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A Decarbonization Roadmap for Taiwan and Its Energy Policy Implications

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Abstract: The objective of this paper is to propose a decarbonization roadmap for Taiwan to achieve net-zero emissions by 2050 by analyzing the status of fossil and non-fossil energies, screening applicable decarbonization technologies for their effectiveness, and then proposing an energy mix for the future. The novelty of this work lies in the screening process, which considers six, instead of one or two, categories: sustainability, security, affordability, reliability, technology readiness, and technology impact. Based on this screening, a decarbonization roadmap is proposed and compared with the announced net-zero emissions (NZE) plan. The proposed roadmap requires renewable electricity to grow at an average annual growth rate of 7% between now and 2050, instead of the 10.1% required by the NZE plan, which is more achievable based on issues identified with renewable energies during our screening exercise. The proposed roadmap improves on the NZE plan in the following aspects: (1) using clean coal technologies to decarbonize existing coal-fired power plants, (2) relying more on gas than wind and solar energies to replace coal and nuclear energy for power generation, (3) accelerating carbon capture and storage (CCS) implementation, (4) delaying the phaseout of nuclear energy until 2050, and (5) using blue instead of green hydrogen to decarbonize the transport and industry sectors. Implications of this roadmap for future research and development and energy policies are also discussed.

Keywords: Taiwan; decarbonization roadmap; energy transition; carbon capture and storage; renewable energies

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1. Introduction

With a population of 23 million and a GDP of 669 billion dollars in 2020, Taiwan is the sixth largest economy in Asia by GDP and 22nd in the world [1]. It has a growing electronics industry, which is ranked among the world's most advanced. In 2020, Taiwan's primary energy consumption (PEC) was 1338 TWh [2], and its total CO_2 emission was 273 Mtpa, making it the sixth largest CO_2 emitter in Asia [3].

1.1. Taiwan's Energy Quadrilemma

Taiwan needs to balance its requirement for energy security, sustainability, and affordability, commonly known as the energy trilemma [4]. It is vulnerable to energy insecurity, as it imported 98% of its total primary energy supply (TPES) in 2020 from overseas, mostly from Saudi Arabia (33%), Kuwait (20%), and the USA (20%) [5]. Taiwan's energy affordability is affected by volatility in oil and natural gas prices, such as the recent hike caused by the post-COVID-19 economic recovery and the Russia–Ukraine conflict. Taiwan's energy sustainability is tied to its CO_2 emission coming from the combustion of fossil fuels. In 2020, Taiwan's per capita CO_2 emission ranked 19th in the world at 11.78 tons/person [6].

In this study, we add to the energy trilemma the additional consideration of energy reliability, hence the energy quadrilemma. Energy reliability deals with energy availability as measured by its capacity factor. Our own calculations show that among renewable energies in Taiwan, solar photovoltaic and wind have the lowest capacity factors of 11% and 28%, respectively, due to their daily variability [7]. Therefore, for the same amount of electricity generation, more solar PV and wind capacity will be needed compared to other forms of energy. This is an important consideration, because the 2050 net-zero emissions (NZE) plan announced by Taiwan's authorities relies heavily on solar PV and wind [8].

1.2. Taiwan's Net-Zero Plan

Taiwan intends to achieve net-zero emissions by 2050 and has published a NZE plan, shown in Figure 1 [8]. In 2020, Taiwan's electricity generation comprised 82% fossil fuels, 11% nuclear, and 7% renewable energies. Taiwan has set an ambitious "20-30-50" goal to have 20% of electricity generated by renewables, 30% by coal, and 50% by gas in 2025. By 2050, 60–70% of electricity generation will come from renewables, with the balance coming from gas and hydrogen. The increase in renewable electricity will come mostly from solar PV and wind. Their combined installed capacity will grow from 6.7 GW in 2020 to 40 GW in 2030. Furthermore, 60% of car sales will be electric vehicles (EVs) by 2035 and 100% by 2040. The planned increase in renewable energies specified by this NZE plan has already created a booming renewable market in Taiwan. The authorities have announced they will spend nearly 30 billion USD by 2030 to implement the NZE plan [8,9]. Private sector investment will be even higher. It has been estimated that current unfinished wind and solar projects in Taiwan are worth approximately 83 billion dollars [10].

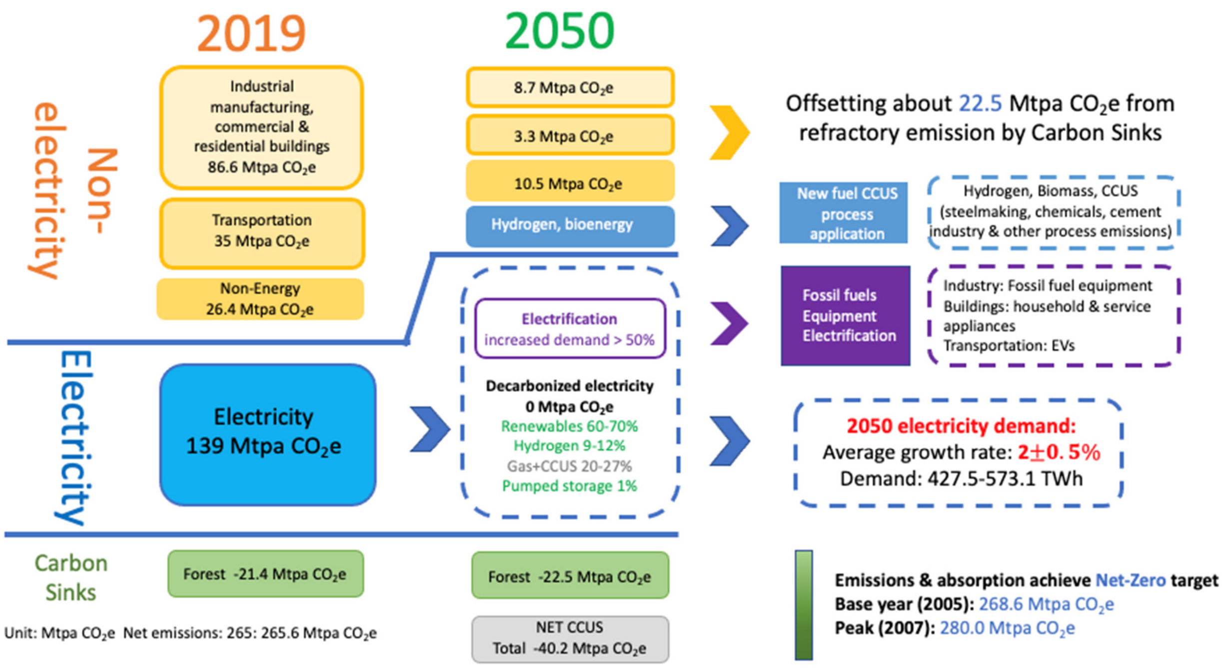

Figure 1. Taiwan's 2050 net-zero emissions plan [8].

1.3. Taiwan's Conundrum: Balancing Energy Consumption among Industries

One unique feature of Taiwan's energy landscape is the competition between the fast-growing electronics (semiconductor) industry and the conventional chemical industry for electricity. Figure 2a shows the history of Taiwan's electricity consumption by sector [5]. Among manufacturing industries, the electronics and chemicals industries are the first and second biggest consumers of electricity, with the former outstripping the latter in 2011. However, in 2016, the electronics industry contributed to 17% of Taiwan's GDP compared to 3.4% by the chemical industry, and it has been the growth engine of Taiwan in the last two decades (Figure 2b) [11]. However, continued growth of the electronics industry will depend on increasing and stable electricity supply. Therefore, if electricity supply is limited, e.g., due to premature phaseout of nuclear energy, Taiwan will face the unfortunate situation of rationing electricity between these industries.

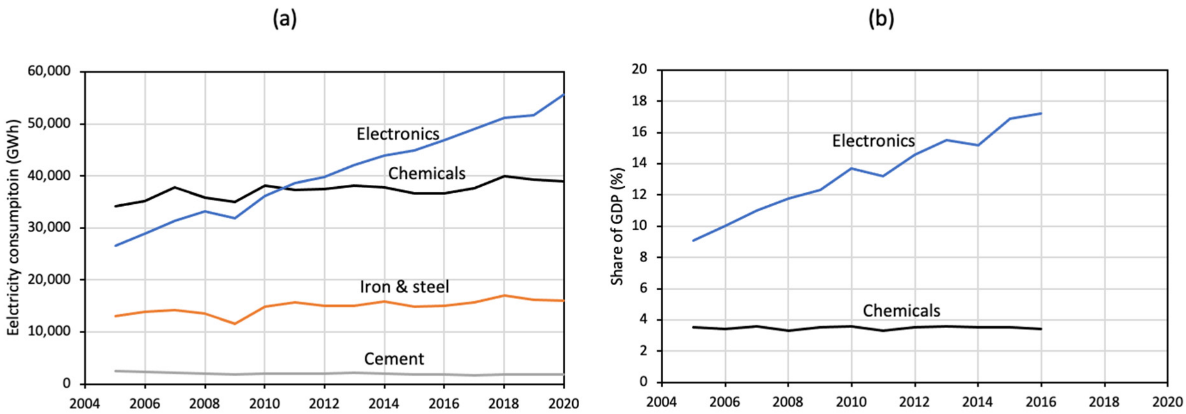

Figure 2. History of (**a**) electricity consumption and (**b**) share of GDP by industry in Taiwan [5,11].

1.4. Liberalization of Taiwan's Energy Market

Another feature of Taiwan's energy landscape is that its electricity and LNG markets are yet to be fully liberalized. Currently, Taiwan's electricity transmission and distribution networks are operated by state-owned Taipower. The Electricity Act (EA) of 2017 ended its monopoly on electricity supply, and it will be restructured into two companies to oversee electricity generation and distribution. EA will allow independent power producers (IPPs) to sell electricity directly to customers, either via their own distribution lines or through the existing grid owned by Taipower. Currently, Taiwan's household electricity price is the second lowest in the world, while its industrial electricity price is the seventh lowest globally due to public subsidy [12]. More liberalization of the electricity market will be needed to encourage private investment. In the natural gas market, state-owned CPC Taiwan and Taipower are the only importers of LNG, with the former owning two LNG import terminals, with a combined capacity of 18.8 Mtpa. Two more LNG terminals with combined capacity of 5.8 Mtpa are under construction by Taipower. Taipower aims to add 13.5 GW of gas-fired capacity by 2025 and a further 3.5 GW by 2028 [10].

To encourage usage of renewable energy, the NZE plan has established a target of 20 GW of solar PV by 2025. In addition, Taiwan has launched a Thousand Wind Turbines Project with a goal of achieving 5.5 GW of wind capacity by 2025 [13]. There is also a plan to achieve 10 GW of offshore wind capacity by 2035 [8]. However, realization of these ambitious goals is hampered by the lack of local expertise and legal protection for private investors, among others [12,14–16].

1.5. Research on Taiwan's Energy Transition Policy

There is a growing body of literature addressing policy aspects of Taiwan's energy transition [17–23]. A large part of Taiwan's energy transition has been based on increasing the share of renewable energies in power generation. Among renewable energies, the biggest recent additions in capacity have been in solar PV and wind energy. Analysis by Tan (2021) shows that between 2000–2010, there has been rapid growth of onshore wind capacity, due partially to favorable feed-in tariff. However, since then, growth has plateaued at around 800 MW due to restriction on available land [17]. On the other hand, offshore wind has grown from nothing in 2016 to 237 MW by 2021. Wang et al. (2021) applied the optimal control theory to study the optimal energy mix for power generation for Taiwan to balance the need for energy security and reduced CO_2 emission [18]. Based on simulation results using a computable general equilibrium model, Feng et al. (2022) point out that offshore wind energy alone would be insufficient for Taiwan's decarbonization. They advocate promulgation of a carbon tax of USD 50–100/t CO_2 to ensure a just energy transition [19]. Chen (2021) analyzes the emissions–energy–economy interaction using the Lotka–Volterra model [20]. Results show that Taiwan's energy transition cannot be accomplished by technological progress alone but will require institutional and human behavior changes. To minimize power blackout, Chen suggests retaining nuclear energy as part of the energy mix, improving energy efficiency, building a smart grid, and developing carbon capture and storage technologies [20]. Calculations by Kung and McCarl (2020) show that Taiwan's renewable sources can only replace 74% of nuclear electricity [21]. Furthermore, renewable resources such as biomass, municipal waste, and onshore wind are almost fully utilized, leaving solar PV the only renewable energy with significant growth potential [21]. Gao et al. (2021) note that Taiwan's research and development (R&D) is insufficient to support its ambitious goal to grow offshore wind energy [22]. Their work shows there is insufficient R&D justifying the high feed-in-tariff proposed for offshore wind. In addition, Taiwan's use of administrative rules instead of legislation to promote offshore wind could cause large investment uncertainty for offshore wind developers. Furthermore, Gao et al. (2018) argue that liberalization of the energy market can have negative effects on renewable energies, as customers may shun expensive renewable electricity in favor of cheaper fossil electricity [23].

The aforementioned studies show that choosing the right roadmap for the ongoing energy transition of Taiwan is a topic of keen interest for policy makers, investors, scientists, and engineers. However, there is no consensus on the right decarbonization roadmap. This study will contribute to the ongoing discussion on Taiwan's energy transition by proposing a decarbonization roadmap based on analysis of existing data.

2. Objective and Methodology

The objective of our study is to propose a decarbonization roadmap for the power, transport, and industry sectors of Taiwan to enable it to achieve net-zero CO_2 emissions by 2050. Our methodology, shown in Figure 3, has four steps. First, we review the status of fossil and non-fossil energies in Taiwan by analyzing the primary energy consumption (PEC), electricity generation, and sector-specific CO_2 emission. Second, we subject a set of 20 sector-specific decarbonization technologies (Table A1) to sustainability screening (Table 1), energy quadrilemma screening (Table 2), and technology mapping to choose those with the highest potential of being achieved. The criteria for these screening and mapping exercises are given in Tables A2–A6. Third, we propose the future energy mix to arrive at a decarbonization roadmap. Fourth, this roadmap is compared with the published NZE plan [8], the difference between them is discussed, and implications for energy policies are then drawn.

The novelty of this study lies in three areas. First, unlike other studies, we use a holistic approach to screen decarbonization technologies according to six categories: sustainability, security, affordability, reliability, technology readiness, and technology impact. This provides a more balanced view of a technology's potential. Second, we consider the unique energy landscape of Taiwan in conducting the technology screening, including availability of energy resources and carbon sinks, land and space limitations, and the current state of R&D. Third, the decarbonization roadmap proposed by this study, though drawing from the NZE plan, improves on it.

