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Analysis of Low Carbon Power Infrastructure of Taiwan

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ABSTRACT

Global warming that is caused by GHG emissions is by far the most important issue faced by humanity. The "Intergovernmental Panel on Climate Change Committee (IPCC)" and Taiwan's government have developed carbon dioxide emissions standards for 2025 and 2030 respectively. The generation of carbon dioxide in power generation is the greatest source of GHG in Taiwan. Based on a variety of data on Taiwan's energy use and the power development plan that have been announced by the BOEMOEA (Bureau of Energy, Ministry of Economic Affairs), this study presents seven power generation scenarios for Taiwan in the years 2025 and 2030 that involve 12 classes of power plants. A program for analyzing the low-carbon power infrastructure of Taiwan is developed to analyze the above seven scenarios to optimize the combination of power plants that can perform well in terms of performance indices—"generation", "emissions", "reserve capacity ratio", and "power generation cost". Reducing carbon emissions involves severe challenges. If by 2025 or 2030, the installed capacity of nuclear power plants cannot be increased to 22.4 GW by on-site-extension or fossil-fueled power plants with "carbon capture and storage (CCS)" technology fail to operate commercially, then no power generation scenario will reach the carbon abatement targets for those years.

Keywords: Power Supply Infrastructure; GHG Emission Abatement; Scenario Analysis; Cost Optimization; Taiwan

1. Global Warming and Emissions Abatement Plans

In recent years, the topic of global warming has attracted people's attention all over the world, and numerous governments have been investing significant resources in the abatement of carbon dioxide emissions. Since the Industrial revolution in 1860, the instruments that are used to measure the surface temperatures of the ground and the sea around the world have been consistently showing global warming [1]. Taking 1905 as the base year, the average temperature of the Earth's surface varied widely with an amplitude of about 0.2 degrees Celsius in the preceding 1000 years, but after 1905, the temperature sharply rose. By the year 2005, the average temperature had risen by 0.74 degrees Celsius [2]. According to various methods of experimental detection, the average surface temperature of the Earth is increasing at a rate of about 0.03 degrees per year [3].

The results of a study concerning the years 2000-2006 indicate that global annual carbon emissions due to human activities were 9.1 billion tons (equivalent to 33.4 billion tons of carbon dioxide), of which emissions from the combustion of fossil fuels were responsible for 7.6 billion tons; the remaining 1.5 billion tons were emitted as a result of changes in land-use. During the same period, the carbon that was emitted into the atmosphere, 2.8 billion tons was absorbed annually by vegetation and soil, 2.2 billion tons entered the ocean, and the other 4.1 billion tons remained in the atmosphere. Accordingly, in recent years, around 45% of carbon dioxide emissions caused human activities could not be absorbed by the oceans, soil or vegetation, and this proportion is increasing. The greenhouse effect has been mostly responsible for a marked worsening of global weather [4].

Within the 1000 years before the year 1750, when the industrial revolution began, the concentration of carbon dioxide in the atmosphere had remained steady at 280 ppm. However, the concentration of carbon dioxide slowly increased after 1750, rising to 381 ppm in 2006; the rate of increase between 2000 and 2006 was 1.93 ppm/yr [4]. The concentration in 2006 was not only the highest in 650,000 years [5], but also may possibly the highest in the past 20 million years [6]. According to the latest observations made by the National Atmospheric and Oceanic Administration of the United States, the concentration of carbon dioxide in the atmosphere reached 388 ppm in 2010.

In 2010, the total emissions of GHGs globally reached about 47 billion tons of carbon dioxide equivalents (CO_2e).

Based on various possible scenarios of economic development and population growth globally over the next few decades, IPCC has generated various estimates of carbon emissions. One of the most optimistic emission scenarios (B1) for 2030 involves global total emissions of 54 billion tons of carbon dioxide equivalents (CO_2e), falling to 23 billion tons in 2100 [7].

