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Power System Decarbonization Assessment: A Case Study from Taiwan

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Abstract: The first global stocktake (GST) at 2023 UN Climate Change Conference (COP28) pointed out that accelerating the phasing down of fossil fuels has become an important mitigation policy to maintain a maximum temperature limit of 1.5 °C. The optimal power portfolio for achieving Taiwan's net-zero emissions by 2050 is evaluated from the perspective of sustainable development. This study is enhances the 2021 research findings of Wang et al. on the sustainable power model, incorporating homogenized cost and technical constraints for empirical analysis. The results indicated that renewable energy sources play a pivotal role in achieving net-zero emissions. Gas power generation requires careful consideration, including early decommissioning or the adoption of carbon capture and storage (CCS) technology to prevent carbon lock-in and compete with hydrogen energy technology. Notably, coal combined with CCS technology offers a viable option for a cost-effective roadmap for a decarburized power generation portfolio by 2050, serving as a reference for national planning strategies for promoting net-zero emissions.

Keywords: net-zero emission; cost effectiveness; sustainable power; power portfolio

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1. Introduction

In response to global warming, a maximum temperature increase of 1.5 °C has been established in the Paris Agreement, and numerous countries have declared a target of "zero net emissions by 2050". However, the sixth IPCC assessment report [1] demonstrated that net-zero emissions can be achieved by significantly reducing carbon dioxide emissions within only a few decades. The International Energy Agency (IEA) [2] has also suggested that deep decarbonization of power systems is the optimal strategy for supply. The first global stocktake (GST) at 2023 UN Climate Change Conference (COP28) [3] indicates that the need for deep, rapid, and sustained reductions in greenhouse gas emissions in line with 1.5 °C pathways and calls on parties to contribute to the following global efforts, in a nationally determined manner via the following: (1) Tripling renewable energy capacity globally and doubling the global average annual rate of energy efficiency improvements by 2030; (2) Accelerating efforts towards the phase-down of unabated coal power; (3) Accelerating zero- and low-emission technologies, including, renewables, nuclear, abatement and removal technologies such as carbon capture and utilization and storage, particularly in hard-to-abate sectors, and low-carbon hydrogen production. Among major countries, such as the European Union, the most recent climate policy, especially the Fit for 55 package, aims to significantly increase renewable energy usage, develop carbon capture and storage (CCS) technologies, and advance green fuel production as key decarbonization drivers to achieve the target of reducing emissions by 55% by 2030 [4]. Japan also consider the development of renewable energy and CCS technologies as crucial strategies for the net-zero transition of the power sector [5]. Additionally, SDG7 (Affordable and Clean Energy) should also be considered to achieve net-zero emissions to establish the optimal portfolio of power generation technologies and to ensure a stable energy supply while giving consideration to environmental sustainability and economic development. In summary, the power mix that meets environmental effectiveness and cost effectiveness will be a key strategy towards low-carbon emission pathways in a country.

How to pursue an appropriate power generation mix based on the characteristics of different power generation technologies to achieve national net-zero goals has also been emphasized in the literature. Wang et al. [6] summarized the relevant literature concerning planning an appropriate power generation portfolio to achieve multiple targets and avoid risks, which can be divided into three main research methods: (1) modern portfolio theory (MPT), (2) multi-criteria analysis (MCAs), and (3) optimal model.

(1) Modern Portfolio Theory (MPT):

Long-term energy planning faces myriad choices between renewable and non-renewable energy combinations. The majority of studies in this realm adopt the MPT proposed by Markowitz [7] as an analytical framework. This theory is utilized to minimize costs under a fixed risk level, or to minimize risk at a fixed cost level, thereby selecting an effective energy portfolio (Refs. [8,9]). In recent years, MPT has been widely used to explore many aspects of the energy market, including energy policy, energy structure, and power generation structure. It provides a diverse solutions and strategic recommendations at various levels for different countries and regions. For example, Awerbuch and Yang [8] planned the power generation ratio of the EU in 2020 using MPT in financial management. deLlano-Paz et al. [10] analyzed the impact of different energy targets in 2030 for the EU Energy Union, considering economic and environmental perspectives and real technology assets; they also discussed the impacts of carbon capture and storage (CCS) technology on the European power technology portfolio. In Africa, Malala and Adachi [11] evaluated the suitability of Kenya's current power portfolio with MPT based on the reliability and affordability of the power system and the influence of climate change. In Asia, Zhu and Fan [12] and Zhang et al. [13] evaluated the optimal power generation technology portfolio for China in 2020 and 2030 using MPT, considering power generation technology preferences. Additionally, addressing the power generation mix issue in Taiwan, Wu and Huang [14] focused on power generation portfolio issues in Taiwan combined with MPT and the learning curve.

(2) Multi Criteria Analysis (MCAs)

Energy system planning involves finding a balance among various goals across economic, environmental, energy, and social dimensions. MCAs is an effective tool for balancing and exploring trade-offs among these multidimensional objectives. It has been widely used on a global scale, providing multiple perspectives and solutions that effectively assist countries in achieving a balance among multiple goals and challenges. For example, Ryu et al. [15] discussed the power portfolios of South Korea and Mongolia in terms of energy security, carbon emission reduction targets, and power generation costs. Similarly, Portugal-Pereira and Esteban [16] established multiple indicators from the viewpoint of energy security to evaluate the power generation technology portfolio in Japan. Moreover, Jayaraman et al. [17] developed a multi-objective model of sustainable development to plan a sustainable energy supply portfolio for the United Arab Emirates in 2030, considering targets related to economic growth, power consumption, and carbon emission. Recent studies also include Choi et al. [18], who developed a multi-criteria decision-making model of an energy system to evaluate the impact of different transformations, such as reducing nuclear power and fuel coal in Korea's power sector; Marques et al. [19] studied Brazil's energy planning using a multi-criteria decision-making model; Laha and Chakraborty [20] evaluated the optimal power portfolio in India using a multi-objective evolutionary algorithm and ranked the optimal schemes by multi-criteria sustainable evaluation.

(3) Optimal model:

The application of optimization methods provides multidimensional analysis and solutions for low-carbon transition. They offer a rich theoretical foundation and empirical support in various aspects, ranging from cost–benefit analysis and carbon emission control to renewable energy storage. For instance, Lee and Rosalez [21] discussed the optimal strategy for Taiwan's low-carbon transformation using the optimal model. Blanco et al. [22] evaluated the annual input cost of the low-carbon transformation of the EU power sector in 2050 using the optimal cost method, which corresponds to approximately EUR 2.5–10 billion. Su and Lee [23] estimated peak greenhouse gas emissions in China by combining the optimal model with the STIRPAT model. Verma et al. [24] established an optimal control problem in the carbon emission reduction strategy for energy use, discussing the optimal solution by reducing CO_2 emission rates and reducing energy use as the control variable. Schrotenboer et al. [25] discussed the optimal strategy of combining wind power generation with green hydrogen storage, applying Markovian decision processes.

The aforementioned literature analysis indicates that although modern portfolio theory can plan alternative strategies that meet the efficiency frontier of the power generation portfolio, it will not be possible to obtain an optimal plan due to failure to consider the multiple objectives of the sustainable power system. Recognizing this limitation, Wang et al. [6] established a sustainable power system based on MPT as the foundation for analysis, clearly defining the significance of low-carbon transition for sustainable power supply. They incorporated the risk associated with the mix of power generation technologies and used an optimal control model to plan the optimal long-term mix of power generation technologies to achieve carbon reduction targets.