There are several limitations to this study. First, it only deals with the supply side of decarbonization. Therefore, demand-side approaches such as improving energy efficiency, use of less carbon-intensive materials, and adoption of a circular economy are outside the scope of this study. Second, some decarbonization technologies with low technology-readiness level, such as direct air capture and biofuels with CCS, are also not included in our study. Third, the technology mapping exercise is best done by a group of experts who have in-depth knowledge of the decarbonization technologies being screened.

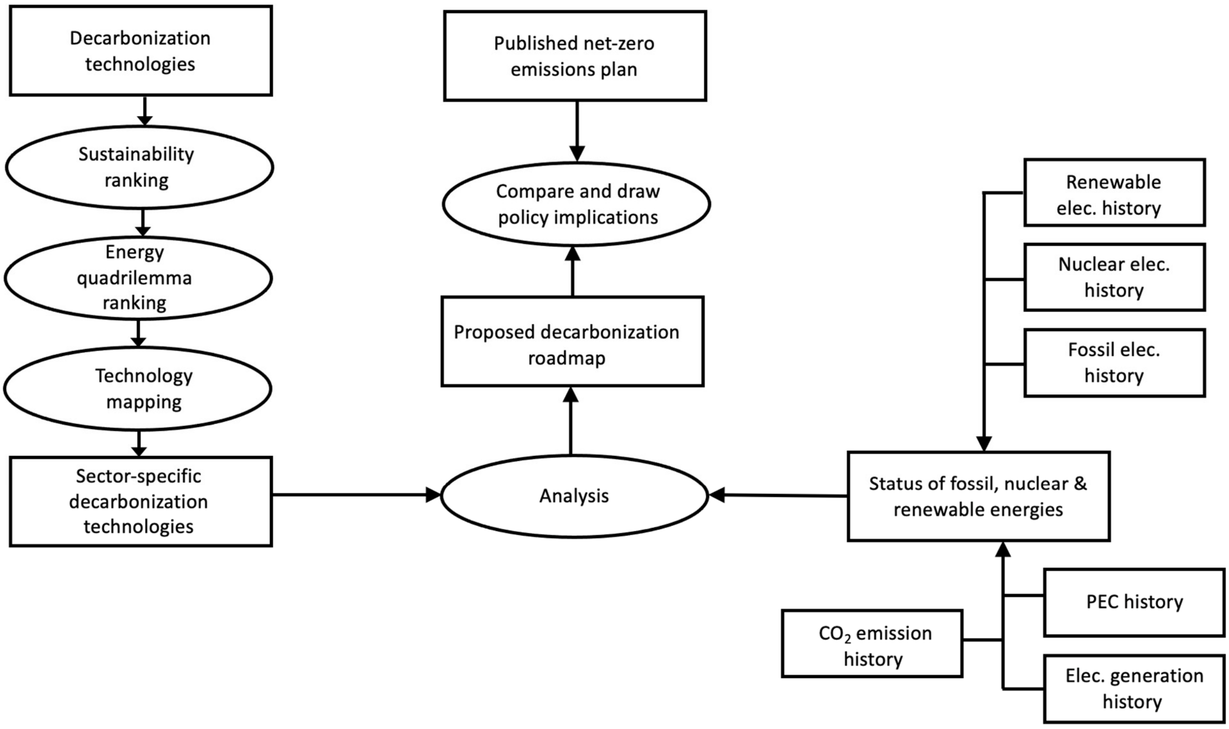

Figure 3. Methodology of study.

3. Status of Fossil and Non-Fossil Energies

3.1. Primary Energy Consumption

Figure 4 gives the history of Taiwan's PEC cumulatively (Figure 4a) and by fuel type (Figure 4b) [2]. In 2020, Taiwan's PEC comprised 39% oil, 34% coal, 19% gas, 6% nuclear, and 2% renewables (Figure 5a). For most of the last two decades, renewable energies contributed to less than 2% of PEC (Figure 5b). Nuclear energy's contribution to PEC peaked at 20% in 1985 and had declined to 6% by 2020.

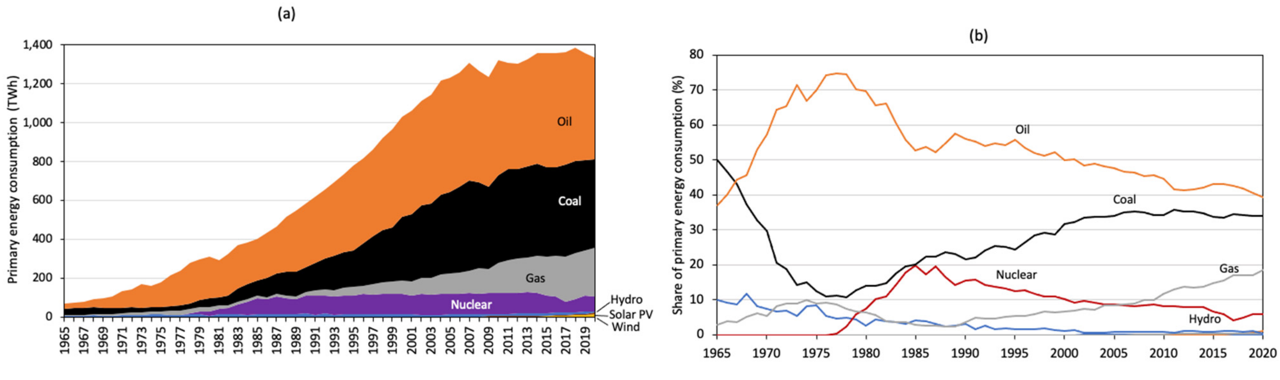

Figure 4. History of Taiwan's primary energy consumption (**a**) cumulatively and (**b**) by fuel type [2].

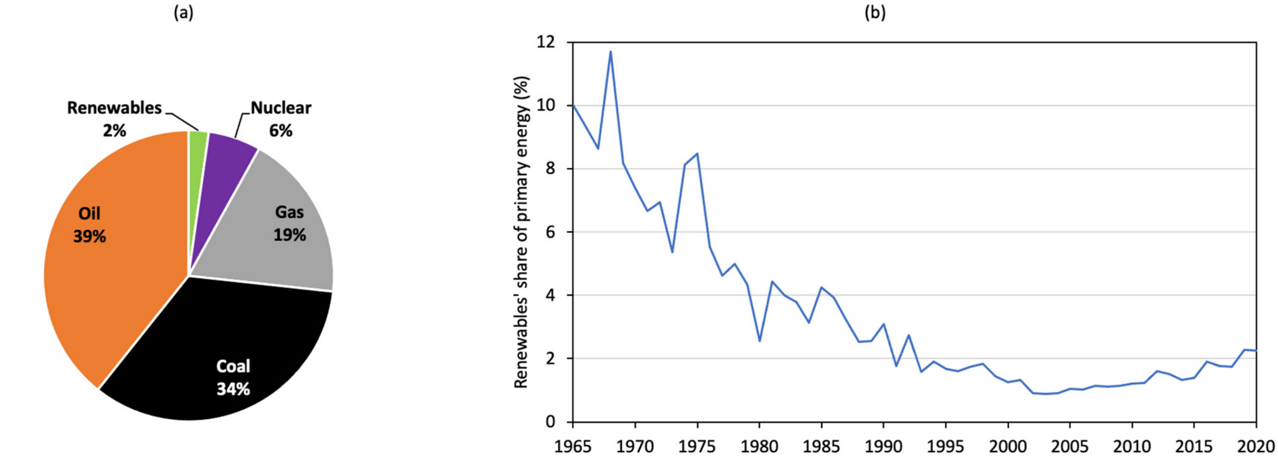

Figure 5. Taiwan's (**a**) PEC by fuel type in 2020, and (**b**) history of renewable energies' share of PEC [2].

3.2. Electricity Generation

Electricity generation in Taiwan in the last two decades had been dominated by coal and gas (Figure 6) [24]. In 2020, 45% of Taiwan's electricity was produced from coal, 36% from gas, 2% from oil, 11% from nuclear, and 6% from renewables (Figure 7a). In fact, renewable energies contributed to less than 6% of Taiwan's electricity in the last two decades (Figure 7b). Figure 8a shows the history of Taiwan's installed electricity capacity by fuel type. Among renewable energies, solar PV has the highest installed electricity capacity, followed by hydropower, wind, and bioenergy (Figure 8b). Solar PV was the only renewable energy with significant capacity additions in the last decade. The dominance of coal in Taiwan's power sector is noteworthy. This is also where the biggest reduction in CO_2 emission can be obtained by using clean coal technologies, implementing CCS, and switching to gas for power generation.

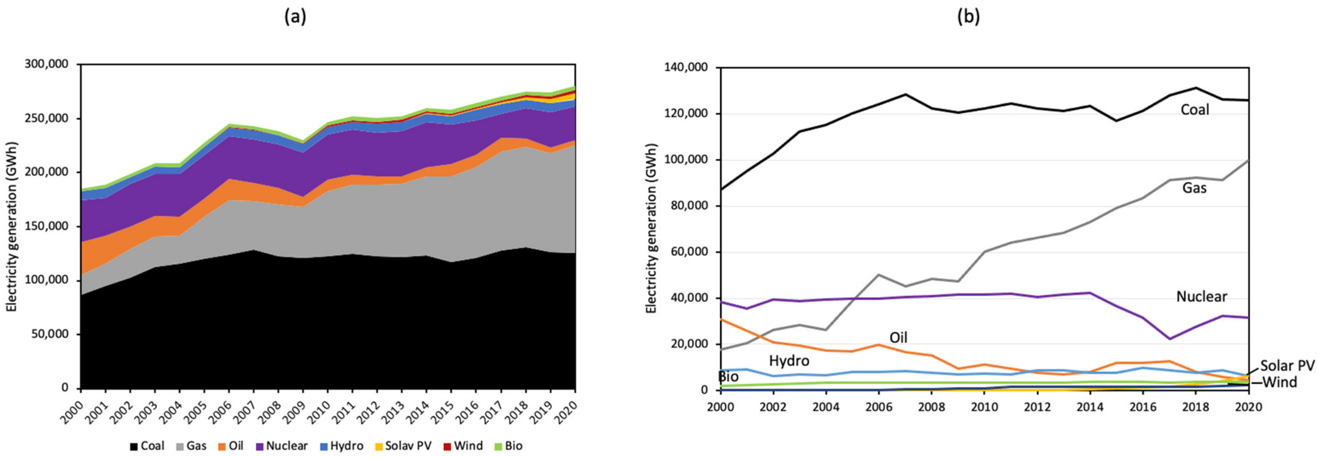

Figure 6. History of Taiwan's electricity generation (**a**) cumulatively and (**b**) by fuel type [24].

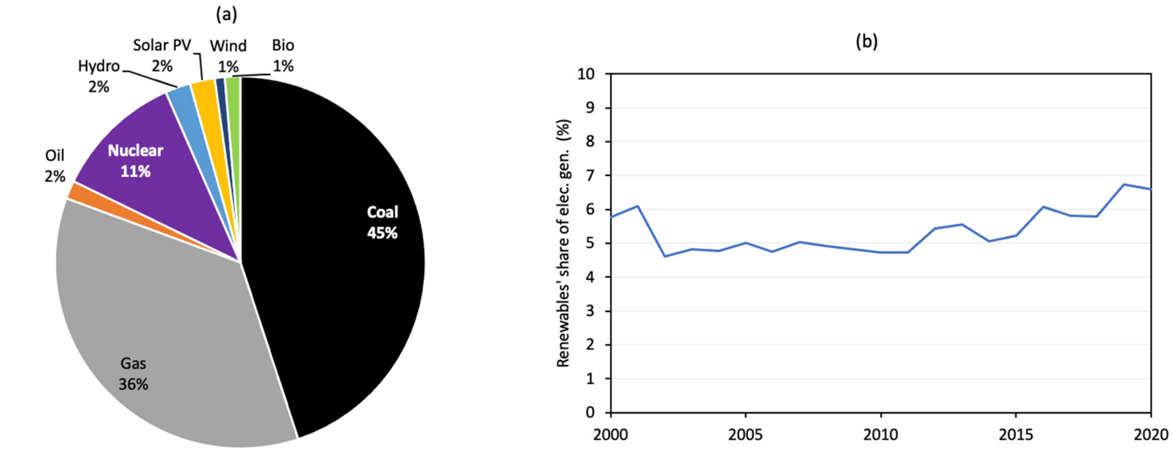

Figure 7. (**a**) Electricity generation by fuel type in 2020, and (**b**) history of renewables' share of electricity generation [24].

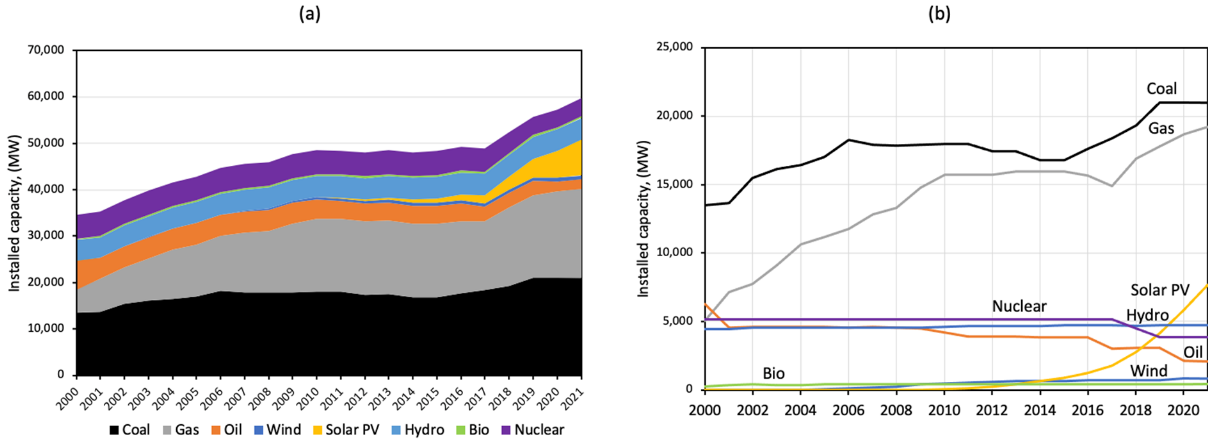

Figure 8. History of Taiwan's installed electricity capacity (**a**) cumulatively and (**b**) by fuel type [24].