When this B1 emission scenario is simulated using 19 meteorological models, the Earth's surface temperature in the year 2100 is found to rise by 1.4 - 2.9 degrees Celsius from that in 1980 to 2000 [8]. The World Climate Conference that was held in Copenhagen at the end of 2009 designated "2˚C" as the target cap on global warming, with a view to mitigating the impact of global warming on human survival. The B1 scenario requires 40 billion tons of global carbon emissions in 2030 [7]. Since the global population is estimated to be 8 billion people in 2030 [9], the global carbon dioxide emissions must be limited to 5 tons/person. The B1 scenario will maintain a carbon dioxide concentration of 550 ppm in the atmosphere.

In 2007, the average annual carbon dioxide emissions per capita in Taiwan were 12 tons. To meet the IPCC's 2030 target of global emissions of 5 tons per capita, Taiwan must reduce its total emissions by 58.3% from 2007 to 2030.

In 2008, Taiwan's government released "Sustainable Energy Development Guidelines". These guidelines propose that a sustainable energy policy should have three main foundations. They are the efficient use of limited resources, the development of environmentally friendly clean energy, and the ensuring of a stable energy supply. With respect to the development of clean energy, an emissions standard was formulated: the carbon dioxide emissions in 2025 should be at the level that prevailed in 2000.

Based on this standard, the average annual emissions of Taiwan must reduce to 9.5 tons per capita in 2025. This reduction is equivalent to an abatement of 20.8% between 2007 and 2025. Obviously, this emissions standard is much looser than that in the B1 scenario of IPCC for 2030.

According to an analysis of Taiwan's GHG emissions, "power generation" is the largest source of emissions in Taiwan. This study will set 2025 and 2030 as the two target years, corresponding to the standards set by the "Sustainable Energy Development Guidelines" and "IPCC's B1 Emissions Scenario", respectively. Under the constraint of minimal cost, this study will optimize Taiwan's low-carbon optimal power generation infrastructure to satisfy the power demand in the future in terms of both amount of power generated and reserve capacity ratio.

2. Emissions of Various Power Generation Facilities

To meet the ISO14000 Standard, the "Life Cycle Assessment (LCA) Method", or the so-called "Cradle to Grave Method" is adopted in this study to calculate the carbon emissions from all power facilities. The LCA calculation considers the GHGs that are emitted from all energy sources throughout the manufacturing chain, including the mining, refining, processing, and transportation of material, as well as energy consumption or generation, including associated operations, maintenance, and downtime, for example.

Please refer to **Table 1**. Although no GHG is emitted during the generation processes associated with solar PV, ocean energy, hydropower, wind power, and other renewable sources, some GHGs are nevertheless released in the manufacturing of turbines, solar panels and so on. Accordingly, renewables can be regarded as low-carbon energy sources.

Solar photovoltaic: the manufacture of solar panels requires the extraction of silicon from quartz at high temperature, which process consumes 60% of the energy consumed in the entire process [10]. Existing technologies emit around about 58 g-CO_2/kWh of PV power generated, which value is expected to fall to 15 g-CO_2/kWh in the future.

Ocean power (wave and tidal): no data on comercialized marine products are yet available; most carbon dioxide is produced in the steel-making process; today, manufacturing a set of wave energy converters requires 665 tons of steel (with a rated power of 750 kW); the

Table 1. The emissions of various power generation technologies.

Type of power plant	Emissions (g-CO_2/kWh)
Solar PV	58
Ocean energy	50
Hydro power	5
Wind power (offshore)	5.3
Wind power (onshore)	4.6
Biomass (*Miscanthus sinensis*)	80
Biomass (wood dust)	25
Nuclear power	5
Coal-fired (IGCC)	800
Coal-fired + CCS	125
Oil-fired	650
Gas-fired	400
Gas-fired + CCS	250

emissions are approximately 50 g-CO_2/kWh; this value is expected to fall to 15 g-CO_2/kWh [10].

Hydropower: its carbon emissions are associated with two sources, which are storage facilities (such as dams, whose construction involves the emission of about 10 g-CO_2/kWh) and power facilities (such as turbines, which emit 3 g-CO_2/kWh). The emissions associated with the storage facilities are higher, because their construction requires large amounts of concrete and steel. Hydropower is an energy option with low carbon emissions, because operating hydropower facilities emit only small amounts of carbon dioxide, but rotted plants in the water release methane [10].