In recent years, Taiwan has been actively promoting its energy transformation. At the end of 2021, Taiwan's power was supplied using fossil fuels (80%), nuclear energy (15%), and renewable energy (5%). In response to trends in global emissions reduction, in March 2022, Taiwan also declared a net-zero emission target by 2050, announcing an act addressing climate change to promote national emissions reduction targets in 2023. Therefore, it is crucial for power management organizations to take into consideration our domestic sources of electricity, and to construct a cost-effective, climate-resilient power generation portfolio in alignment with the 2050 net-zero pathway based on the unique characteristics of each type of power resource. This approach will be a key strategy for Taiwan to achieve energy transformation and presents a challenge in realizing the net-zero objective.

In view of this, the objective of this study is to map out Taiwan's electricity structure trajectory up to 2050. Drawing on the sustainable power model developed by Wang et al. [6], this research enhances the analysis of correlations between the generation volumes, installed capacities of different technologies, and fuel usage to explore the optimal power mix pathway. This study strengthens empirical analysis, considering the United Nations' Sustainable Development Goal 7 (SDG 7), which is to ensure access to affordable, reliable, and sustainable energy, planning various net-zero pathway scenarios, and outlining the development trends and limitations of different power generation technologies, with a special focus on renewable energy and CCS technology. Renewable energy is an important alternative power source for energy transition and low-carbon pathways, while CCS is a key technology for carbon reduction in current thermal power plants, providing a comprehensive and net-zero pathway-compliant power generation technology portfolio. Additionally, this study incorporates the levelized cost of electricity (LCOE) to cover all electricity generation costs, including traditional generation costs as well as additional carbon reduction and energy storage costs, to reflect the true cost of electricity generation (including environmental costs) as closely as possible. Based on these comprehensive considerations, this study plans an optimal power generation technology portfolio that fully considers cost, risk, and sustainability factors under the premise of meeting Taiwan's 2050 net-zero emission goals, providing a reference for the government to plan our country's medium- and long-term (2030, 2050) energy transition policy planning. In the development towards net-zero emissions, with the rapid advancement of hydrogen and CCS technologies, renewable energy, hydrogen energy, and thermal power plants with CCS technology will be key technologies for Taiwan's net-zero electricity transition.

This paper is structured into five sections: Section 1 outlines the background and objectives of the study. Section 2 introduces a theoretical model for the power mix. Section 3 describes the methods of empirical analysis. Section 4 contains the results and subsequent analysis. Finally, Section 5 provides a conclusion and offers recommendations.

2. Sustainable Power Model

Taiwan's power system is a single electricity system, operated by the Taiwan Power Company, comprising domestic power plants, which include those utilizing fossil fuels, nuclear energy, and renewable sources. Initially, this article determines the representative power costs of these power plants. Subsequently, Wang, Lee, Hong, and Cheng [6] develop a cost-effective sustainable power model, integrating the MPT with optimal control theory and taking into account the sustainability criteria of the power system. Building upon the insights derived from this sustainable power model, this study delves into the interconnections among electricity generation, fuel usage, and installed capacity, thereby laying the groundwork for further empirical analysis.

2.1. Model of Power Supply Costs

For the purpose of simplifying model calculations, this study assumes that the power system is composed of two representative power plants, which can be any type of power generation technology. The expected average power cost in the tth stage is as shown in Equation (1), with related parameters detailed as shown in Equations (2) and (3):

$$E(AC_t) = \sum_{i=0}^{2} s_{it}[TC_{it}/Q_{it}(K_{it}, F_{it})] \tag{1}$$

$$TC_i = P_{Ii}I_i + P_{Fi}F_i + \overline{O}_i + \overline{\varphi}_i Q_i + \overline{R}_i Q_i + P_{Ai}A_i + P_{ei}E_i \tag{2}$$

$$E_i = e_i F_i - A_i \tag{3}$$

where AC_t is the average power generation cost of the representative power plant during the tth stage, which is obtained by dividing the total power generation cost (TC_{it}) by the total power generation quantity (Q_{it}), a quasi-concave function of device capacity (K_{it}) and fuel (F_{it}), and s_{it} is the power generation ratio of representative power plants during the tth stage.

In addition to considering the traditional power generation cost (construction cost ($P_{Ii}I_i$), fuel cost ($P_{Fi}F_i$), and operation and maintenance cost ($\overline{O}_i$), all of which are assumed to be fixed values), the cost ($\overline{\varphi}_i$) for responding to changes in renewable energy (such as setting up energy storage facilities) is also strengthened. Furthermore, the waste cost of the power plant can be comprehensively considered ($\overline{R_t}$). In addition, costs associated with carbon reduction technology (A_t) and carbon emissions (E_t) may be considered in response to climate carbon reduction, where e_{0i} is the fuel emission factor of the ith power generation technology.

2.2. Sustainable Power Model

This study employs the results of the sustainable power model developed by Wang, Lee, Hong, and Cheng [6]. To quantify the mix in power supply and to delve further into the relationship between power generation, fuel usage, and installed capacity, a Cobb–Douglas function with constant returns to scale (CRTS) is assumed for the power generation function, as depicted in Equation (4).

$$Q_{it} = \overline{\omega}_i K_{it}^{\alpha} F_{it}^{1-\alpha} \tag{4}$$

where α is a fixed parameter, and $0 \le \alpha \le 1$ $\overline{\omega}_i$ denotes the capacity factor of the i^{th} type of power generation technology.

Equation (5) can be obtained by substituting and transforming the variable; refer to Wang, Lee, Hong and Cheng [6] for a detailed explanation.

$$Q_i = \overline{\omega}_i(\frac{1-\alpha}{\alpha})^{1-\alpha}[\frac{P_{Ii}(\delta_i - r)}{P_{Fi} + P_{Ai}e_{0i}}]^{1-\alpha} K_i \tag{5}$$

To ensure that the renewable energy is not affected by fuel, α is set to 1, simplifying Equations (5) and (6)

$$Q_{it} = \overline{\omega}_i K_{it} \tag{6}$$

On the other hand, considering that the thermal power plant is affected by fuel, the hypothesis is simplified, $\alpha = 0.5$ is used, simplifying Equations (5)–(7). Taking into account the operational practices of power plants, the result of Equation (8) below shall be <1 in unit time.

$$Q_{it} = \overline{\omega}_i[\frac{P_{Ii}(\delta_i - r)}{P_{Fi} + P_{Ai}e_{0i}}]^{0.5} K_{it} \tag{7}$$

$$\overline{\omega}_i[\frac{P_{Ii}(\delta_i - r)}{P_{Fi} + P_{Ai}e_{0i}}]^{0.5} < 1 \tag{8}$$

3. Empirical Analysis of Power Plant Cost Minimization

Drawing insights from the research findings of Awerbuch and Yang [8], an empirical analysis was performed for the levelized cost of electricity (LCOE) by evaluating future technologies and development constraints for each power plant.