3.3. CO_2 Emission

Figure 9 shows the history of Taiwan's CO_2 emission by source [3]. In 2020, 57% of Taiwan's CO_2 emission came from coal, 24% from oil, and 17% from gas (Figure 10). Consequently, by switching from coal to gas for power generation, Taiwan can reduce its CO_2 emission by roughly 80 Mtpa (Figure 9a), as gas emits about half as much CO_2 as coal when combusted.

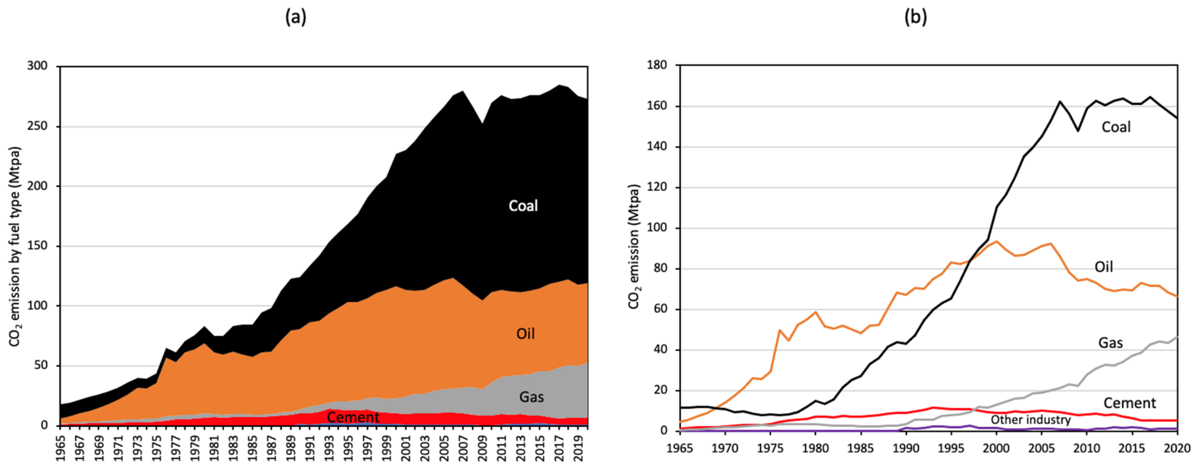

Figure 9. History of Taiwan's CO_2 emission (**a**) cumulatively and (**b**) by fuel type [3].

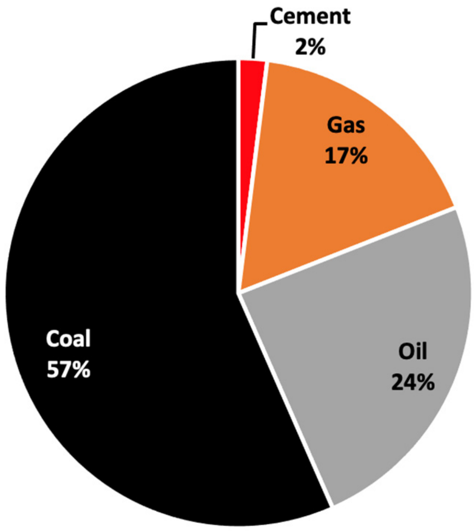

Figure 10. Taiwan's CO_2 emission by source in 2020 [3].

4. Status of Renewable and Nuclear Energies in Taiwan

Figure 11 shows the history of Taiwan's renewable electricity generation and installed capacity [24]. In 2020, hydroelectricity, which includes both conventional dam-based hydropower and pumped storage, had the biggest contribution (47%) to Taiwan's renewable electricity generation (Figure 11a). This is followed by solar PV (22%), bioenergy (21%), onshore wind (9%), and then offshore wind (1%). It is worthwhile to note that although solar PV had the highest installed capacity (5.8 GW or 48%) in 2020 (Figure 11b), it contributed to only 6,095 GWh or 22% of renewable electricity generation (Figure 11a). This was due to its low capacity utilization of around 12%, based on our calculations.

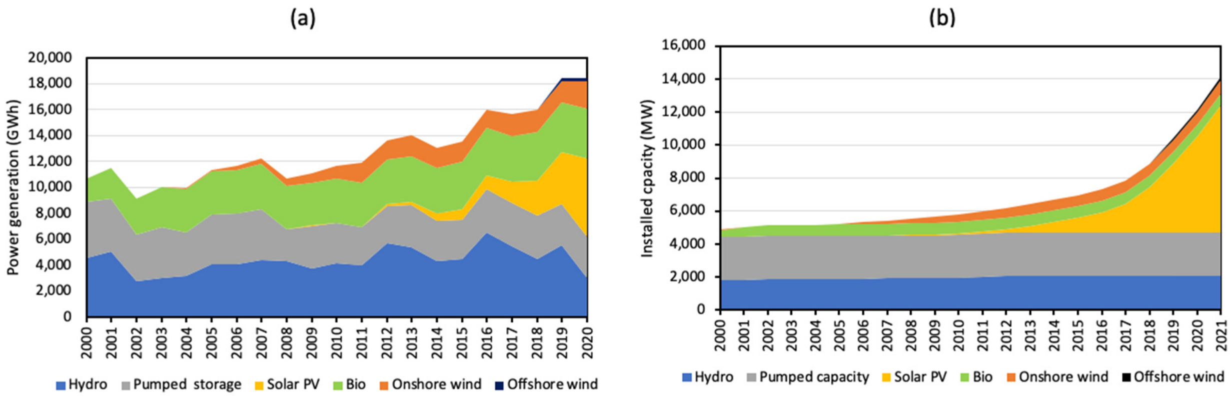

Figure 11. History of (**a**) renewable electricity generation and (**b**) renewable electricity capacity in Taiwan [24].

4.1. Status of Wind Energy

Figure 12 shows the history of Taiwan's electricity generation and installed capacity by wind. As of 2021, Taiwan had 1.033 GW of wind energy capacity. Of this, 0.796 GW came from onshore wind and 0.237 GW from offshore wind (Figure 12a). However, the growth of onshore wind capacity has slowed in recent years due to land constraints [17]. Offshore wind installation began in 2017 and has been growing ever since [25–28]. However, this growth is constrained by several issues. First, offshore wind is mostly limited to the west coast of Taiwan, where the average wind speed approaches 10 m/s or higher, which is conducive to wind turbine operations. However, during the summer months, Taiwan is also subject to typhoons with wind speed exceeding 50 m/s. Strong winds and waves can damage wind turbine blades, towers, mooring systems, and substructures of offshore wind turbines. Consequently, offshore wind turbines in Taiwan need to be typhoon-resistant [29–33]. At present, the most advanced wind turbines are designed for North Sea operations and are inadequate to withstand typhoon conditions. More focused R&D is needed on typhoon-resilient wind turbines. Some innovations being considered include stronger material for the tower, flexible and shorter blades, backup power for nacelle yawing during strong winds, and vertical axis wind turbines. In addition, there are sustainability issues with offshore wind in Taiwan. For example, the west coast of Taiwan is a habitat for the endangered Indo-Pacific humpback dolphin [34]. Furthermore, sites designated for offshore wind development are also rich fishing grounds for coastal communities. Installation of offshore wind farms, which may interrupt or prohibit the use of marine resources on Taiwan's west coast, will encounter resistance from local communities [34].

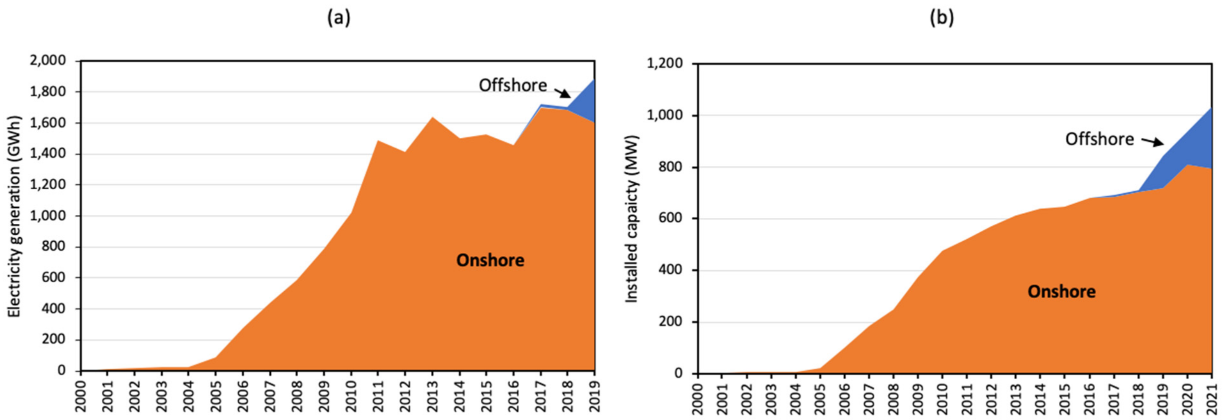

Figure 12. History of (**a**) electricity generation by and (**b**) installed capacity for wind in Taiwan [24].

4.2. Status of Solar PV

Figure 13a,b shows the history of Taiwan's electricity generation and installed capacity of solar PV, respectively [24]. Solar PV capacity has grown rapidly in the last decade [35–40]. In 2020, solar PV generated 6095 GWh of electricity, which was 2.2% of total electricity and 33% of renewable electricity. However, installation of solar PV has encountered local resistance due to a number of issues, including lack of environment impact assessment, unsuitable land being assigned, and lack of transmission lines [36]. Taiwan's NZE plan will install 20 GW of solar PV capacity by 2025, with 8 GW on rooftops and 12 GW on the ground [39]. As of 2021, only 7.7 GW of solar PV capacity has been installed (Figure 13) [24], mostly by IPPs [41]. It is unlikely that another 12.3 GW, or 1.6 times current solar PV, will be installed by 2025.

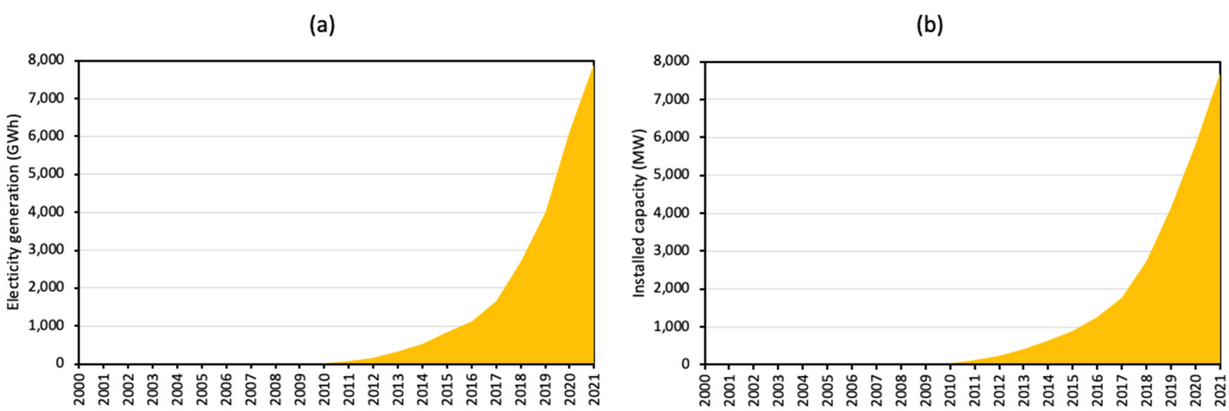

Figure 13. History of (**a**) electricity generation by and (**b**) installed capacity for solar PV in Taiwan [24].

4.3. Status of Hydropower

As Taiwan receives an abundance of rainfall annually, hydroelectricity is the largest source of renewable electricity, despite challenges in water resource management such as dense population, mountainous terrain, typhoons, and droughts [41–43]. Figure 14 shows the history of Taiwan's hydropower [24], consisting of conventional hydroelectricity and pumped storage. The capacity of both has remained constant over the last two decades (Figure 14b), as development has already been saturated [44]. Taiwan's hydropower plants are evenly distributed across the island. The Dajiaxi power plant in Taichung and the Mingtan power plant in Nanton are the largest [41]. Future increase in hydropower will likely consist of smaller run-of-the-river stations with less environmental impact [45].

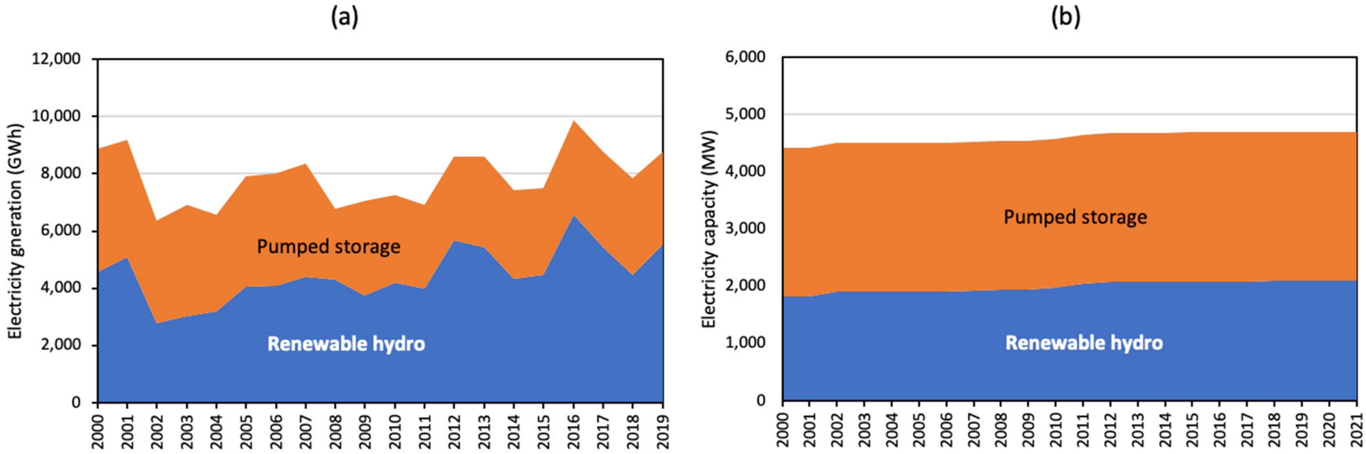

Figure 14. History of (**a**) electricity generation by and (**b**) installed capacity for hydropower in Taiwan [24].

