in the United States captured CO_2 from coal-fired power plants to increase oil recovery using enhanced oil recovery (EOR) technology [73]. The facility captured more than 2 million metric tons of CO_2 annually, accounting for 95% of the total volume of CO_2 targeted. However, the project was halted in May 2020, due to the uneconomic nature of petroleum sales compared to the operating costs of CCUS [73]. In the short term, the capacity of CCUS technologies to reduce CO_2 emissions is limited unless carbon prices rise high enough to be a key driver for triggering investment in innovative clean technology, along with incentives to account for CCUS costs [73].

4. Conclusions

This article examined Taiwan's roadmap towards achieving net-zero carbon emissions and focused on the energy transition, which is responsible for the largest share of carbon emissions. While increasing the installed capacity of renewable energy and promoting self-produced energy can help reduce the risk of high energy dependence on imports, integrating multiple renewable energy sources into the power system and ensuring stable operation remains a challenge for the government, Taipower and renewable energy companies. Decentralized renewable-energy systems, energy storage systems, demand response and ancillary services markets are potential strategies to reduce the negative impact of intermittent renewable energy on the grid and enhance energy autonomy and supply stability.

Moreover, given the changing public attitudes towards nuclear energy, and the trade-offs involved in various CCUS technologies, this article highlights the neglected characteristics and offers guidance for all stakeholders, including governments, businesses, investors, and citizens, to collaborate on a coordinated plan to address climate change.

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