This study establishes carbon reduction goals as primary constraints while recognizing electrification as a major trend towards achieving net-zero emissions by 2050. The inevitable growth in electricity demand driven by the development of residential, industrial, and information and communication systems is also considered. Various pathway scenarios are explored by adopting different reduction pathways (NDC and Reduction Ambition) and electricity demand growth scenarios (medium growth, low growth, zero growth) as depicted in Table 1. In each scenario analysis, a comprehensive evaluation of existing viable power generation technologies (including coal, oil, gas, nuclear, and renewable sources like solar and wind) and their associated carbon reduction technologies (such as CCS) is conducted. Additionally, the study considers the technological research and commercialization progress of prospective emerging technologies like hydrogen and ocean energy.

Table 1. Scenario settings for Taiwan's net-zero carbon emission pathway by 2050.

Scenario	Electricity Demand Growth	Reduction Pathway	Power Technologies and Decarbonization Technologies
Medium Growth	Medium Growth	NDC [1]	• Renewable (solar PV, offshore wind, and others)
	Medium Growth	Reduction Ambition [2]	
Low Growth	Low Growth	NDC	• LNG with/without CCS
	Low Growth	Reduction Ambition	• Coal with CCS (sub scenario)
Zero Growth	Zero Growth	NDC	
	Zero Growth	Reduction Ambition	• Hydrogen

Source: this research. Note: [1] NDC Pathway: As announced by Taiwan in December 2022, the target is to reduce emissions by 24 ± 1% from 2005 levels by 2030 to 2005, and actively moving towards net-zero emissions by 2050. [2] Reduction Ambition Pathway: Based on IEA recommendations, the target is to reduce carbon emissions by 40% from 2005 levels by 2030, and achieve net-zero emissions by 2050.

To further plan for a sustainable power generation mix to achieve net-zero emissions by 2050, this study employs the commercial mathematical optimization software LINGO (The LINGO software is developed by LINDO Systems Inc., located in Chicago, IL, USA. The trial version can be downloaded from https://www.lindo.com/index.php/ls-downloads/try-lingo, accessed on 20 January 2024). Under the constraints of the levelized cost of electricity (LCOE) for power plants, targeted secure power generation, carbon emissions from the power system, and new renewable energy installations, a linear programming phased solution approach is adopted to minimize the cost of the power system. The detailed solution process is illustrated in Figure 1. It is noteworthy that the LINGO software package has been extensively applied across various domains including supply chain management, water resource planning, and grid planning, as seen in the works of Sitek and Wikarek [26]; Sabale and Jose [27]; Su et al. [28]; and Vaezihir et al. [29]; among others.

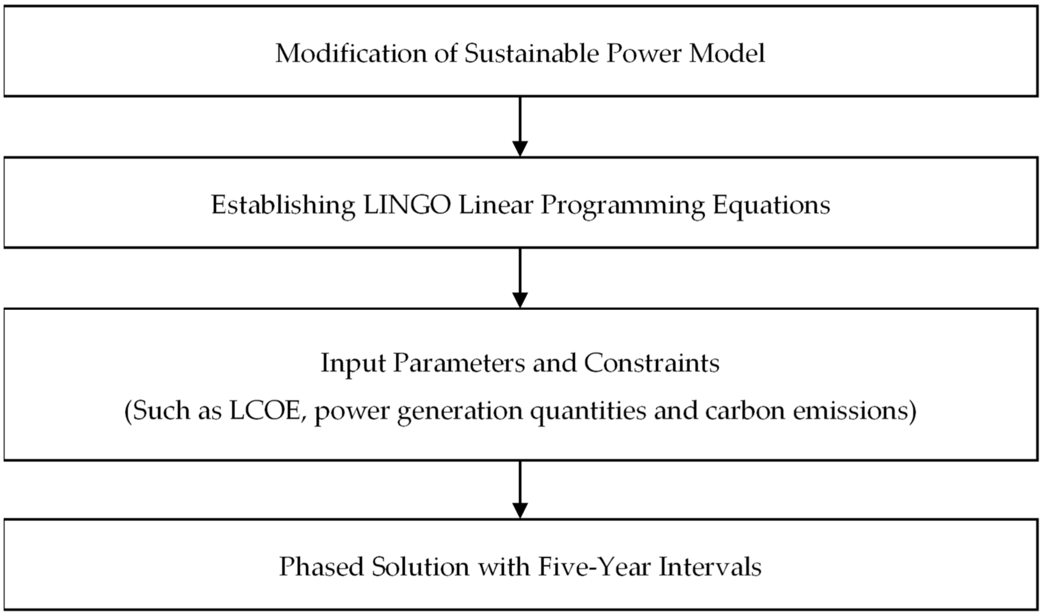


Figure 1. The framework of LINGO Model.

3.1. Scenario Setting for Net-Zero Carbon Pathway by 2050

This research takes into account the criteria of SDG7 (ensuring access to affordable, reliable, sustainable, and modern energy for all) in its empirical analysis. Specifically, "affordable" is the criterion used to evaluate the minimization of power plant costs. "Modern energy" is realized through advancements in power generation technology, "reliable" is centered on ensuring a stable power generation, and "sustainable" is defined as achieving carbon reduction to attain net-zero emissions.

3.1.1. Sustainable: Carbon Reduction to Attain Net-Zero Emissions

The aim of this study is to explore the impact of two different reduction pathways towards achieving the net-zero emission goal by 2050 on the structure of Taiwan's power sector.

I. NDC Pathway: As announced by Taiwan announced in December 2022, the target is to reduce emissions by 24 $\pm$ 1% from 2005 levels by 2030, and actively moving towards net-zero emissions by 2050.

II. Reduction Ambition Pathway: Based on IEA recommendations, the target is to reduce carbon emissions by 40% from 2005 levels by 2030, and achieve net-zero emissions by 2050.

Then, the carbon dioxide emission target of the power system was set based on statistics relating to carbon dioxide emissions from fuel combustion in Taiwan (BOE, 2021); the power system accounts for approximately 55% of the total national emissions. It is assumed herein that 10% of overseas carbon emission rights represent the upper limit for discussing the emissions of the power sector. (See Table 2 for details)

Table 2. Reduction pathways for Taiwan's net-zero goal by 2050.

Year	NDC Scenario				Reduction Ambition Scenario			
	Target (%)	Overseas Carbon Credits (%)	Total Emissions ($MtCO_2e$)	Power Sector ($MtCO_2e$)	Target (%)	Overseas Carbon Credits (%)	Total Emissions ($MtCO_2e$)	Power Sector ($MtCO_2e$)
2025	−10%		241	132.6	−10%		241	132.6
2030	−24%		203.5	111.9	−40%		160.7	88.4
2035	−39%		163.4	89.8	−60%		107.1	58.9
2040	−55%	10%	147.3	81	−80%	10%	80.3	44.2
2045	−77%	10%	88.4	48.6	−90%	10%	53.6	29.5
2050	−100%	10%	26.8	14.7	−100%	10%	26.8	14.7

Source: this research.

3.1.2. Reliable: Stable Power Generation

The safe power generation target refers to the power generation quantity required to meet the power demand. In March 2022, the National Development Council of Taiwan announced that the long-term power demand of Taiwan in 2050 is expected to grow by $2 \pm 0.5\%$. In this paper, medium and low growth toward the expected 2050 power demand were set at 2.0% and 1.5% annually, respectively. Furthermore, considering the IEA prioritizes saving power as the primary net-zero strategy for emissions reduction [2], the European Union also regards energy efficiency (EE) as a key driver for decarbonization [4]. To assess the impact of energy saving on achieving emission reduction targets and influencing the power structure, a zero-growth scenario (0% growth after 2030) was implemented for analysis. Power generation was estimated based on an average line loss rate of 4% (Table 3).