4.4. Status of Bioenergy

Figure 15 shows the history of Taiwan's electricity generation by and capacity for bioenergy, which consists of renewable municipal waste and solid biofuels [24]. Municipal waste can further be categorized as household, commercial, or industrial. Taiwan's rapid industrial growth has resulted in significant growth in industrial waste. In 2020, renewable municipal waste energy accounted for 19% of all renewable electricity generation in Taiwan [24]. In the 1980s, Taiwan faced a massive waste crisis due to limited landfill capacity. Since then, Taiwan has used incineration to convert waste treatment into ash, heat, and gas. Today, there are 24 incineration plants in Taiwan. Taiwan's annual household waste generation is 7.2 Mt or 0.8 kg/person per day [42]. There is concern that incinerators may result in release of toxic heavy metals and particulate matter (PM2.5) to the environment. There is room for Taiwan's incinerators to be upgraded to reduce their environmental impact. Taiwan also produces a small amount of solid biofuels from wood and other plants. However, Taiwan does not have a biocrop industry [42,44]. Recently, some researchers have shown interest in using waste from rice paddies to generate biofuels [46]. Given its large population, limited arable land, and the high value Taiwan places on its forests as CO_2 sinks, it is unlikely that biocrop plantation will increase significantly in the future.

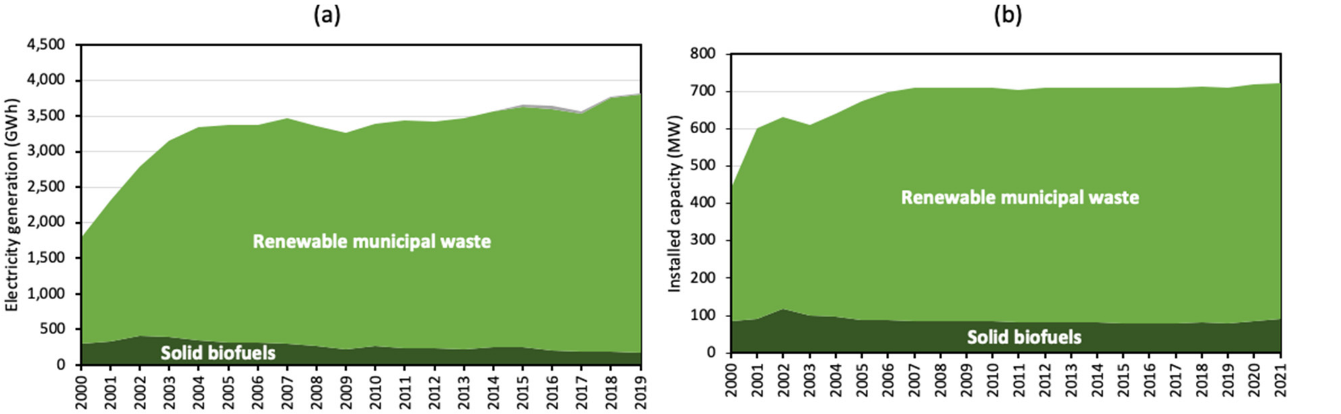

Figure 15. History of (**a**) electricity generation by and (**b**) installed capacity for bioenergy in Taiwan [24].

4.5. Status of Geothermal Energy

Located in the middle of the "Ring of Fire", Taiwan has good potential for geothermal energy [45,47–51]. It has been estimated that Taiwan's geothermal resources amount to 27 GWe within 2 to 3 km from the earth's surface. Nine high-geothermal-gradient areas have been identified [50]. However, large-scale development of geothermal energy in Taiwan has yet to begin. Built in 2021, the Qingshui Geothermal Power Plant in Yilan county is Taiwan's only operating geothermal power plant. It produces 180 °C hot water for power generation from a geothermal reservoir located 1.2–2.1 km below the earth's surface and has an installed capacity of 4.2 MW [48].

4.6. Status of Nuclear Energy

Figure 16 shows the history of Taiwan nuclear electricity generation and installed capacity [24]. Taiwan has three operating nuclear power plants with a combined capacity of 3.87 GW, which produced 31.44 TWh of electricity or 11% of total electricity generation in 2020 [24]. A fourth power plant was under construction but was cancelled. In response to Japan's Fukushima nuclear incident in 2011, Taiwan's NZE plan will phase out nuclear power by 2025 [8,52–57]. However, some researchers have warned this will cause a shortfall of electricity [57].

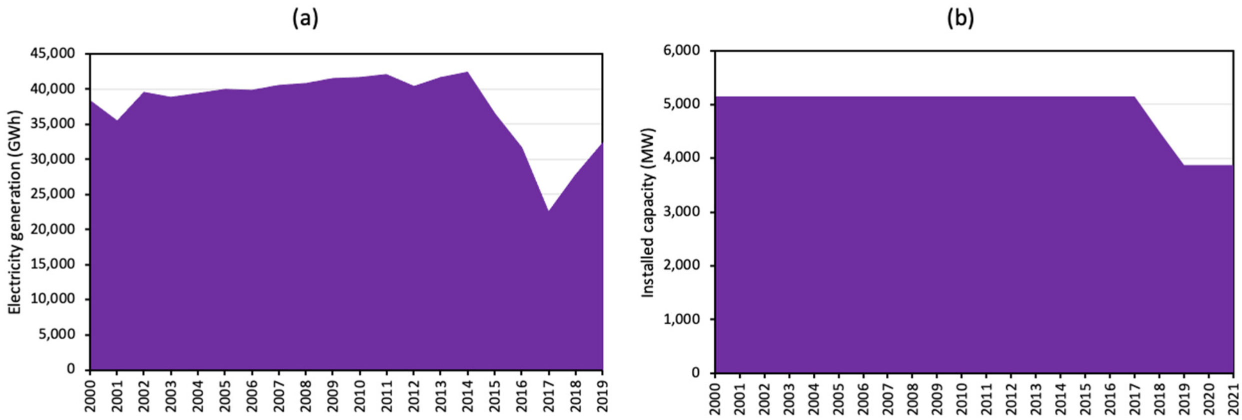

Figure 16. History of nuclear (**a**) electricity generation and (**b**) installed capacity in Taiwan [24].

5. Status of Fossil Energies in Taiwan

5.1. Status of Coal-Fired Power Plants

Figure 17 shows the history of Taiwan's fossil electricity generation and capacity [24]. In 2020, coal, gas, and oil contributed to 45%, 36%, and 1.6%, respectively, of Taiwan's total electricity generation (Figure 17a). Their installed capacity was 21 GW, 19 GW, and

2.1 GW, respectively, representing 35%, 32%, and 3.5% of Taiwan's electricity capacity in 2021 (Figure 17b). According to the NZE plan, there will be no new coal-fired plants after 2025, and all coal-fired power plants will be phased out by 2050 [8].

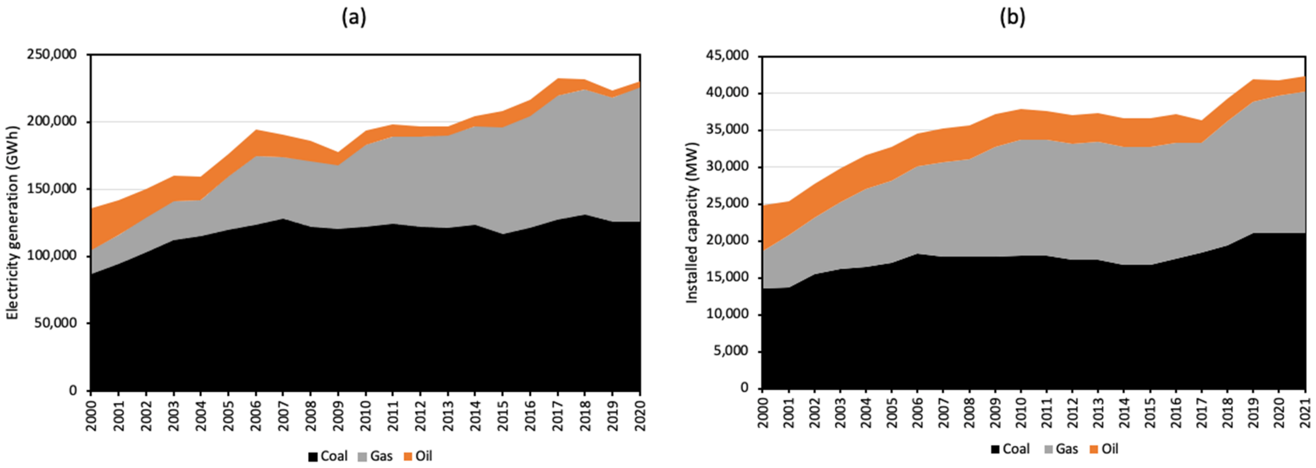

Figure 17. History of fossil (**a**) electricity generation and (**b**) installed capacity in Taiwan [24].

There are 20 coal-fired power stations in Taiwan, with a combined capacity of 21 GW in 2021 [58]. Together, they produced 86 Mtpa CO_2 [59]. Figure 18 shows the CO_2 emission and capacity of coal-fired power plants in Taiwan [59]. The Taichung and Mailiao power plants are the biggest coal-fired fired power plants in Taiwan, with capacity of 5.5 GW and 3.9 GW, respectively. They emit 28 Mtpa and 19 Mtpa CO_2, respectively, and are therefore candidates for application of clean coal technologies. If all coal-fired power plants are replaced by gas-fired power plants, Taiwan's CO_2 emission can be reduced by 43 Mtpa or by 15%.

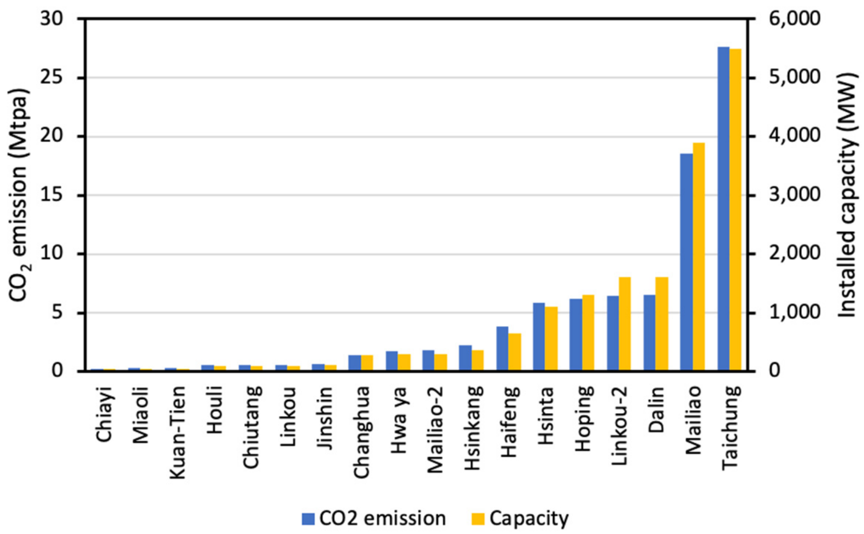

Figure 18. CO_2 emission and capacity of coal-fired power plants in Taiwan.

5.2. Status of Gas-Fired Power Plants

There are 11 gas-fired power plants in Taiwan, with a combined capacity of 19 GW in 2021 [24]. They emitted about 32 Mtpa CO_2 [59]. Figure 19 shows the CO_2 emission and installed capacity of gas-fired power plants in Taiwan. Taiwan imported 17.7 Mtpa of LNG in 2020, with 84% being used for generation of electricity and cogeneration [5].

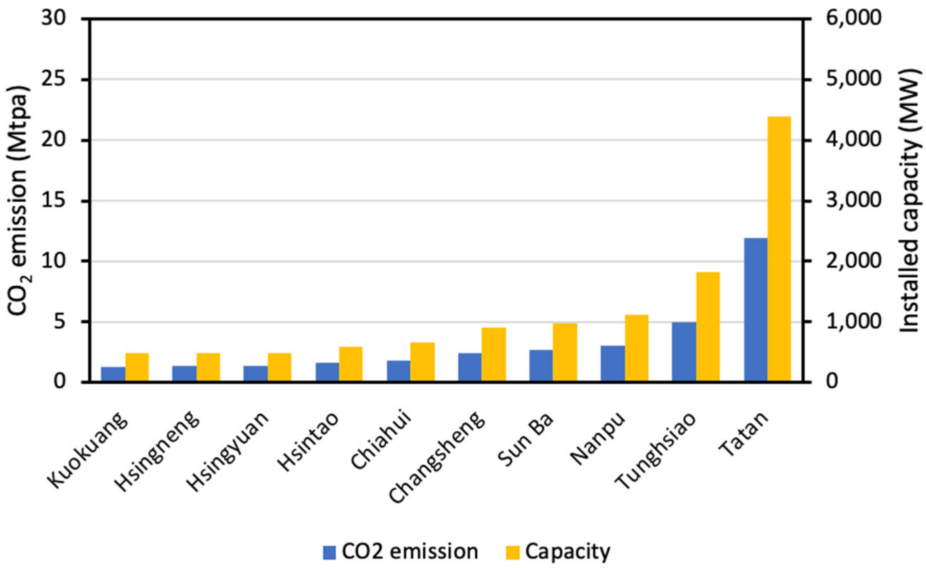

Figure 19. CO_2 emission and installed capacity of gas-fired power plants in Taiwan.

5.3. Fossil-Related CO_2 Emission

Figure 20 shows Taiwan's fossil-related CO_2 emission by sector [60,61]. In 2011, the power, industry, transport, and building sectors contributed to 56%, 27%, 13%, and 4% of Taiwan's CO_2 emission, respectively (Figure 20b). In 2011, the power sector alone emitted 155 Mtpa CO_2, the industry sector 75 Mtpa, and the transport sector 35 Mtpa (Figure 20a). This suggests that switching from coal to gas in the power and industry sector can have a significant impact on reducing overall CO_2 emission. In addition, applying CCS to gas-fired power and industry plants can also contribute to significant reduction in overall CO_2 emission.