Wind power: about 98% of carbon emissions associated with wind power occur in the construction process, because the manufacture and construction of the tower frame, foundation and blades require steel, cement, glass fiber and resin. During operation, the lubricant and transportation required for maintenance are associated with carbon emissions [10]. According to the life cycle assessment of wind generation facilities, the carbon emissions associated with onshore wind turbines are around 4.6 g-CO_2/kWh, while those associated with offshore wind turbines are approximately 5.3 g-CO_2/kWh (partially owing to their larger foundations) [10].

Biomass power: this source is regarded as a "carbon-neutral" source of energy, because the carbon dioxide that is released during the combustion of biomass fuels equals that absorbed by the plant during its growth period. However, if the fertilizers that are required in the growth period of the plant are considered, then biomass can still only be regarded as low-carbon source of energy. Hence, a preferable source of biomass is an energy crop with a short growth period, such as shrub willow, grass, *Miscanthus sinensis*, straw and wood dust. Since energy crop has a low energy density, the transport of a large amount of biomass is associated with significant carbon dioxide emissions per unit of energy produced. The emissions associated with the generation of power by the combustion of *Miscanthus sinensis*, gasified wood dust, and straw are about 80 g-CO_2/kWh, 25 g-CO_2/kWh, and 230 g-CO_2/kWh, respectively. To estimate the emissions associated with biomass in Taiwan, consider *Miscanthus sinensis* as the only biomass crop that is cultivated in land that is suitable for any biomass crop: the planting area would be around 2580 km^2, and thus would yield approximately 9.23×10^6 tons/year of wood dust and straw [11].

Nuclear power generation: the emissions per unit power generation are about 5 g-CO_2/kWh. Nuclear power plants offer exceptional emission abatement—especially when operated as base load power plants. Because no fuel is combusted, its operational emissions account for less than 1% of all associated emissions. Most of its carbon emissions are associated with uranium-mining (40%), -enrichment, and fuel preparation; down-time accounts for about 35% of emissions [10].

Coal-fired power plant: coal is the largest emission source among all thermal power plants. If Taiwan were to introduce coal-fired power plants with IGCC (Integrated Gasification Combined Cycle)—a new gasification technology with combined cycles, their emissions would be around 0.8 kg-CO_2/kWh [10].

Oil-fired power plant: emissions from oil are next to those from coal-fired power plants, at approximately 0.65 kg-CO_2/kWh. Owing to the volatility of international oil prices, existing oil-fired power plants are slowly being replaced by coal-fired or gas-fired power plants that feature CCS, to reduce financial risk.

Gas-fired power plant: such plants rank third in emissions per unit power generation, at about 0.4 kg-CO_2/kWh [10]. Emissions per unit power generation by municipal waste incineration are around 1.36 kg-CO_2/kWh.

Table 1 presents the above data.

3. Taiwan's Low-Carbon Electricity-Generating Options and Taipower's Power Supply Plan

According to the Energy Statistics Handbook 2009 [12], published by the BOEMOEA, the demand side of the domestic energy structure still mainly comprises fossil fuels, such as coal and coal products (30.45%), crude oil and petroleum products (51.82%), and natural gas (8.62%). Scientists have identified GHGs—mainly carbon dioxide that is produced by burning fossil fuels—as the main cause of global climate change. Taiwan's emissions in 2009 totaled about 240 Mt (million metric tons) in carbon dioxide equivalents, accounting for around 1% of global emissions. This statistic and Taiwan's annual emission growth rate of more than 5.9% over the past 20 years are quite shocking. Renewable energy is non- or low-polluting sustainable energy. Unfortunately, the proportion of renewable energy on the supply side in Taiwan is still very low—only 0.26% for hydro power, and only 0.06% for solar photovoltaic and wind power. Furthermore, since most of the aforementioned fossil fuels are imported, mostly from politically unstable countries in the Middle East or Southeast Asia, security of energy supply is a serious concern for Taiwan.

Based on existing data and assessment of Taiwan's current situation, the low-carbon power options available to Taiwan are renewable energy, coal-fired and gas-fired power plants with CCS and nuclear power plants. The reserves of relevant resources and the feasibility of the future development of these forms of power generation (plants) are described below.