Table 3. Long-term electricity demand scenarios.

Year	Medium Growth		Low Growth		Zero Growth	
	Average Annual Growth (%)	Electricity Demand (GWh)	Average Annual Growth (%)	Electricity Demand (GWh)	Average Annual Growth (%)	Electricity Demand (GWh)
2020	-	271,200	-	271,200	-	271,200
2030	2.5%	347,000	2.5%	347,000	1.0%	300,000
2040	1.9%	417,000	1.1%	386,000	0%	300,000
2050	1.8%	500,000	1.0%	427,500	0%	300,000

Source: this research.

3.2. Assumptions and Limitations on Power Generation Technology Design

This study takes into account the trends in traditional fossil fuel power generation technologies, nuclear power, and renewable energy development, while also considering the application of future technologies, including the development and commercialization of CCS technology, energy storage technology, and hydrogen energy technology. Additionally, the study acknowledges the significant impact of retrofitting coal-fired power plants with CCS technology on costs, carbon emissions, and public acceptance. Therefore, we have designed sub-scenarios to more comprehensively assess the impact of adding CCS technology to coal-fired power plants on carbon emissions and the energy structure. This report details the design conditions and limiting assumptions of each scenario's power generation technology, as outlined in Table 4. Through these assumptions, a comprehensive and current politically and environmentally trend-compliant energy development pathway is provided.

Table 4. Scenario of power generation technology.

<table>
<tr><th>Energy Type</th><th>NDC Scenario</th><th>Ambitious Reduction Scenario</th></tr>
<tr><td>Renewable Energy</td><td colspan="2">The development of renewable energy is constrained by natural conditions, with an expected limitation on the annual installation volume.
The annual increase in solar PV is 3 GW by 2050, with an upper limit of 95 GW by 2050.
The annual increase in wind power is 2 GW by 2035 and 3 GW by 2050, with an upper limit of 70 GW by 2050.</td></tr>
<tr><td>Natural Gas</td><td colspan="2">Natural gas as a bridge energy source, with the addition of new gas-fired power generation to fill the power gap.
All gas-fired power generation will either transition to using CCS technology or be decommissioned early.</td></tr>
<tr><td>Oil</td><td colspan="2">All large oil-fired units retired by 2024.</td></tr>
<tr><td>Nuclear</td><td colspan="2">Following Taiwan’s “Nuclear-Free Homeland” policy since 2016 and the 2021 referendum confirming the non-restart of the Fourth Nuclear Power Plant, nuclear capacity will be zero by 2026.
The study does not consider nuclear energy options, including new technologies like Small Modular Reactors (SMR) or nuclear fusion.</td></tr>
<tr><td>Pumped Hydro Storage</td><td colspan="2">Pumped hydro storage capacity and generation will remain at current levels.</td></tr>
<tr><td>Energy Storage</td><td colspan="2">A certain proportion of future solar photovoltaic and wind power generation will be equipped with energy storage systems to enhance the stability and reliability of renewable energy, and to provide a buffering mechanism for the fluctuations in power supply from renewable sources.</td></tr>
<tr><td>Hydrogen Energy</td><td colspan="2">Large-scale production of green hydrogen requires a significant amount of renewable energy, exceeding current plans for renewable energy, and hence, domestic hydrogen energy has not been estimated.
The proportion of power generation from imported hydrogen energy should not exceed 15%, to ensure the feasibility of hydrogen imports and to avoid over-reliance on them.</td></tr>
<tr><td>Coal</td><td>No new coal-fired plants and existing coal-fired plants reduce load or decommission early.</td><td>No new coal-fired plants and all existing coal-fired plants decommissioned before 2035.</td></tr>
<tr><td>CCS Technology</td><td>Complete trials by 2030, with a sequestration capacity reaching 1 million tons.
Rapid commercialization, achieving a sequestration capacity of 40 million tons by 2040.</td><td>Complete trials by 2030, with a sequestration capacity reaching 1 million tons.
Rapid commercialization, achieving a sequestration capacity of 40 million tons by 2040.</td></tr>
<tr><td>Coal with CCS (Sub-Scenario)</td><td>Allowance for new coal-fired units with CCS.</td><td>• All coal-fired power plants must be equipped with CCS technology before 2035 to continue operation.
• Allowance for new coal-fired units with CCS.</td></tr>
</table>

Source: this research.

3.3. Cost of Representative Power Plants

This research performs an empirical evaluation of cost variations in representative power plants until the 2050s. For new power plants, the levelized cost of energy (LCOE) is employed to assess the various costs, and the effects of plants decommissioned early are examined. In the case of existing power plants, to simplify the calculations, this research assumes that the costs of existing plants remain at their 2020 levels. However, adjustments are made in the cost analysis to account for long-term fluctuations in fuel prices and additional costs resulting from carbon emission constraints. These adjustments provide a foundation for further empirical analysis.

3.3.1. Levelized Cost of Energy (LCOE) of New Power Plants

The values of relevant parameters were collected, and the LCOE of representative power plants was estimated. The calculation formula is as follows:

$$\boldsymbol{LCOE} = \frac{\sum \boldsymbol{TC_t}(\mathbf{1}+\boldsymbol{r})^{-t}}{\sum \boldsymbol{Q_t}(\mathbf{1}+\boldsymbol{r})^{-t}} \tag{9}$$

The total cost $\boldsymbol{TC}$ is shown in Equation (9), and the relevant parameters are described as follows (Table 5).

Table 5. Cost parameters of LCOE for new representative power plants.

Items	2025	2030	2035	2040	2045	2050
Construction costs ($P_{Ii}I_i$)						
LNG (NTD/Kw)	26,200	26,200	26,200	26,200	26,200	26,200
Solar PV (NTD/Kw)	37,738	33,766	30,211	27,031	24,186	21,640
Wind (NTD/Kw)	126,931	104,409	85,882	70,644	58,109	47,798
Fuel costs ($P_{Fi}F_i$)						
Coal (NTD/Kwh)	1.30	1.30	1.31	1.31	1.31	1.32
LNG (NTD/Kwh)	1.92	2.00	2.08	2.16	2.24	2.33
Flexible cost ($\overline{\varphi}_i$)						
Energy storage costs (NTD/Kwh)	7.0	6.0	5.0	4.0	3.5	3.0
Proportion of new renewable energy storage (%)	2.0	5.0	10.0	20.0	30.0	40.0
Carbon emission costs (E_t)						
NDC Scenario (NTD/tCO_2)	300	1200	2250	3300	4650	6000
Reduction Ambition Scenario (NTD/tCO_2)	1500	2700	3750	4800	5400	6000
Carbon reduction technology costs (A_t) (NTD/tCO_2)		3000	2640	2250	1890	1500
Discount rate (r) (%)	3.0	3.0	3.0	3.0	3.0	3.0

Source: this research.

The cost parameters are defined as follows:

I. Construction cost ($P_{Ii}I_i$): assuming fixed thermal power generation (using construction costs in 2020), renewable energy has a rapid reduction trend because it is necessary to consider the learning effect; the reduction rate is estimated based on wholesale purchase rates provided by the Energy Bureau of the Ministry of Economic Affairs.

1. Fuel cost ($P_{Fi}F_i$): future fuel prices are estimated on the basis of fuel costs in 2020 and by using the binomial stochastic process conforming to the geometric Brownian motion. More detailed parameters and the calculation process are described in the Appendix A.