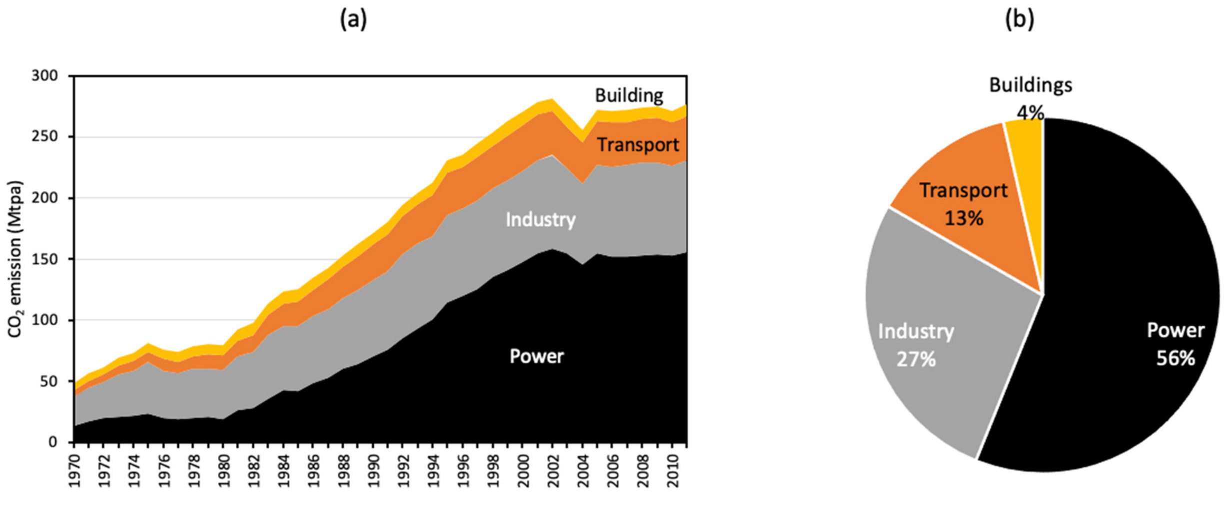

Figure 20. Taiwan's (**a**) history of fossil-related CO_2 emission by sector and (**b**) in year 2011 [60,61].

Figure 21 shows CO_2 emission from the power and industry sectors of Taiwan in 2020 [59]. In the industry sector, iron and steel, cement factories, and refineries produced 65, 17, and 17 Mtpa CO_2, respectively.

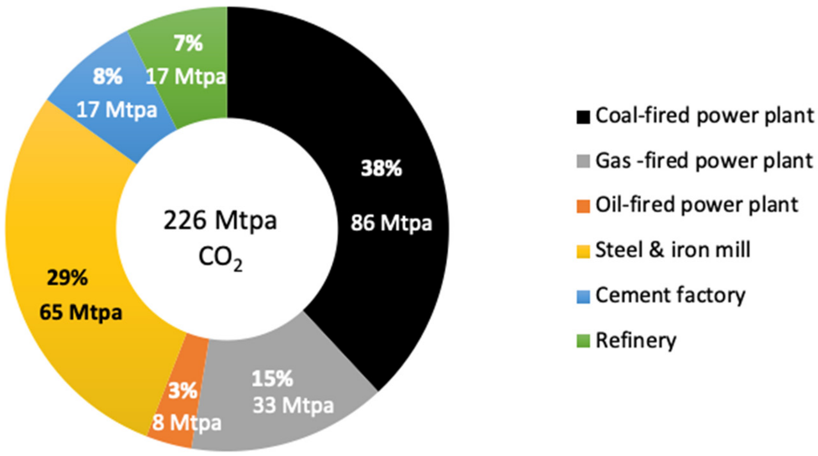

Figure 21. CO_2 emission from the power and industry sectors of Taiwan in 2020 [59].

6. Decarbonization Technologies

Table A1 lists a set of 20 decarbonization technologies for the power, transport and industry sectors, which have been discussed in recent publications [62–64]. In this study, we screen these technologies according to six categories (sustainability, security, affordability, reliability, readiness, and impact) to determine those with the most potential for Taiwan.

6.1. Sustainability Screening

In sustainability screening, we rank each technology on five categories: CO_2 emission, material footprint, and impact on people, animals, and environment. The criteria used are given in Tables A2–A4 in the Appendix A. The details of the screening are given in Tables A8 and A9 in Appendix B. Results are given in Table 1. It is worthwhile to note that renewable electricity technologies including hydro, solar PV, wind, and geothermal rank high in material footprint due to large amounts of materials needed to produce each TWh of electricity, according to estimates by the US Department of Energy (Table A8). This also causes green hydrogen to rank high in material footprint. EV is ranked high in material footprint because of large amounts of material extracted and processed per EV battery (Table A9). Nuclear, hydro, wind, and bio have medium rank in impact on people, animals, and environment, with details given in Table A9.

Table 1. Sustainability screening for decarbonization technologies.

Sector	Technology	CO_2 Emission	Material Footprint	Impact on People	Impact on Animals	Impact on Environ.
All	Green H_2	L	H	L	L to M	L to M
	CCU	L	L to H	L	L	L
Power	Nuclear	L	L	M	M	M
	Hydropower	L	H	M	M	M
	Solar PV	L	H	L	L	M
	Onshore wind	L	H	L	M	M
	Offshore wind	L	H	L	M	M
	Bioenergy	L	M	M	M	M
	Geothermal	L	H	L	L	L
	Coal→gas	M	L	L	L	L
	CP-CCS	L	M	L	L	L
	GP-CCS	L	L	L	L	L
	Clean coal	M	M	L	L	L

Table 1. *Cont.*

Sector	Technology	CO_2 Emission	Material Footprint	Impact on People	Impact on Animals	Impact on Environ.
Transport	EV	L	H	L	L	L
	HFCV	L	L	L	L	L
	H_2-marine	L	L	L	L	L
	Bio-aviation	L	M	M	M	M
Industry	Coal→H_2-CCS	L	M	L	L	L
	Gas→H_2-CCS	L	L	L	L	L
	Ind-CCS	L	L	L	L	L

Color code: Green, yellow, and red signify low, medium, and high, respectively.

6.2. Energy Quadrilemma Screening

Energy quadrilemma refers to energy sustainability, security, affordability, and reliability. The criteria for ranking in energy quadrilemma are given in Table A5. The results of sustainability ranking are carried forward to energy quadrilemma ranking. Energy security refers to whether the energy resource is available domestically. A low rank means the energy resource is either unavailable domestically or has to be imported. Energy affordability refers to whether the technology is readily affordable for large-scale application. We rank a technology's reliability according to its capacity factor, i.e., the percent of time in a year that this technology can be operated. The capacity factors for Taiwan's electricity technologies, based on the authors' estimates using data published in [24], are given in Table A7.

Ranking results are given in Table 2. Green hydrogen, hydropower, solar PV, wind, geothermal, and EV are ranked low (red) in one or more categories of the energy quadrilemma. Green hydrogen is ranked low (red) in affordability, because it is unavailable in industrial quantities in Taiwan and is expensive ($3–7/kg) [65]. Solar PV is ranked low (red) in reliability because of its low capacity utilization (11%) (Table A7). In addition, green hydrogen, hydro, solar PV, wind, geo, and EV are ranked low in sustainability because of their high material footprint (Table 1).

Table 2. Energy quadrilemma screening for decarbonization technologies.

Sector	Technology	Sustainability	Security	Affordability	Reliability
All	Green H_2	L	L	L	H
	CCU	M	H	H	H
Power	Nuclear	M	M	H	H
	Hydropower	L	H	H	M
	Solar PV	L	H	H	L
	Onshore wind	L	H	H	M
	Offshore wind	L	H	H	M
	Bioenergy	M	H	H	H
	Geothermal	L	M	H	H
	Coal→gas	M	M	H	H
	CP-CCS	M	M	H	H
	GP-CCS	H	M	H	H
	Clean coal	M	M	H	H
Transport	EV	L	H	H	H
	HFCV	H	H	H	H
	H_2-marine	H	H	M	H
	Bio-aviation	M	H	M	H
Industry	Coal→H_2-CCS	M	M	M	H
	Gas→H_2-CCS	H	M	M	H
	Ind-CCS	H	H	H	H

Color code: green, yellow, and red signify high, medium, and low ranking, respectively.

6.3. Technology Mapping

Each decarbonization technology is also ranked according to its readiness level and impact on decarbonization. The criteria for the mapping are given in Table A6. Results are given in Figure 22. The color of different quadrants is unimportant, but the color of the technology carries meaning. Red color denotes a low ranking (red) in one or more categories of the energy quadrilemma. Yellow color denotes a medium ranking (yellow) in one or more category in the energy quadrilemma and no red ranking. Green color denotes a high ranking (green) in all categories of the energy quadrilemma. Technologies that are ranked high in impact and low in readiness (upper left quadrant in Figure 22) are those that need more R&D before large-scale applications can be made.

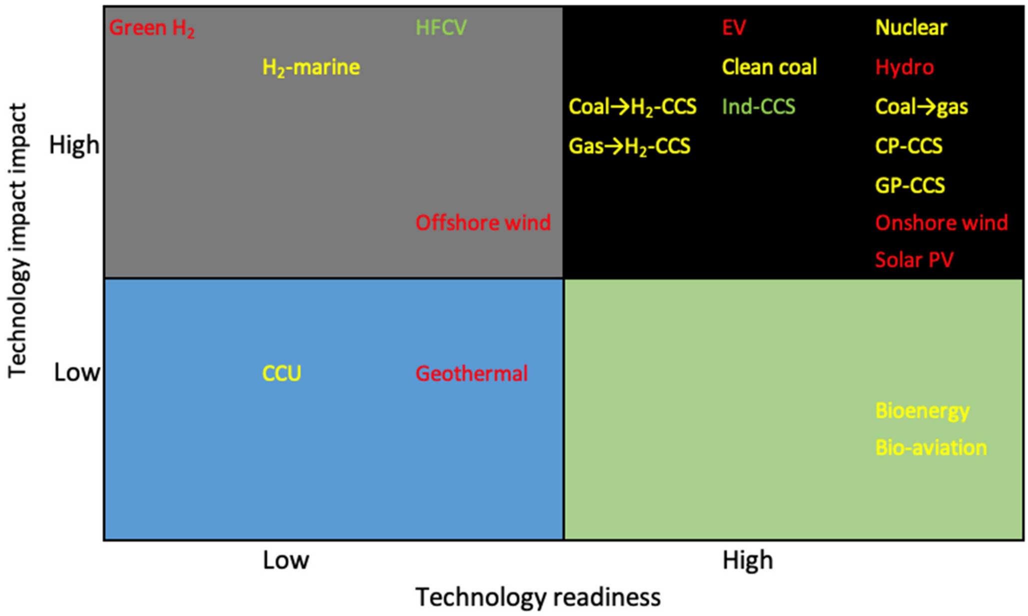

Figure 22. Technology mapping for decarbonizing Taiwan.

6.4. Composite Ranking

Figure 23 shows the composite ranking of the 20 decarbonization technologies in radar charts. In each chart, a technology is ranked according to six categories: sustainability, security, affordability, reliability, readiness, and impact. Rankings of 1, 2, and 3 refer to low, medium, and high ranking in each respective category. Of all the technologies, only Ind-CCS has a high ranking in all six categories. GP-CCS, HFCV, EV rank high in five out of six categories. Seven technologies (hydro, bio, solar PV, nuclear, coal→gas, CP-CCS, and Clean coal) rank high in four out of six categories. Four technologies (Onshore wind, CCU, bio-aviation, Gas→H_2-CCS) rank high in three out of six categories. Figures 22 and 23 can be used together to determine a technology's potential for decarbonization and areas that need more R&D.

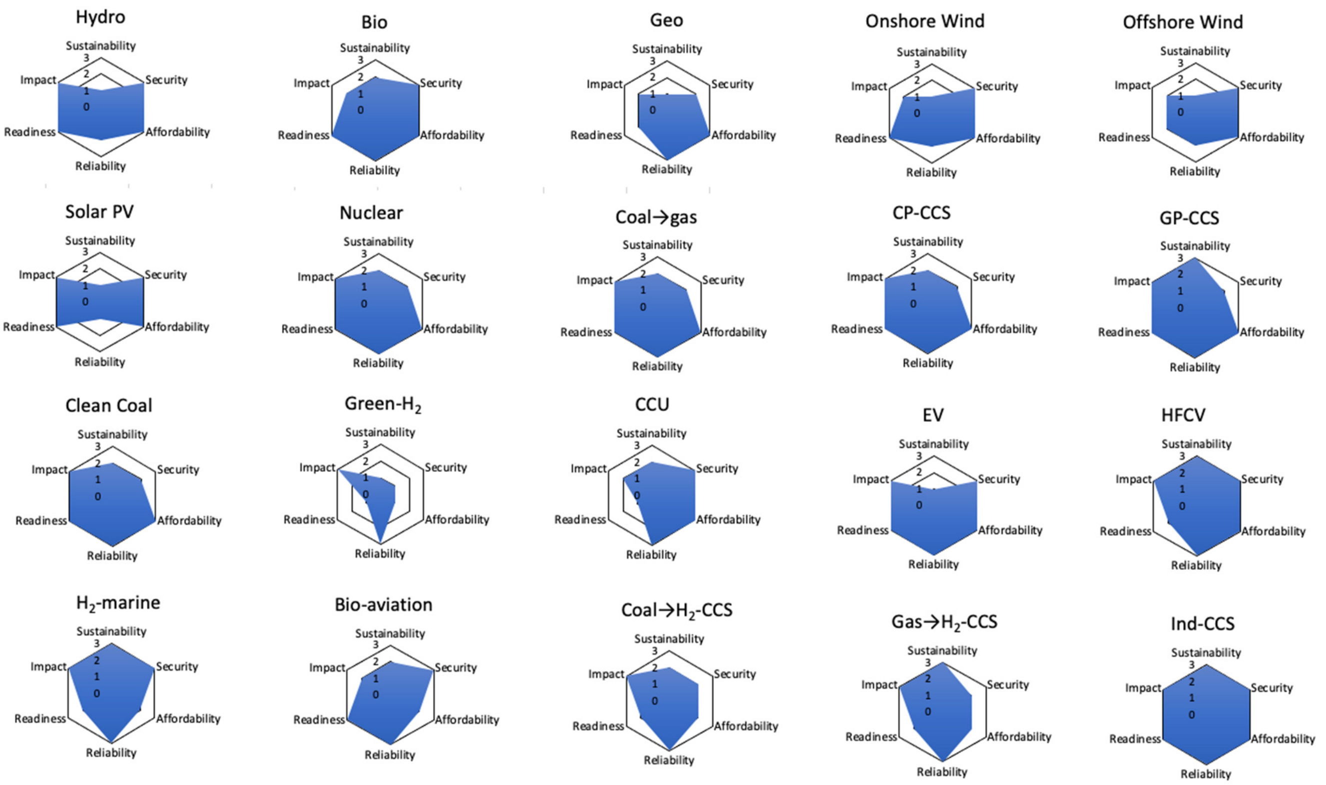

Figure 23. Composite ranking of decarbonization technologies for Taiwan.

7. Proposed Decarbonization Roadmap

Based on the technology ranking exercises described in the previous section, technologies that have the most potential for Taiwan's decarbonization are listed in Table 3. Technologies are divided into three tiers according to their potential.

Table 3. Ranking of decarbonization technologies.