3.1. Renewable Energy Power Plants

Please refer to **Table 2**. According to the results of Chen

Table 2. Statistics of the power potential of renewable energy reserves in Taiwan (in kWh/d/p).

	Solar	Wind	Biomass	Marine	Geothermal	Hydro	Total
Reserves	24.27	29.90	1.82	4.57	0.67	16.79	78.02
Proportion	31.3%	38.3%	2.3%	5.8%	0.8%	21.5%	100%

et al. [11], the reserves of renewable energy in Taiwan are 24.27 kWh/d/p of solar energy, 29.9 kWh/d/p of wind energy, 1.82 kWh/d/p of biomass energy, 4.57 kWh/d/p of marine energy, 0.67 kWh/d/p of geothermal energy, and 16.79 kWh/d/p of hydro energy. The total reserved power is 78.02 kWh/d/p—2.86 times the total electricity that was generated in Taiwan in 2009 (27.32 kWh/d/p). Indeed wind alone could supply all necessary power to Taiwan. However, various technical and implementation difficulties must be overcome, and an optimistic target year for the full development of these potential energy sources is 2050, which is far into the future. At that time, Taiwan will require four times as much energy as it required now, (based on the global average predicted by Energy Technology Overlook 2008, IEA,) because of economic development. However, the total renewable energy reserves will still be approximately 70% of the required energy supply, and so will remain very important.

3.2. Coal-Fired + CCS and Gas-Fired + CCS Power Plants

In 2009, the installed capacities of coal-fired power plants in Taiwan were 17.9 GW, or 37.35% of the total installed capacity. These plants generated 122.53 billion kilowatt-hours of electricity. The highest efficiency of a coal-fired power plant is near 50%, which value is expected to reach 55% in the future [13]. However, coal-fired power plants around the world have an average efficiency of only around 31%, leaving much room for improvement. In the 19th century, the emissions of the first coal-fired generators were 37 kg-CO_2/kWh and their efficiency was only 1%. The emissions of today's coal-fired power plants are approximately 1.2 kg-CO_2/kWh [13]. Efficiency can be further improved by increasing the temperature and pressure of the steam, correspondingly reducing emissions. To reduce significantly the emissions from a coal-fired power plant, carbon capture and storage (CCS) can be utilized. CCS technology can reduce the carbon emissions of a traditional coal-fired power plant by 80% - 90% but it increases energy consumption by 10% - 40%. Pulverized coal-fired power plants have a 24% - 40% lower energy efficiency than conventional plants and IGCC power plants have a 14% - 25% lower efficiency.

In 2009, Taiwan had gas-fired power plants with installed capacities of 14.8 GW, accounting for 30.77% of the domestic installed capacity. They generated 46.742 billion kilowatt-hours of electricity. The emissions from a single-cycle gas-fired power plant are 0.63 kg-CO_2/kWh, while those from a natural gas combined cycle (NGCC) plant are about 0.4 kg-CO_2/kWh. The gas-fired power plants with CCS are less efficient in carbon abatement than the coal-fired power plants with CCS. For example, the emissions from a "NGCC + CCS" power plant are reduced to only around 0.25 kg-CO_2/ kWh [10]. The NGCC power plant has an efficiency of 50.8%, and the "NGCC + CCS" has an efficiency of 43.7%. Introducing CCS causes an NGCC power plant to consume 11% - 22% more energy.

3.3. Nuclear Power Plant

Currently, three nuclear power plants are operating in Taiwan, with a total installed capacity of 5.14 GW, accounting for 10.72% of the domestic installed power generation capacity. In 2009, the nuclear power plants in Taiwan generated a total of 41.571 billion kilowatt-hours of electricity. The installed capacity of the planned fourth nuclear power plant will be 2.7 GW. After this fourth plant has been constructed, if the service lives of all existing nuclear power plants are extended, the total installed capacity of nuclear power plants will reach 7.84 GW. If a more aggressive plan is implemented, then new generators with an additional capacity of 14.6 GW may be installed at the original sites, which, together with the 7.84 GW already specified, will yield a total installed nuclear power generation capacity in Taiwan of 22.4 GW.