II. Considering that Taiwan's future hydrogen energy will mainly be imported from abroad and that the import price includes transportation and liquefaction costs, it is difficult to directly estimate these costs. Due to the active promotion of long-term hydrogen strategies by the United States, the European Union, Australia, and Japan, it is assumed that the production and transportation technologies related to green hydrogen will mature by 2040, making the cost of hydrogen fuel lower than that of LNG.

III. Operation and maintenance cost ($\overline{O}_i$): the annual cost is preset at 2–4% of the construction cost (depending on energy).

IV. Flexible cost ($\overline{\varphi}_i$): only the cost of the power plant (adding energy storage facilities for renewable energy) is considered; the proportion of new renewable energy units used with energy storage units is considered to gradually increase, and the energy storage cost decreases with the maturation of technology.

V. Waste cost ($\overline{R_t}$): the decommissioning cost is preset at 5% of the construction cost.

VI. Carbon emission costs (E_t): these are set in reference to the carbon price settings from the IEA World Energy Outlook 2022. Under the "NDC Scenario", this study assumes the introduction of a lower carbon price in 2025, which will gradually increase to stimulate carbon reduction behaviors. Under the " Reduction Ambition Scenario", this study assumes the immediate implementation of a higher carbon price in 2025 to more effectively drive carbon reduction effects.

VII. Carbon reduction technology cost (A_t): with the advancement of technology and the expansion of economic scale, the cost of carbon reduction technology will gradually decrease. This study assumes that the cost of carbon reduction technology must be lower than the carbon price to ensure its practical feasibility in reducing carbon emissions.

IX. Discount rate(r): 3%.

X. Power generation quantity(Q_t): as shown in Equation (7).

XI. Capacity factor ($\overline{\omega}_i$): the capacity factor range (15–85%) of the thermal power unit is set according to a full load and a minimum load; renewable energy cannot be regulated with weather changes but is instead defined according to the actual value.

XII. Adjustment factor: thermal power is adjusted according to Equation (8), and renewable energy is not adjusted.

The LCOE of new power plants is calculated according to the above parameters (Table 6). With increasing energy and carbon prices, the LCOE of fuel gas also increases, whereas the LCOE of solar PV and wind power decreases with technological progress, eventually becoming lower than that of fuel gas. Units with LCOE change during the operation of gas-fired power plants are further inspected. At the end of operations, the levelized cost of 25 is gradually increasing, becoming close to the LCOE of the combination of fuel with CCS after 2040, indicating that it has become an acceptable option for planning the combination of fuel gas with CCS technology instead of the early decommissioning of gas-fired power plants, as shown in Table 7.

Table 6. LCOE of new representative power plants.

Year	Coal + CCS		Gas		GAS + CCS		Solar PV	Wind Power	Hydrogen (Imported)
	NDC	Reduction Ambition	NDC	Reduction Ambition	NDC	Reduction Ambition			
2025			5.78	6.23			3.29	3.49	-
2030	5.14	5.51	6.47	6.84	6.58	6.62	3.24	2.93	7.29
2035	4.67	4.81	6.89	7.15	8.11	8.37	3.37	2.49	6.46
2040	4.64	4.65	7.31	7.46	6.55	6.56	3.75	2.17	5.64
2045	4.50	4.50	7.72	7.76	6.55	6.55	4.08	1.90	4.92
2050	4.32	4.32	8.03	8.03	6.52	6.52	4.23	1.67	4.22

Source: this research.

Table 7. LCOE changes during the operation of a new gas-fired power plant.

Year	2025 Build	2030 Build	2035 Build	2040 Build	2045 Build	2050 Build
2025	5.78	-	-	-	-	-
2030	6.13	6.47	-	-	-	-
2035	6.29	6.60	6.89	-	-	-
2040	6.50	6.79	7.03	7.31	-	-
2045	6.87	7.01	7.19	7.44	7.72	-
2050		7.35	7.33	7.54	7.79	8.03

Source: this research.

3.3.2. Cost of Existing Power Plants (Adjusted by Fuel Price and Carbon Cost)

This study takes into account the operational costs of existing thermal power units, among which fuel costs constitute a major portion. To more accurately estimate the future operational costs of existing thermal units, we employ long-term stochastic fuel cost adjustments (detailed in the Appendix A). Moreover, in light of the more stringent carbon emission restrictions in the future, we have also included carbon emission costs in the future operational costs. For the remaining cost items, this study assumes the data from

2020 will be maintained. In summary, the adjusted operational costs for existing power plants are detailed in Table 8.

Table 8. Changing costs of existing power plants (adjusted by fuel price and carbon cost).

Year	Coal		Gas		Renewable Energy		
	NDC	Reduction Ambition	NDC	Reduction Ambition	Solar PV	Wind Power	Other
2025	1.84	2.84	2.26	2.78	4.45	3.77	3.88
2030	2.55	3.75	2.68	3.27	4.45	3.77	3.88
2035	3.40	4.59	3.17	3.77	4.45	3.77	3.88
2040	4.11	5.26	3.53	4.06	4.45	3.77	3.88
2045	5.15	5.72	4.10	4.36	4.45	3.77	3.88
2050	6.18	6.18	4.66	4.66	4.45	3.77	3.88

Source: this research.

4. Empirical Analysis Results and Discussion

This study analyzes based on the aforementioned empirical analysis results and discusses the prioritization of net-zero technologies, the social acceptance of coal-fired power plants with CCS, the impact of zero growth in electricity demand, and the limitations of the research.

4.1. Empirical Analysis Results

This study compiles the planning outcomes for various scenarios in 2030 and 2050 as depicted in Figure 2. The analysis reveals that achieving the 2030 emission reduction targets necessitates a substantial increase in the use of renewable energy. The share of renewable energy is expected to increase from 5.5% in 2020 to 2030, while the share of coal-fired power generation will drastically decrease from 44.9% to 10.4%. The remaining gap in power generation will be bridged by natural gas power, with the expected carbon emission factor of electricity reducing to 0.284 kg CO_2e/kWh by 2030, already below the emission intensity of gas combined cycle units. Consequently, the average cost of the power system is anticipated to rise to 4.67 NTD/kWh by 2030. Under the zero-electricity-growth scenario, the total power generation by 2030 is likely to be less, leading to a reduction in thermal power generation. The overall carbon emission factor for electricity is expected to reduce to 0.319 kg CO_2e/kWh.