	Power Sector	Transport Sector	Industry Sector
Tier 1 technology (highest potential)	GP-CCS [2]	EV [1]	Ind-CCS
Tier 2 technology (high potential)	Coal→gas [1,2] CP-CCS [1,2] Clean coal [1,2] Nuclear [1,2]	HFCV [5]	Gas→H_2-CCS [2,3,5]
Tier 3 technology (moderate potential)	Solar PV [1,4] Onshore wind [1,4,6] Offshore wind [1,4,5,6] Hydro [1,4] Bio [1,6]	H_2-marine [3,5] Bio-aviation [1,3,6]	Coal→H_2-CCS [1,2,3,5]

[1] sustainability, [2] security, [3] affordability, [4] reliability, [5] technology readiness, [6] technology impact issues exist.

7.1. *Power Sector Decarbonization*

7.1.1. Clean Coal Technologies

In 2020, 45% of Taiwan's electricity generation came from coal-fired power plants, which had a combined capacity of 21 GW. Together, they emitted 86 Mtpa CO_2 or 31% of Taiwan's total annual CO_2 emission. The NZE plan will stop construction of new coal-fired power plants by 2025 and phase out all coal-fired power plants by 2050. However, before existing coal-fired power plants are decommissioned, there is an urgent need to reduce their CO_2 emission. The International Energy Agency (IEA) has identified four groups of clean coal technologies (CCTs) which have the capability to reduce CO_2 emission from coal-fired power plants: coal upgrading, efficiency improvement, advanced technologies, and CCS [66]. Coal upgrading includes coal washing, drying, and briquetting, which can reduce CO_2 emissions by as much as 5%. In addition, efficiency improvements in existing conventional sub-critical plants can achieve thermal efficiencies of up to 40% and reduce CO_2 emission by up to 22%. They include heating pulverized coal to produce supercritical (540–566 °C and 250 bar) or ultra-supercritical (590 °C and 250 bar) steam for high-efficiency (up to 45%) electricity generation. Advanced technologies include integrated gasification combined cycle (IGCC) and pressurized fluidized bed combustion. They can reduce CO_2 emission up to 25%. There is much room for improving the thermal efficiencies of Taiwan's coal-fired power plants. The prime targets for decarbonization are the sub-critical Taichung and Mailiao coal-fired power plants, which emit 28 and 19 Mtpa CO_2, respectively (Figure 18). In this study, we exclude CCS from CCTs, as it is discussed separately.

7.1.2. CP-CCS

Installing CCS in Taiwan's coal-fired power plants will enable them to reduce CO_2 emission to near-zero. Post-combustion carbon capture can be retrofitted into existing coal-fired power plants [67]. Recently, Zhang et al. (2022) have suggested capturing CO_2 from power and industry plants in Taiwan and transporting it to the Tiechenshan gas field for CO_2-enhanced gas recovery or to saline aquifers in the West Taiwan Basin for permanent storage [59].

7.1.3. Coal→Gas

Replacing coal with gas for power generation will go a long way toward decarbonizing Taiwan's power sector. If all coal-fired power plants are converted to gas-fired power plants, CO_2 emission in Taiwan will be reduced by 43 Mtpa or 16%. This will be a significant reduction. Some of Taiwan's coal-fired power plants have installed new gas-fired units. However, retiring old coal-fired units and replacing them with new gas-fired units will make a significant contribution to Taiwan's decarbonization.

Wholesale replacement of coal-fired power plants by gas-fired power plants will require securing more long-term LNG contracts and building additional LNG terminals. Taiwan is the world's fifth-largest LNG importer, receiving 17.7 Mtpa LNG in 2020, with 28% from Qatar, 27% from Australia, and 13.5% from Russia [5]. Taiwan has two LNG import terminals and plans to build two new ones to increase LNG importing capacity to 30 Mtpa by 2027 [68].

7.1.4. GP-CCS

Installing CCS in current and future gas-fired power plants will be important for Taiwan to achieve net-zero by 2050. Collateral learnings from Norway's Longship and the UK's East Coast Cluster projects will be useful [69,70].

7.1.5. Nuclear Power Plants

Taiwan's NZE plan will phase out all nuclear power by 2025 [8]. In 2020, the three nuclear power plants in Taiwan generated 31.44 TWh or 11% of Taiwan's electricity [24]. They have a combined capacity of 3.872 GW. Retiring all of them by 2025 may result in power shortage, as it is unlikely that wind or solar PV will completely replace nuclear by then [57]. We recommend a gradual phasing out of nuclear energy by 2050.

7.1.6. Onshore Wind

According to Figure 12b, installed capacity of onshore wind has plateaued at around 800 MW since 2020, due to lack of suitable land [17]. The NZE plan includes 40 GW of wind power installed by 2030, with 10 GW in onshore wind [8]. It is unlikely that this goal will be reached by 2030 due to limited available land.

7.1.7. Offshore Wind

As discussed in Section 4, offshore wind faces headwind due to the lack of typhoon-resilient design and water depth limitation to 120 m [71]. Other technology barriers include a lack of installation vessels and local companies with sufficient manufacturing capability [20]. More R&D is needed to mature typhoon-resistant wind turbine design in Taiwan. Furthermore, sustainability concerns for the effect of offshore wind turbines on marine life and fishing activities need to be addressed. Offshore wind turbines had a capacity of 237 MW in 2021 [24]. The NZE plan will increase it to 30 GW by 2030 [8]. Given the low technology readiness of offshore wind (Figure 22), it is unlikely that this goal can be achieved.

7.1.8. Solar PV

Despite its rapid growth, solar PV contributed to only 2.18% of total electricity generation in Taiwan and 10% of total installed capacity in 2020. Taiwan's NZE plan will increase solar PV capacity from 7.7 GW in 2021 to 20 GW in 2025 [8]. There are three types of solar PV in Taiwan: rooftop, on ground, and on water. Rooftop solar PV will eventually be limited due to space constraints. On-ground solar PV faces competition for scarce arable land and other types of land usage. On-water solar PV is limited to relatively calm water or inland lakes. Furthermore, solar PV suffers from a low capacity-utilization factor of around 11% by our calculations. Practically, this means that more solar PV capacity is needed to produced the same output of electricity compared to other forms of renewable or fossil energy. There is no consensus as to rooftop solar PV's potential in Taiwan. Chen et al. (2010) estimate it to be 65 TWh/y [72], Yue and Huang (2011) estimate it to be 36.1 TWh/r [73], and Ko et al. (2015) estimate it to be 15.4 TWh/y [74]. It is unlikely that solar PV will reach 20 GW by 2025, as per the NZE plan, due to space limitation, high capital investment, and decreasing feed-in tariffs [39].

7.1.9. Hydropower

Taiwan's hydropower capacity has stayed constant at 4.695 GW in the last decade [24]. Furthermore, Taiwan's hydropower stations are old and require modernization. There is currently no plan to increase hydropower capacity. Construction of new dams in large rivers will face sustainability issues including loss of sediment, adverse impact on fishery, biodiversity, and impact on riparian communities. There may be room for small run-of-the-river hydropower plants to be installed, especially in mountainous areas [45].

7.1.10. Hydrogen

At present, there is no industrial production of either blue or green hydrogen for power generation. Electricity generation by green hydrogen will be more expensive than any form of renewable electricity [65]. Although the NZE plan mentions the use of hydrogen for power generation, there is no detail. It probably will not occur until there is an abundance of renewable electricity. However, Taiwan needs a hydrogen strategy as part of its national energy policy.

7.1.11. Proposed Decarbonization Roadmap for the Power Sector

Among decarbonization technologies, the ones that have the highest potential of making a difference in the power sector are: (1) GP-CCS, (2) coal→gas, (3) CP-CCS, (4) CCTs, and (5) nuclear energy (Table 3).

We propose a power sector decarbonization roadmap shown in Figures 24 and 25. In constructing this roadmap, we make the following assumptions: (1) electricity generation will increase at average annual growth rate (AAGR) of 2% annually, (2) renewable electricity generation will grow at an AAGR of 7%, (3) oil-fired power plants will be phased out by 2025, (4) nuclear power plants will be phased out by 2050, (5) hydrogen will be used in the transport and industry sectors but not in the power sector, (6) coal-fired power plants will be phased out by 2050, and (7) CCS will be installed in coal- and gas-fired power plants as soon as possible. Assumptions (1), (3), and (6) are the same as those in NZE plan. Assumption (4) differs from the NZE plan, which will phase out nuclear energy by 2025. Assumption (7) differs from the NZE plan by bringing CCS forward. Assumption (2) is the major difference between this study and the NZE plan, which assumes an AAGR of 10.1% for renewable electricity generation.

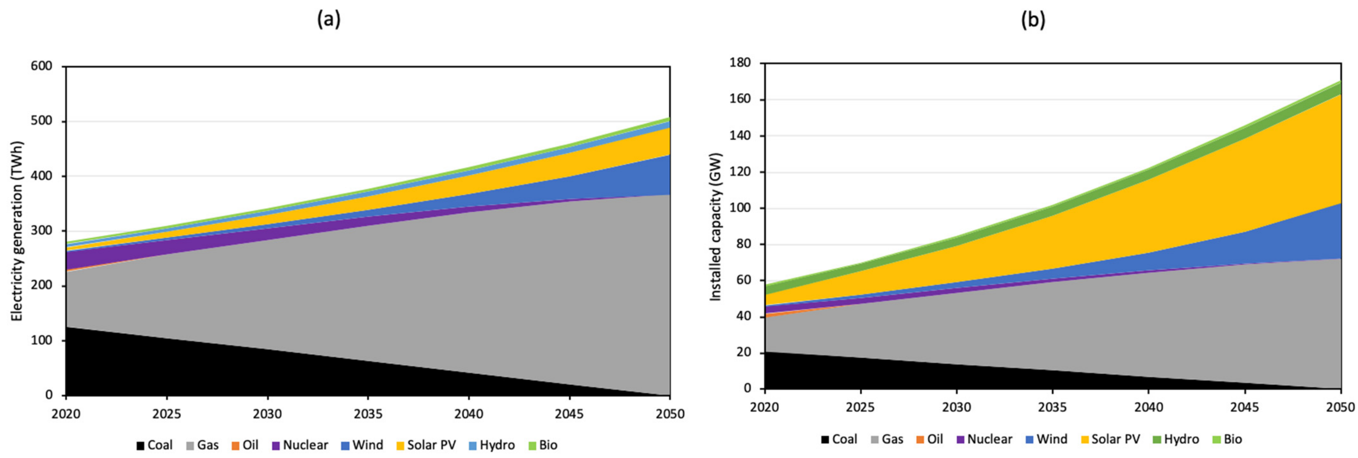

Figure 24. Proposed decarbonization roadmap for (**a**) electricity generation and (**b**) installed capacity.

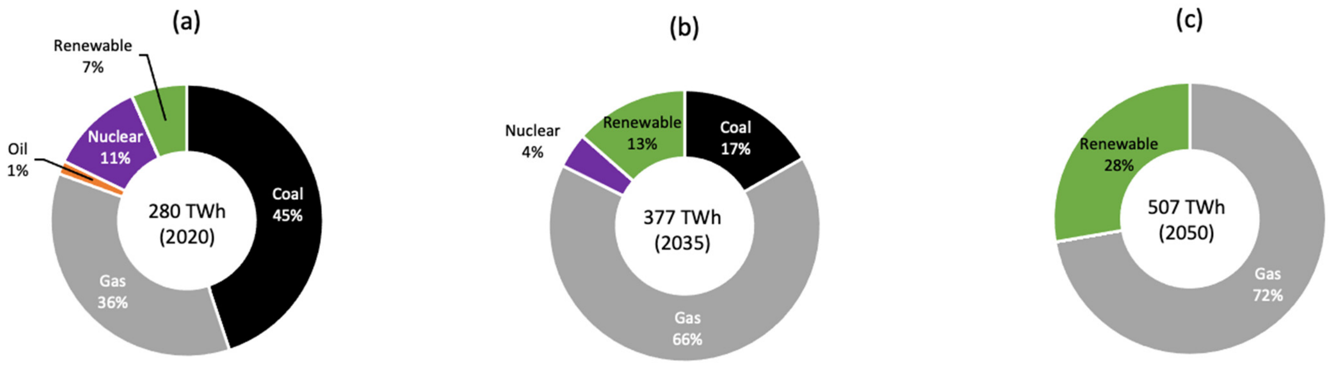

Figure 25. Proposed decarbonizing roadmap for the power sector in (**a**) 2020, (**b**) 2035, and (**c**) 2050.

The key features of this decarbonizing roadmap are as follows. First, renewables' share in electricity generation increases from 7% in 2020 to 28% in 2050 (30 years) (Figure 24), while renewable electricity generation increases from 18 TWh to 141 TWh (Figure 25). This increase is shared by both solar PV and wind, with moderate increase in other forms of renewable energies (Figure 24a). Second, gas' share in electricity generation increases from 36% in 2020 to 72% in 2050, while electricity generation from gas increases from 100 TWh in 2020 to 367 TWh in 2050 (Figure 25). Third, CCS is gradually increases to mitigate CO_2 emission from gas-fired power plants, achieving 151 Mtpa CO_2 by 2050. Fourth, between now and 2050, clean coal technologies and CCS are used to mitigate CO_2 emission from coal-fired power plants.

7.1.12. Comparison with Decarbonization Roadmap Announced by Taiwan's NZE Plan

The power sector decarbonization roadmap announced by the NZE plan can be derived from Figure 1. Results are shown in Figures 26 and 27. A comparison between them and Figures 24 and 25 reveals several differences between the two roadmaps. First, the NZE roadmap relies heavily on renewable energy to replace nuclear and coal. In the NSE plan, renewable energy has an AAGR of 10.1%. We believe this is unachievable due to technology readiness and sustainability issues for both wind and solar PV discussed earlier. Second, in the NZE plan, CCS will not be installed in coal- and gas-fired power plants until

2040. On the other hand, this study proposes installing CCS in coal- and gas-fired power plants as soon as possible. Third, in the NZE plan, hydrogen will contribute to 11% of power generation by 2050 (Figure 25c). This study does not use hydrogen for power generation but instead for decarbonizing hard-to-decarbonize industries such as iron and steel mills and cement factories. Fourth, in the NZE plan, gas' contribution to power generation increases from 36% in 2020 to 55% in 2035 and then decreases to 24% in 2050 (Figure 27). In the roadmap proposed by this study, gas' contribution to electricity generation increases from 36% in 2020 to 66% in 2035 and then to 72% in 2050. The major difference between the two roadmaps is that the NZE roadmap relies more on wind and solar PV to replace coal and nuclear. This study's roadmap relies heavily on gas to replace coal and nuclear while also allowing for significant increase in wind and solar PV capacity. In addition, CCS plays a key role and will be implemented as soon as possible. The differences between the two roadmaps are listed in Table 4. Although the NZE plan stipulates about 11% of electricity generation by hydrogen, no details of how to achieve this are given [8].