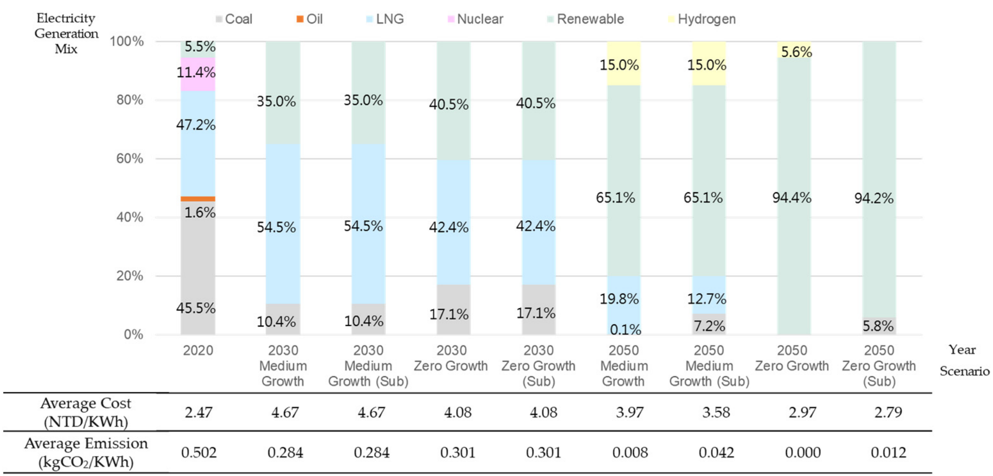


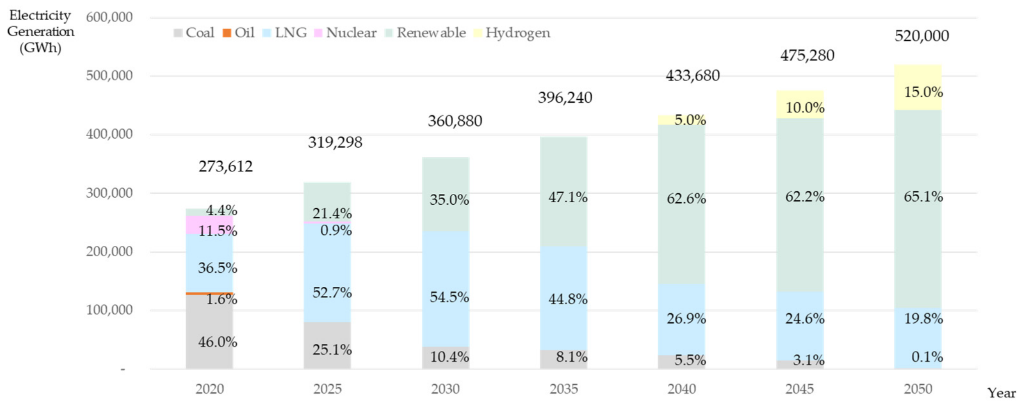
Figure 2. Power structure, cost, and carbon emission coefficient of each net-zero carbon emission pathway scenario.

Furthermore, to achieve the net-zero targets by 2050 under the medium-growth scenario, the priority is on maximizing the use of renewable energy in technology selection.

Renewable energy's share of power generation is expected to reach up to 65.1% and the promotion of carbon-neutral hydrogen energy is expected to reach a planned generation share of up to 15%. The remaining 19.8% gap in power generation will be addressed by natural gas combined with CCS technology as a crucial option for the transition. Under the pressure of carbon emissions and high carbon prices, the operation of remaining coal-fired units at reduced loads to maintain the stability of the power supply system is considered more beneficial than their generation efficiency, with the overall power carbon emission factor being 0.008 kg CO_2e/kWh. If the barriers to public acceptance can be overcome, then constructing new coal-fired power plants combined with CCS technology would be a more favorable technological option, with an expected coal power generation share of 7.2% and an increase in the power carbon emission factor to 0.042 kg CO2e/kWh. In a scenario of zero growth, significantly reducing electricity consumption may prioritize the reduction in thermal power generation, thereby achieving a 100% net-zero electricity system goal in conjunction with hydrogen energy.

4.1.1. Medium-Growth Scenario Results

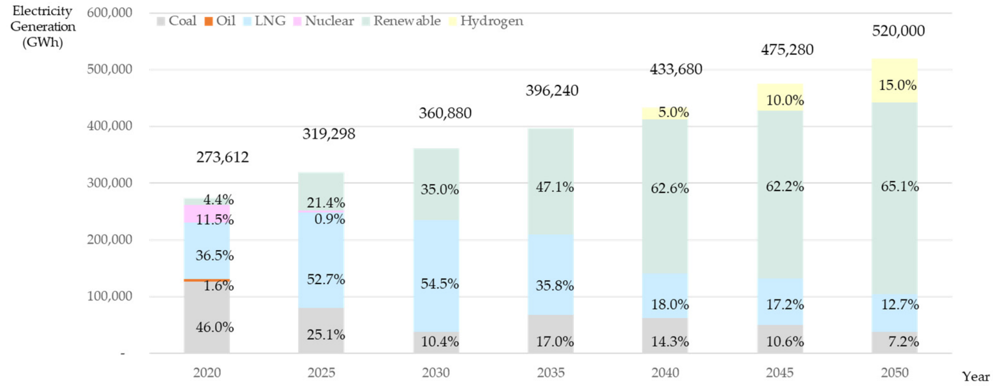
This study presents the results of the medium-growth scenario as shown in Figure 3. In terms of electricity generation technology choices, renewable energy is key to achieving national low-carbon goals. However, limited by actual installation capacity, the share of power generation from renewable sources is expected to reach 35.0% by 2030 and 65.1% by 2050 as the upper limit. Facing the pressure of carbon reduction and rapidly increasing carbon prices, some existing coal-fired units will be downgraded or decommissioned early, with the share of coal-fired power generation decreasing to 10.4% by 2030 and nearly completely phased out by 2050. Additionally, considering the large-scale construction of gas units between 2025 and 2030 to replace coal-fired units, the share of gas-fired power generation will increase to 54.4% by 2030. As carbon emission restrictions become increasingly stringent, gas-fired units will need to transition to CCS plants or hydrogen power units, with the share of gas-fired power generation decreasing to 19.8% by 2050, while the share of hydrogen power generation increases to 15%.



	2020	2025	2030	2035	2040	2045	2050
Average Cost (NTD/KWh)	1.98	3.73	4.67	4.75	3.96	3.70	3.97
Average Emission (kgCO_2/KWh)	0.544	0.415	0.284	0.188	0.117	0.037	0.008

Figure 3. Planning results of medium-growth scenario.

This study assesses the impact of introducing coal-fired power generation with CCS technology in sub scenarios, as shown in Figure 4. Considering the commercialization process of CCS, CCS is not yet commercialized by 2030, which does not affect the choice of coal-fired units. Therefore, if CCS can be successfully commercialized by 2035, coal combined with CCS is expected to replace gas with CCS applications. According to model predictions, newly established or retrofitted coal units (with CCS) will account for 22.1% of the total power generation after 2035. Yet, by 2050, coal-fired power combined with CCS will directly compete with renewable energy and hydrogen power, leading to a decrease in its share of power generation to 7.2%.

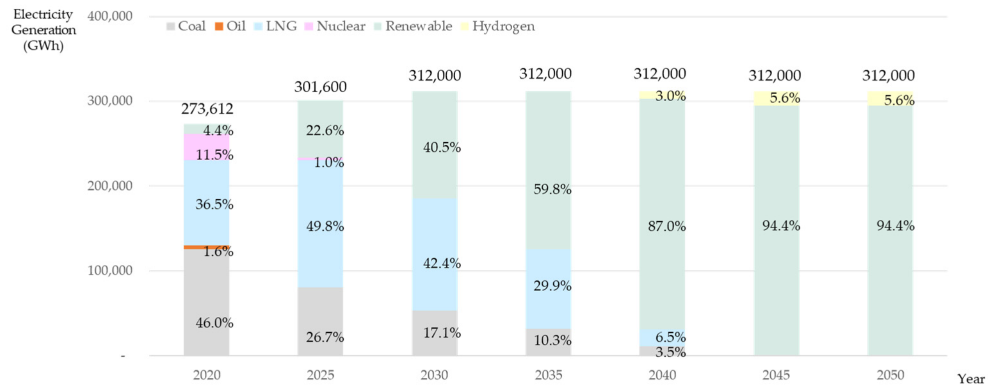


Average Cost (NTD/KWh)	1.98	3.73	4.67	4.22	3.77	3.99	3.58
Average Emission ($kgCO_2$/KWh)	0.544	0.415	0.284	0.203	0.124	0.089	0.042

Figure 4. Impact of coal-fired plant + CCS technology in medium-growth scenario.

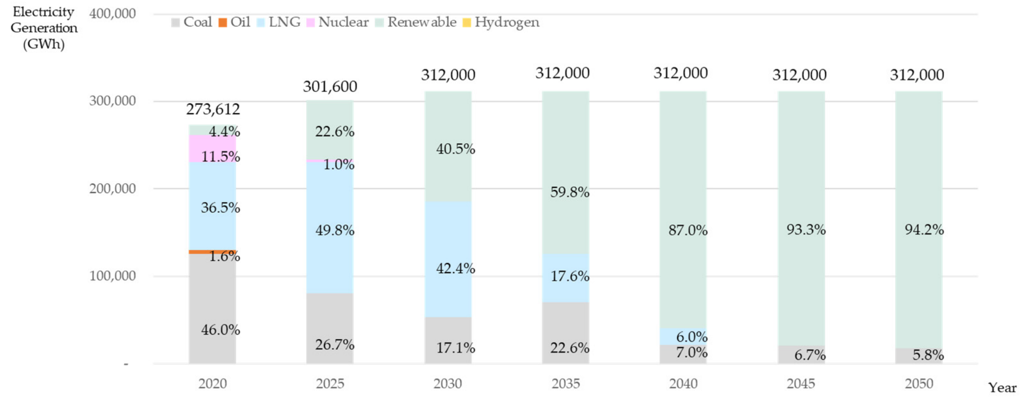
4.1.2. Zero-Growth Scenario Results

The results of the zero-growth planning assessment are presented in Figures 5 and 6. The evaluation indicates that if electricity demand achieves zero growth, the reduction in electricity demand will have a significant carbon emission reduction effect. Assuming unchanged generation technologies and constraints, there will be a priority to reduce thermal power generation, leading to the early decommissioning of existing coal-fired and newly added gas-fired units before 2050. The proportion of renewable energy generation will gradually increase, expected to reach 40.5% by 2030 and approach 100% by 2050, with the integration of hydrogen energy by 2050, accomplishing a completely net-zero emission target for the power system. The assessment also points out that a significant reduction in electricity demand is equivalent to more carbon emission space. Therefore, the main competitors of coal with CCS have shifted from gas with CCS to renewable energy, making coal with CCS lose its cost competitiveness and rendering it no longer a viable option in the energy transition process.



Average Cost (NTD/KWh)	1.98	3.59	4.08	3.98	3.09	3.05	2.97
Average Emission ($kgCO_2$/KWh)	0.544	0.419	0.301	0.196	0.056	0.000	0.000

Figure 5. Planning results of zero-growth scenario.



	2020	2025	2030	2035	2040	2045	2050
Average Cost (NTD/KWh)	1.98	3.59	3.41	3.49	2.92	2.88	2.79
Average Emission (kgCO_2/KWh)	0.544	0.419	0.301	0.169	0.042	0.014	0.012

Figure 6. Impact of coal-fired plant + CCS technology in zero-growth scenario.

4.2. Discussion

This study aims to further explore several key areas, including evaluating the impact of prioritizing different technologies on the power system and its costs, investigating the social acceptance of coal-fired power plants equipped with CCS, assessing the implications of achieving zero growth in electricity demand, and identifying the limitations of the current model to propose future research directions that address these gaps and enhance the findings.

4.2.1. The Impact of Technological Selection Priority on the Power System and Costs

Based on the evaluation results of this study, the priority ranking for long-term net-zero power generation technology choices by 2050 is as follows: renewable energy (wind, solar PV), coal with CCS, hydrogen energy, gas with CCS, and gas. Under the pressure of carbon emissions and high carbon prices, coal-fired power generation is no longer a viable technology option. In a pathway aimed at an ambitious reduction, most existing coal-fired units will be decommissioned early, a result that aligns with the European Union's key decarbonization drivers and the conclusions of the COP28 global stocktake. Further considering technological advancements, with CCS not yet commercialized, a significant number of gas-fired units will be built between 2025 and 2030 to replace coal-fired units. These will operate until before 2050, when newly built gas units will reach the end of their operational life. At that time, gas units will be decommissioned or decommissioned early to transition to CCS plants or hydrogen units. From the perspectives of cost and reduction effectiveness, both are viable strategy options, suitable as short-to-medium term bridging energy sources. Additionally, hydrogen is an important future energy source. However, considering the need for a balance between supply and demand in electricity, if surplus renewable energy is used for hydrogen production, it necessitates an expansion in renewable energy planning, which would exceed the limits for new renewable energy installations. Moreover, using renewable energy for hydrogen production and then generating electricity would have a similar effect as energy storage facilities. Therefore, this paper evaluates the use of imported hydrogen, taking into account the long-term cost reductions in hydrogen production in exporting countries (such as Australia) and the transport and distribution costs of long-distance maritime shipping, estimating costs to be close to LNG fuel prices, making it competitive relative to gas with CCS.

Based on prioritizing net-zero electricity technologies, the power mix in medium- and low-growth scenarios reveals that while the average cost of electricity might increase to above 4 NTD/kWh between 2030 and 2035, increasing the pressure on consumer electricity prices, the average cost of electricity will continue to decrease by 2050. Compared to maintaining the status quo with a power generation system heavily reliant on fossil fuels, this will significantly reduce carbon reduction expenditure. Therefore, this study recommends that the government should accelerate the deployment of net-zero electricity technologies.

4.2.2. Social Acceptance of Coal Power Coupled with CCS Technology

Coal-fired power plants are high-pollution, high-carbon emission facilities, which are generally opposed by the public for neighborhood installation. When coal units are equipped with CCS technology, their carbon emissions are only slightly higher than those of gas-fired power plants with CCS. However, due to the relatively lower fuel costs of coal, they have a cost-efficiency advantage. Nonetheless, the general public may find it difficult to understand the differences in carbon reduction technologies, necessitating societal communication and energy education to increase the social acceptance of coal-fired power plants. If coal-fired plants can overcome public acceptance barriers, then new coal-fired plants equipped with CCS technology could be a more favorable technology option than gas with CCS. However, considering the carbon storage cap of 40 million CO2 by 2050, it is only possible to replace a portion of gas-fired power plants with CCS. Additionally, under an ambitious reduction scenario, the decommissioning of existing coal units by 2030 and the need to consider the integration of new coal units with CCS technology by 2035 presents a challenge. At the same time, the increased gas units required to meet the 2030 electricity demand could lead to a significant reduction in generation, creating stranded asset risks for gas power plants. This, in turn, adds extra costs and resistance to promoting coal with CCS option.