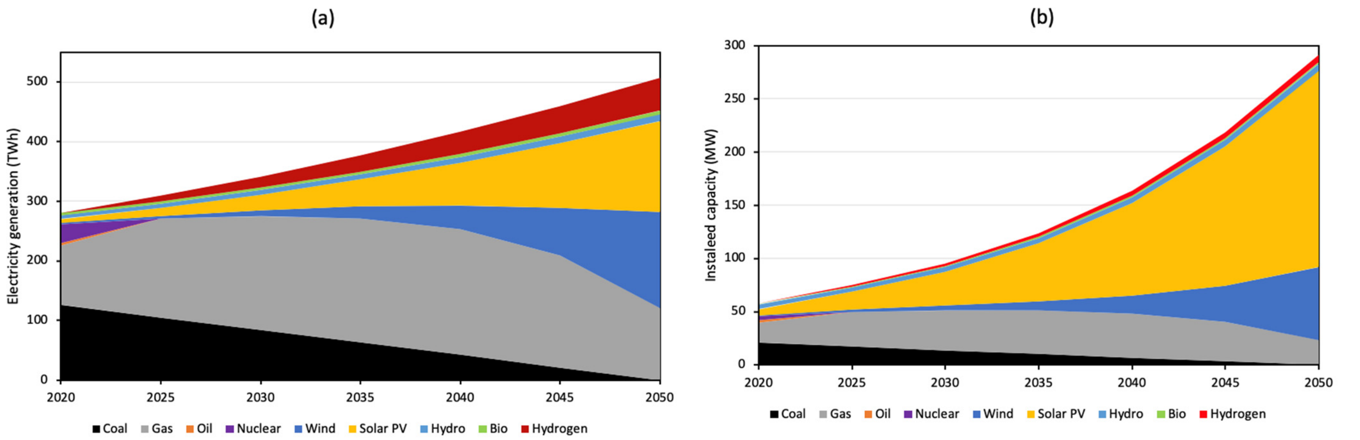

Figure 26. Decarbonization roadmap for (**a**) electricity generation, and (**b**) installed capacity in the NZE plan.

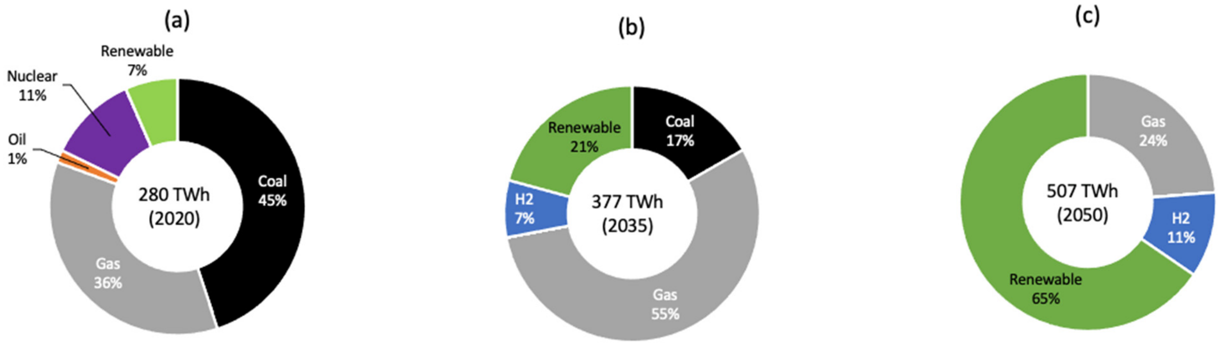

Figure 27. Power sector decarbonization roadmap in the NZE plan in (**a**) 2020, (**b**) 2035, and (**c**) 2050.

Table 4. Comparison between decarbonization roadmaps for power sector proposed by NZE plan (peach color) and this study (blue color).

		NZE Plan				This Study			
	Unit	**2020**	**2025**	**2035**	**2050**	**2020**	**2025**	**2035**	**2050**
Non-renewable generation	TWh	262	279	299	175	262	283	326	367
Coal	TWh	126	105	63	0	126	105	63	0
Gas	TWh	100	166	209	121	100	152	247	367

Table 4. *Cont.*

		NZE Plan				This Study			
	Unit	**2020**	**2025**	**2035**	**2050**	**2020**	**2025**	**2035**	**2050**
Oil	TWh	4	0	0	0	4	0	0	0
Nuclear	TWh	31	0	0	0	31	26	16	0
H_2	TWh	0	9	27	55	0	0	0	0
Renewable generation	TWh	18	30	78	332	18	26	51	141
Wind	TWh	2	5	20	161	2	4	13	73
Solar PV	TWh	6	14	45	153	6	11	24	50
Hydro	TWh	6	7	8	11	6	7	8	11
Bioenergy	TWh	4	4	5	7	4	4	5	7
Geothermal	TWh	0	0	0	0	0	0	0	0
Total generation	TWh	280	309	377	507	280	309	377	507
RE share	%	7	10	21	65	7	8	14	28
Non-renewable capacity	GW	46	51	55	31	46	51	61	72
Coal	GW	21	17	10	0	21	17	10	0
Gas	GW	19	33	41	24	19	30	49	72
Oil	GW	2	0	0	0	2	0	0	0
Nuclear	GW	4	0	0	0	4	3	2	0
H_2	GW	0	1	3	7	0	0	0	0
Renewable capacity	GW	12	24	69	261	12	20	41	99
Wind	GW	1	2	8	68	1	2	6	31
Solar PV	GW	6	17	54	184	6	13	29	60
Hydro	GW	5	4	5	7	5	4	5	7
Bioenergy	GW	1	1	1	1	1	1	1	1
Geothermal	GW	0	0	0	0	0	0	0	0
Total capacity	GW	58	75	124	291	58	70	102	171
RE share in capacity	%	21	32	56	89	21	28	40	58
CO_2 to be mitigated by CCS	Mtpa	173	175	150	50	173	169	166	151

7.2. Transport Sector Decarbonization

For the transport sector, the major decarbonization approach is replacing internal combustion engine (ICE) vehicles with electric vehicles (EVs). The NZE plan calls for all new car and scooter sales to be electric by 2040. The increase in electricity demand due to electrification of road transport is assumed to be included in the 2 ± 0.5% AAGR in electricity generation. There is no mentioning of how marine and aviation transport are to be decarbonized. However, the plan proposed by this study differs from the NZE plan in advocating HFCV, H_2-marine, and bio-aviation in the medium- to long-term future.

7.3. Industry Sector Decarbonization

In the industry sector, the NZE plan advocates using green hydrogen, biomass, and CCUS in the steelmaking, chemical, and cement industries, starting in 2040. This study advocates using CCS in these industries as soon as possible and using blue hydrogen in the medium future. Green hydrogen is produced by electrolysis of water using renewable electricity, whereas blue hydrogen is produced from either coal by coal gasification or natural gas by steam methane reforming, with CCS used to mitigate the produced CO_2 [65,67]. In 2020, Taiwan emitted 65 Mtpa CO_2 from steel and iron mills, 17 Mtpa CO_2 from cement factories, and 17 Mtpa CO_2 from refineries (Figure 21). These are also targets for CCS, to be implemented as soon as possible. In the medium term, use of blue hydrogen to decarbonize steelmaking and cement industries is preferred. Furthermore, in this study, CCS will play an important role due to its high technology-readiness level, while the role of CCU may be limited until its technology-readiness level is increased by more R&D.

8. Role of CCS in Decarbonization

CCS has an important role to play in the ongoing energy transition [67]. The International Energy Agency (IEA), Intergovernmental Panel on Climate Change (IPCC), and International Renewable Energy Agency (IRENA) have all stated that reaching a net-zero emissions economy will be impossible without CCS [75–77].

As of 2020, there were 28 large-scale CCS projects in operation worldwide, storing a total of 41 Mtpa CO_2 [78], and more are being planned. Actual CCS projects being planned in Europe include the Longship project with a CCS target of 0.8–5.0 Mtpa CO_2 [69,70], the UK's East Coast Cluster project (27 Mtpa CO_2) [79] and Acorn project (5–10 Mtpa CO_2) [80], and the Netherlands' Porthos CCS projects (2.5 Mtpa CO_2) [81].

Recently, Zhang et al. (2022) estimated that there is 416 Gt of CO_2 storage capacity in India, with 99% residing in saline aquifers. This is enough to store two centuries of CO_2 emission from the power and industry sectors [82]. Bokka et al. (2022) estimate there is 141 Gt of subsurface CO_2 storage capacity in the western states of Maharashtra and Gujarat in India, which is enough to store four centuries of CO_2 emission from these states [83]. Zhang and Lau (2022) estimate there is 386 Gt of subsurface CO_2 storage capacity within a 1000 km radius from Singapore, which is enough to store one century of stationary CO_2 [84]. Zhang et al. (2022) estimate there is 79 Gt of subsurface CO_2 storage capacity in Thailand which is enough to store 554 years of stationary CO_2 emissions [85].

These authors have proposed establishing regional CCS corridors to facilitate implementation of CCS projects by using economies of scale [86]. Recently, the Indonesian government has been planning to install CCS in the depleted giant Arun gas field in North Sumatra [87,88].

Zhang et al. (2022) recently estimated that there is 3.6 Gt of CO_2 storage capacity in saline aquifers in the West Taiwan basin, which can serve as storage sites for anthropogenic CO_2 emission from the west coast of Taiwan [59]. Future work is needed to characterize these saline aquifers with respect to reservoir temperature and pressure, porosity, permeability, connectivity, seal integrity, reservoir boundaries, and existence of nearby faults. Reservoir simulations on pressure buildup and CO_2 plume migration during CO_2 injection will also be needed before field implementation. Nonetheless, such work is common in field development planning of oil and gas projects. In the NZE plan, CCS will be deployed beginning in 2040. In this study, we propose deploying CCS at scale as soon as possible, as it will play a critical role in Taiwan's decarbonization.

9. Energy Policy Implications

9.1. Promulgating a Credible Carbon Tax

Taiwan currently has neither a carbon tax nor a carbon credit, although one is being planned for 2022. In Asia, Singapore is the only country with a carbon tax of USD 3.6/ton, which will be increased to USD 18/ton in 2024 and then USD 36–57/ton in 2030 [89]. Promulgating a credible carbon tax is the first step towards incentivizing companies, including state-owned utility companies, to reduce CO_2 emission [22]. Revenue from the carbon tax can also be used to fund R&D in low-carbon technologies. However, it will take strong political will to impose a credible carbon tax. It is no wonder that countries that are planning large-scale implementation of CCS projects are those with the highest carbon tax [69,70,80,81].

9.2. Switching from Coal to Gas in Power Generation

Switching from coal to gas should be a key component of Taiwan's energy transition plan. One major difference between the plan proposed by this report and the NZE plan is the role of gas in the energy transition. In the NZE plan, coal-fired power plants will be replaced by renewable power plants, mostly by wind and solar PV. In this study, they will be replaced mostly by gas-fired power plants equipped with CCS and secondarily by renewable power plants. Our proposal is based on our estimate that future increase in wind and solar PV capacities will be slower than that proposed by the NZE plan due to technology readiness and sustainability issues discussed earlier.

However, large-scale increase in gas-fired power plants will require building more LNG import terminals and acquiring additional long-term LNG contracts. It is also beneficial from an energy security viewpoint for Taiwan to diversify its LNG sources, e.g., by increasing its share of LNG import from the US.

9.3. Implementation of Clean Coal Technologies in Existing Coal-Fired Power Plants

The average age of Taiwan's 20 coal-fired power plants is 19 years [90]. Only five of them use supercritical or ultra-supercritical technologies. The rest use subcritical technologies. Since it will take almost 30 years to totally phase out all of these coal-fired power plants, implementing CCTs such as supercritical steam, ultra-supercritical steam, IGCC, and pressurized fluidized bed combustion can reduce CO_2 emission significantly. The Taichung and Mailiao coal-fired power plants are the biggest CO_2 emitters using subcritical technologies. They are prime targets for CCTs.

9.4. Funding R&D in CCS

The decarbonization roadmap proposed by this report and the NZE plan both rely on CCS to mitigate CO_2 emitted from fossil power and industry plants. However, in the roadmap proposed by this study, CCS will be implemented as soon as possible, whereas the NZE roadmap calls for CCS to be installed beginning in 2040. Since CCS is the key enabling technology for the power and industry sectors, public funding of CCS R&D is important. Much of the needed research will include detailed characterization of offshore saline aquifers on the West Taiwan Basin and identification of the candidate aquifers for CO_2 storage. Geophysical, petrophysical, and reservoir data collection will be needed. In addition, creation of static and dynamic reservoir models will be needed to determine the storage capacity, well injectivity, and number of wells needed.

9.5. Installing CCS in Fossil Fuel Power Plants and Industrial Plants as Soon as Possible

Beyond CCTs, CCS will also be needed to achieve near-zero emissions. In fact, CCS is the only mature technology that can mitigate CO_2 at the scale of millions of tons per year [65]. Our plan calls for implementing CCS as soon as possible, whereas the NZE plan stipulates CCS beginning in 2040. CCS implementation can be facilitated through use of CCS hubs, passing of CO_2 injection regulations, raising acceptance of CCS by public engagement, funding CCS R&D, and using private–public partnership for financing and project management [67]. Public sector leadership in all these areas will be important.

9.6. Funding R&D in Offshore Wind

Among various forms of renewable energies, offshore wind has the highest potential to be applied on a large scale in the future. However, technology breakthroughs are needed in a number of areas, including typhoon-resilient wind turbines, high-voltage subsea cable design, floating structures beyond 120 m water depth, and smart grid integration [71,91]. Furthermore, sustainability issues related to offshore wind such as impact on marine life and coastal communities need to be resolved.

9.7. Delaying Phaseout of Nuclear Power

If all nuclear power plants are to be phased out by 2025 according to the NZE plan, Taiwan will probably face a shortage of electricity supply, as there will be inadequate addition of solar PV and wind capacity to replace nuclear capacity [55]. Consequently, gradually phasing out nuclear power plants by 2050 is recommended by this study.