4.2.3. Analysis of the Impact of Zero Growth in Electricity Demand

Given the expected improvements in living standards, the increase in electrical appliances, the demand for electricity by electric vehicles, and the electrification of industrial equipment, it is anticipated that Taiwan's electricity demand will continue to grow at an annual rate of $2 \pm 0.5\%$. Even with the implementation of aggressive energy-saving measures and the introduction of market-based tools such as white certificates, it is only possible to suppress electricity demand, not reduce it to zero or negative growth. Achieving such a reduction would require regulatory mandates or a very-high-intensity electricity pricing mechanism, which would also result in significant electricity costs for the public. Although achieving zero growth in electricity demand would have a clear effect on reducing carbon emissions from electricity use and could lower generation costs, considering the additional costs on the demand side and the burden on the public might alter the cost–benefit analysis. This remains an area for further research.

4.2.4. Model Limitations and Future Research Directions

The empirical analysis of this study faces significant limitations due to data availability constraints and the uncertainties associated with long-term forecasting. Moreover, this study was unable to assess carbon reduction costs in detail and could only make predictions based on future carbon fee prices referenced from the IEA. Market mechanisms, such as carbon trading markets that could lower mitigation costs, were not incorporated, representing a potential area for further enhancement in future research. Additionally, as this study focuses on long-term planning with electricity generation as the primary analysis target for stable supply, it inevitably overlooks the consideration of peak loads in short-to-medium-term power system planning. In particular, the intermittent generation characteristics of a large-scale integration of renewable energy and issues like the duck curve were not deeply explored. Although this study assumes some renewable energy sources are paired with energy storage facilities to improve power flexibility, subsequent research should continue to quantify and incorporate related costs of grid-side ancillary services and others to more comprehensively measure electricity costs.

5. Conclusions

Within the framework of sustainable development, this study optimizes the sustainable power system model originally proposed by Wang et al. [6]. Its goal is to plan a comprehensive pathway that integrates carbon emission reduction, ensures power supply security, and pursues optimal power generation costs toward achieving net-zero emissions by 2050. According to the model results, achieving net-zero emissions by 2050 is feasible in all scenarios, with renewable energy playing a pivotal role in this endeavor. By 2030, as the ambition for reduction targets increases, significant transformation costs and risks will be faced. However, such a pace will accelerate the decarbonization of the power system, further solidifying the achievement of the net-zero emissions goal by 2050.

In terms of energy technology choices, maximizing the transition to renewable energy holds immense potential. With adequate energy storage facilities, the power grid will gain high flexibility, allowing the proportion of renewable energy in the electricity mix to exceed 65%. Additionally, the pressure to reduce emissions by 2030 will compel coal-fired power plants to operate at reduced capacity and potentially be decommissioned early, making natural gas a viable transitional energy source to replace coal.

In the long term, under the pressure of rising carbon prices and carbon emission restrictions, if CCS technology can be fully commercialized by 2035, using CCS with natural gas or coal-fired power generation would be a more appropriate strategy. If public acceptance of coal-fired power plants can be increased, then coal with CCS would be a more cost-effective option. However, the integration of new power plants by 2035 and the stranded asset risk for gas units will be significant challenges.

Furthermore, the development of hydrogen energy technology makes it feasible to either retrofit natural gas infrastructure or construct hydrogen facilities. This is beneficial for reducing generation costs and achieving carbon emission reduction targets. The advancement of hydrogen technology could play a crucial role in the energy transition, especially in sectors where direct electrification is challenging.

Finally, in the zero-growth scenario, the significant reduction in electricity demand leads to substantial changes in the cost and carbon emission competitiveness of different energy options. There is even a possibility of achieving 100% net-zero electricity in combination with this scenario, which must be thoroughly considered in future policy formulation.

In summary, this study provides a wealth of suggestions on how to achieve the 2050 net-zero emission target amid multiple challenges and pressures. It offers significant reference value for Taiwan's net-zero emission policies. The study underscores the importance of a strategic and flexible approach in energy planning, recognizing the dynamic nature of technological advancements, market trends, and policy environments. Emphasizing the need for a balanced mix of renewable energy, transitional technologies like natural gas, and innovative solutions like CCS and hydrogen energy, the research provides a comprehensive framework for moving towards a sustainable and low-carbon future.

Based on these findings, the study also suggests that the government should expedite the deployment of renewable energy, especially in combination with energy storage technologies. It also calls for increased investment in the research and development of low-carbon technologies to promote the development and application of CCS and hydrogen energy. Moreover, raising public awareness and participation is crucial. Not only can it encourage more individuals and communities to engage in low-carbon living and sustainable development, but it can also increase public support for implementing coal power plants with CCS in the future.

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Appendix A. A Random Estimation of Long-term Fuel Price

In the present study, the standard Brownian motion or Wiener Process formula of the stochastic process is used to estimate the long-term stochastic price. Referring to the estimation method of Copeland and Antikarov [30], the growth rate and decrease rate formulas of power generation cost per unit of different fuels are obtained as follows:

$$u = e^{gt} \tag{A1}$$

$$d = 1/u \tag{A2}$$

$$x = \frac{\left(1 + r_f\right) - d}{u - d} \tag{A3}$$

where u is the increase rate of power generation cost per unit fuel; d is the decrease rate of power generation cost per unit fuel; g is the average annual growth rate of fuel cost; t is the time interval of each stage, and $t = 5$ is assumed in the present study. The u and d values of power generation technologies with different fuel types are summarized as shown in Table A1.

Table A1. Summary of relevant data of power generation technologies with different fuel types.

Parameter \ Technology	Fuel Coal	Fuel Gas
Average annual growth rate of power generation cost per unit of different fuels (g) (%)	−1.44	−5.95
Risk-free interest rate (r_f) (%)	1.60	1.60
Average growth rate of power generation cost per unit of different fuels (u) (%)	0.93	0.76
Average decrease rate of power generation cost per unit of different fuels (d) (%)	1.07	1.32
Increasing the path allocation ratio (x) (%)	40.68	54.12
Decreasing path allocation ratio $1 - x$ (%)	59.32	45.88

Source: this research.

In the present study, the long-term stochastic fuel costs of different power generation technologies can be estimated by using the data in Table 1. The stochastic fuel costs of future power generation technologies are divided into high, medium, and low scenarios for analysis, where the high scenario refers to the average cost of each year greater than or equal to the median value (including the median value), the medium scenario refers to the average cost of all stochastic costs, and the low scenario refers to the average cost of each year less than or equal to the medium value (including the medium value). The stochastic fuel costs of fuel coal and fuel gas in the high-, medium-, and low-cost scenarios in the future are summarized, as shown in Table A2.

Table A2. Estimation of stochastic fuel costs in high-, medium-, and low-cost scenarios in the future.

Year	Coal			LNG		
	Low	Middle	High	Low	Middle	High
2020	1.30	1.30	1.30	1.85	1.85	1.85
2025	1.21	1.30	1.39	1.40	1.92	2.45
2030	1.21	1.30	1.40	1.41	2.00	2.58
2035	1.17	1.31	1.45	1.25	2.08	2.90
2040	1.17	1.31	1.45	1.30	2.16	3.02
2045	1.14	1.31	1.49	1.15	2.24	3.33
2050	1.14	1.32	1.49	1.20	2.33	3.47
2055	1.11	1.32	1.53	1.08	2.42	3.77
2060	1.12	1.32	1.53	1.12	2.52	3.91
2065	1.09	1.33	1.56	1.02	2.62	4.21
2070	1.10	1.33	1.56	1.06	2.72	4.38
2075	1.08	1.34	1.61	0.98	3.02	5.07

Source: this research. Unit: NTD/kWh.

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