9.8. Formulating a Hydrogen Strategy

Taiwan needs a hydrogen strategy as part of its decarbonization roadmap. To guide future public and private investment in hydrogen, this strategy should stipulate the form of hydrogen, its use in various sectors, need for hydrogen infrastructure, and routes for either domestic manufacturing or importing of hydrogen. As of 2020, ten countries have announced their hydrogen strategy [86]. It is expected that global production of hydrogen will increase from 88 Mt in 2020 to 212 Mt in 2030 [92].

10. Discussion

Based on a detailed analysis of the status of fossil and non-fossil energies in Taiwan and technology screening considering sustainability, security, affordability, technology readiness, and technology impact, this study proposes a decarbonizing roadmap for Taiwan different from the NZE plan. It calls for (1) a delayed phaseout of nuclear power until 2050, (2) implementing CCT in existing coal-fired power plants, (3) accelerating CCS implementation in the power and industry sectors, (4) more reliance on gas than wind and solar PV to replace coal and nuclear in electricity generation, and (5) use of blue instead of green hydrogen for decarbonizing the transport and industry sectors. In addition, implications of this roadmap for future R&D and energy policies are discussed.

Our work differs from previous studies in several aspects. First, we screen applicable decarbonization technologies on not one but six categories: sustainability, security, affordability, reliability, technology readiness, and technology impact. This approach is more comprehensive than that found in previous studies. Second, we estimate the likelihood of large-scale application of each technology based on issues identified from this screening. As a result, we find out that further implementation of onshore wind is limited by available land. Implementation of offshore wind awaits development of typhoon-resistant designs and availability of local expertise. Solar PV suffers from availability of suitable land and a low capacity factor. Further application of bioenergy suffers from competition for arable land and a lack of biocrop industry. Green hydrogen is, in the near to medium future, too expensive to be widely used, thus making blue hydrogen a good candidate for decarbonizing hard-to-decarbonize industries. Third, we analyze the published NZE plan and find that it requires an AAGR of 10.1% for renewable power generation. We estimate this is unlikely to be happen, given the issues identified for wind and solar PV. We therefore propose an alternative roadmap based on a more achievable 7% AAGR in renewable electricity generation. We then draw policy implications from the proposed roadmap. It is hoped that this proposed roadmap will contribute to the ongoing debate on choosing the energy transition roadmap to enable Taiwan to achieve net-zero by 2050.

11. Conclusions

The following conclusions can be made from this study.

1. Twenty decarbonization technologies have been screened for sustainability, security, affordability, reliability, technology readiness, and technology impact. Results show that for the power sector, the technology with the highest potential is GP-CCS. This is followed by coal→gas, CP-CCS, clean coal, and nuclear. For the transport sector, EV has the highest potential, followed by HFCV. For the industry sector, the technology with the highest potential is Ind-CCS. This is followed by gas→H_2-CCS.
2. Based on these findings, a decarbonization roadmap for the power sector is proposed. This roadmap requires a 7% AAGR in renewable electricity generation, which is more achievable than the 10.1% required by the NZE plan.
3. In the power sector, the proposed roadmap improves on the NZE plan in the following aspects: (1) using clean coal technologies in existing coal-fired power plants, (2) relying more on gas than solar PV and wind in replacing coal and nuclear, (3) bringing forward CCS, and (4) delaying phaseout of nuclear until 2050.

4. For the transport sector, the major difference between the two roadmaps is the use of HFCV, H_2-marine, and bio-aviation in the medium future in the roadmap proposed by this study. Both roadmaps advocate EVs as the major decarbonization method.
5. For the industry sector, the major differences between the roadmaps are (1) bringing forward CCS to decarbonize industrial plants and (2) using blue instead of green hydrogen for long-term decarbonization.
6. Energy policy implications from this study include (1) promulgating a credible carbon tax, (2) switching from coal to gas for power generation, (3) implementing clean coal technologies in existing coal-fired power plants, (4) funding R&D in CCS and offshore wind, (5) implementing CCS in existing fossil power and industry plants as soon as possible, and (6) delaying phaseout of nuclear energy until 2050.

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Nomenclature

AAGR	Average annual growth rate
Bio	Bioenergy
Bio-aviation	Biofuels for aviation
Blue hydrogen	Hydrogen produced from fossil fuels with CCS
CCS	Carbon capture and storage
CCT	Clean coal technology
CCU	Carbon capture and utilization
Coal→gas	Replacing coal by gas for power generation
Coal→H_2-CCS	Hydrogen production by coal gasification with CCS
CO_2	Carbon dioxide
CO_2-EGR	Carbon dioxide enhanced gas recovery
CO_2-EOR	Carbon dioxide enhanced oil recovery
CP-CCS	Coal-fired power plant with carbon capture and storage
EGR	Enhanced gas recovery
EOR	Enhanced oil recovery
EV	Electric vehicle
Gas→H_2-CCS	Hydrogen production by methane steam reforming with CCS
GDP	Gross domestic product
Geo	Geothermal energy
GP-CCS	Gas-fired power plant with CCS
Green H_2	Hydrogen produced by electrolysis with renewable electricity
Gt	10^9 ton
GWh	10^9 Wh
H_2	Hydrogen
H_2-marine	Hydrogen as fuel for ships
Hydro	Hydropower
ICE	Internal combustion engine
IGCC	Integrated gasification combined cycle
Ind-CCS	CCS in industrial plants
HFCV	Hydrogen fuel cell vehicle
Mtpa	10^6 tons per year
MW	10^6 W
NZE	Net-zero emissions
PEC	Primary energy consumption
RE	Renewable energy

Solar PV	Solar photovoltaic
TPES	Total primary energy supply
TWh	10^{12} Wh
Wind	Wind energy

Appendix A. Technology Ranking Criteria

Table A1. Description of sector-specific decarbonization technologies.

Sector	Technology	Description
All	Green H_2	Hydrogen produced from electrolysis of water by renewable electricity
	CCU	Converting captured CO_2 to chemicals or products
Power	Nuclear	Nuclear power plant
	Hydro	Hydroelectricity
	Solar PV	Solar photovoltaic for on-grid electricity generation
	Bioenergy	Bioenergy for electricity generation
	Onshore wind	Onshore wind turbine for electricity generation
	Offshore wind	Offshore wind turbine for electricity generation
	Geothermal	Geothermal power plant
	Coal→gas	Switching from coal to gas for thermal power generation
	CP-CCS	Using CCS to capture and store CO_2 emitted from a coal-fired power plant
	GP-CCS	Using CCS to capture and store CO_2 emitted from a gas-fired power plant
	Clean coal technologies	Supercritical or ultra-supercritical technologies to reduce CO_2 emission in coal-fired power plants
Transport	EV	Electric vehicle
	HFCV	Hydrogen fuel cell vehicle
	H_2-marine	Hydrogen as fuel for ships
	Bio-aviation	Biofuels as fuel for planes
Industry	Ind-CCS	Using CCS to capture and store CO_2 emitted from an industrial plant
	Coal→H_2-CCS	Blue hydrogen generated from coal gasification (with CCS) for use in heating and/or feedstock in an industry plant
	Gas→H_2-CCS	Blue hydrogen generated from steam methane reforming (with CCS) for use in heating and/or feedstock in an industry plant

Table A2. Ranking criteria for CO_2 emission and material footprint.

Category	Low	Medium	High
CO_2 emission (kg/kWh)	<0.37	0.37 to 0.45	>0.45
Material footprint (t/TWh)	<1000	1000 to 2000	>2000

Notes: For benchmarking, CO_2 emissions from US coal-, gas-, and oil-fired power plants are 1.011, 0.413, and 0.966 kg/kWh, respectively [93]. Material footprints for gas- and coal-fired power plants are 572 and 1185 t/TWh, respectively [94].

Table A3. Ranking criteria for impact on people and environment. Green, yellow and red colors signify low, medium, and high impact, respectively.

Consequence			Increasing Probability		
Severity	**Impact on People**	**Impact on Environment**	**Has Occurred in Industry**	**Has Occurred in Taiwan**	**Occurred Several Times a Year in Taiwan**
0	Zero injury or impact	Zero impact	Low	Low	Low
1	Slight injury or impact	Slight impact	Low	Low	Medium
2	Minor injury or impact	Minor effect	Low	Medium	Medium
3	Major injury or major impact	Local effect	Medium	Medium	High

Table A3. *Cont.*

Consequence			Increasing Probability		
Severity	**Impact on People**	**Impact on Environment**	**Has Occurred in Industry**	**Has Occurred in Taiwan**	**Occurred Several Times a Year in Taiwan**
4	Single fatality or single major impact	Major effect	Medium	High	High
5	Multiple fatalities or massive impact	Massive effect	Medium	High	High

Table A4. Ranking criteria for impact on animals. Green, yellow and red colors signify low, medium, and high impact, respectively.

Consequence		Increasing Probability		
Severity	**Impact on Animals**	**Has Occurred in Industry**	**Has Happened in Taiwan**	**Has Happened Multiple Times in Taiwan**
0	Zero injury	Low	Low	Low
1	Slight injury	Low	Low	Medium
2	Single fatality	Low	Medium	Medium
3	Multiple fatalities	Medium	Medium	High
4	Single fatality to endangered species	Medium	High	High
5	Multiple fatalities to endangered species	Medium	High	High

Tables A3 and A4 are similar to risk assessment matrix for evaluating health, safety, and environmental risks commonly used in the oil and gas industry [95].

Table A5. Criteria for energy quadrilemma ranking.

Category\Ranking	Low	Medium	High
Security	Lacking in domestic energy resources	Some domestic resources but import needed	Sufficient domestic resources to be import independent
Affordability	Too expensive to be applied on a large scale	Due to high cost, application is limited in scope	Readily affordable for application on a large scale
Sustainability	Ranked high in any category in Tables A2–A4	Ranked medium in any category in Tables A2–A4. No category ranked low in Tables A2–A4	Ranked low in all categories in Tables A2–A4
Reliability	<20% capacity factor	20–40% in capacity factor	>40% capacity factor

Table A6. Criterion for ranking in technology readiness and impact.

Category	Sector\Ranking	Low	High
Technology readiness	All	Never or unlikely to be used	Used or readily used based on results from other countries
Technology impact	Power	Low degree of power generation	High degree of power generation
	Transport	Usable in some vehicles, ships, or planes	Usable in most vehicles, ships, or planes
	Industry	Usable in some industrial plants	Usable in most industrial plants

Table A7. Capacity factor for Taiwan's power plants according to authors' estimates using data from Reference [24].

Coal	Gas	Oil	Wind	Solar PV	Hydro	Bio	Nuclear
78%	55%	30%	28%	11%	20%	57%	83%

Appendix B. Technology Ranking Results

Table A8. Material footprint for various electricity generation technologies [94].

Materials (ton/TWh)	Gas	Nuclear	Biomass	Coal	Geo-Thermal	Wind	Hydro	Solar PV
Aluminum	1	0	6	3	100	35	0	680
Cement	0	0	0	0	750	0	0	3700
Concrete	400	760	760	870	1100	8000	14,000	350
Copper	0	3	0	1	2	23	1	850
Glass	0	0	0	0	0	92	0	2700
Iron	1	5	4	1	9	120	0	0
Lead	0	2	0	0	0	0	0	0
Plastic	0	0	0	0	0	190	0	210
Silicon	0	0	0	0	0	0	0	57
Steel	170	100	310	3300	3300	1800	67	7900
Total	572	870	1080	5261	5260	10,260	14,068	16,447

Table A9. Results of sustainability screening for Taiwan. Green, yellow and red colors signify low, medium and high impact, respectively.

Sector	Technology	CO_2 Emission	Material Footprint	Impact on People	Impact on Animals	Impact on Environ.
Power	Green H_2	None	High due to power from wind or solar	Low	Low for solar power; Medium for wind power	Low for solar power; Medium for wind power;
	CCU	Minimum	Depends on technology	Low	Low	Low
	Nuclear	None	Low(Table A8)	Medium (Chernobyl, 1986; Fukushima, 2011 [96,97])	Medium (Chernobyl, 1986; Fukushima, 2011 [96,97])	Medium (Chernobyl, 1986; Fukushima, 2011 [96,97])
	Hydro	None	High (Table A8)	Medium (Teton Dam, USA, 1976 [98])	Medium (Teton Dam, USA, 1976 [98])	Medium (Lawn Lake Dam, USA, 1982 [99])
	Solar PV	None	High (Table A8)	Low	Low	Medium (Used panels are solid waste per US EPA [100])
	Onshore wind	None	High (Table A8)	Low	Medium (Avian death [45])	Medium (Turbine blades cannot be recycled [101])
	Offshore wind	None	High (Table A8)	Low	Medium (Avian death; endangered Indo-Pacific humpback dolphin [34])	Medium (Turbine blades cannot be recycled [101])
	Bio	Minimum	Medium (Table A8)	Medium (1st generation biocrop affects food security)	Medium (affects biodiversity due to changed land usage)	Medium (Clearing of forest for biocrop will have major impact)
	Geothermal	Minimum	High (Table A8)	Low	Low	Low
	Coal→gas	Medium (0.41 kg/kWh)	Low (Table A8)	Low	Low	Low
	CP-CCS	Minimum	Medium (Table A8)	Low	Low	Low
	GP-CCS	Minimum	Low (Table A8)	Low	Low	Low
	Clean coal	Medium (0.37–0.45 kg/kWh)	Medium (Table A8)	Low	Low	Low
Transport	EV	None	High (226t of material extracted per EV battery [102])	Low	Low	Low
	HFCV	Minimum (assuming blue or green H_2)	Low (assuming blue H_2)	Low (assuming blue H_2 or green H_2 from solar or wind electricity)	Low (assuming blue H_2 or green H_2 from solar PV)	Low (assuming blue H_2)
	H_2-marine	Minimum (assuming blue or green H_2)	Low (assuming blue H_2)	Low (assuming blue H_2 or green H_2 from solar or wind electricity)	Low (assuming blue H_2 or green H_2 from solar PV)	Low (assuming blue H_2)
	Bio-aviation	Minimum	Medium (Table A8)	Medium (1st-generation biocrop affects food security)	Medium (Changed land usage affects biodiversity)	Medium (Clearing of forest for biocrop may have major impact)
Industry	Coal→H_2-CCS	Minimum	Medium (Table A8)	Low	Low	Low
	Gas→H_2-CCS	Minimum	Low (Table A8)	Low	Low	Low
	Ind-CCS	Minimum	Low	Low	Low	Low

Notes: For CO_2 emission column, "none" means no CO_2 emission, "minimum" means a small amount of emission. For material footprint column, Table A8 is used for various type of electricity generation technologies [93]. For impact on people and environment columns, screening criteria in Table A3 are used. For impact on animals column, screening criteria in Table A4 are used.

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