3.4. Long-Term Power Development Planning of BOEMOEA

This study takes 2025 and 2030 as the two target years to meet domestic and global emissions standards, respectively. A rigorous mathematical model is utilized to plan the optimal power generation infrastructure (including 12 classes of power generation facility) that will yield the required "generation", "emissions", "reserve capacity ratio", and "total cost" in Taiwan in the future. To minimize the impact on the existing power infrastructure, the long-term power development plan that was originally announced by BOEMOEA is adopted as a planning basis, and is referred to here as the "BAU (Business As Usual)" power infrastructure.

In February 2010, the BOEMOEA published "Taiwan's long-term power load forecast and power development planning summary report" ("Power Planning Report" hereafter). Based on the various factors—growth of power demand, mix of power structure, stability of fuel supply, energy safety, environmental protection, and regional demand-and-supply balance—the power demand and installed capacity for Taiwan in the future were forecast.

From 2010 to 2018, the power supply in Taiwan will grow from 225.58 billion kilowatt-hours to 372.2 billion kilowatt-hours, with an average annual growth rate of 2.82%. To establish the required power sources in advance, long-term load planning up to 2018 was undertaken. The plans include installed capacity of each kind of power plant, such as nuclear power plant, fossil-fueled power plant, and renewable energy power plant. Taipower or private industry will have to construct new plants to achieve the goal of adequate long-term power supply.

In March 2010, the BOEMOEA published the "Annual Targets and Penetration of Renewable Energy", which contained a Taiwan blueprint for the installed capacity of the various renewable energy plants from 2009 to 2030. In terms of the installed capacity of renewable energy, this blueprint was more positive than the "Power Planning Report". The planning of renewable power plants (including waste power generation) in the BAU scenario in this study will use the data from the "Annual Targets and Penetration of Renewable Energy", but will include "marine energy", "geothermal" and "hydrogen fuel cell" in "offshore wind power generation", while the planning of the fossil-fueled power plants in the BAU scenario will be based on the "Power Planning Report".

Table 3 details the estimates of the capacities of the 12 types of power generation facility in 2025 and 2030 based on the plans of the BOEMOEA and the BAU scenario. **Table 3** also lists the incremental capacities of various power plants since 2010 (based on the plans of the BOEMOEA and linear estimates).

Table 3. Under BAU scenarios planned by BOEMOEA for 2025 and 2030, the capacities to be installed of various types of power generation facilities (unit: GW) are listed, wherein the fossil-fueled power plants are based on "Power Planning Report", while the renewables power plants are based on "Annual Promotion Goal and Proportion of Renewable Energy".

Type of power plant	Installed capacity in 2009 (GW)	The capacity to be additionally installed (BOEMOEA) (GW)		Total expected installed capacity (BAU) (GW)	
		2010-2025	2010-2030	2025	2030
Coal-fired	17.92	10.32	13.55	28.25	31.47
Coal-Fired + CCS	0.00	0.00	0.00	0.00	0.00
Gas-fired	14.76	3.56	4.68	18.32	19.44
Gas-fired + CCS	0.00	0.00	0.00	0.00	0.00
Oil-fired	4.49	−1.62	−2.12	2.87	2.37
Nuclear	5.14	2.70	2.70	7.84	7.84
Hydro	1.94	0.56	0.56	2.50	2.50
Wind power (onshore)	0.44	0.62	0.72	1.06	1.16
Wind power (offshore)	0.00	1.95	3.30	1.95	3.30
Solar PV	0.01	1.99	2.49	2.00	2.50
Biomass	0.02	0.01	0.01	0.03	0.03
Waste energy	0.79	0.58	0.58	1.37	1.37

4. Optimization of Power Infrastructure

In this study, a program called "Optimization of Low-Carbon Power Infrastructure in Taiwan" is developed. It is firstly applied to determine whether the current power infrastructure plan (BAU scenario) can meet the requirements of "generation", "emissions", and "reserve capacity ratio" for Taiwan in 2025 and 2030. If it cannot, then low-carbon power generation (including gas-fired power generation, renewable power generation, and carbon capture and storage) will have to be added in the BAU scenario within a reasonable range. Once the program has been used to optimize the infrastructure that meets the "generation" requirement, the total "emissions" and "investment cost" are determined.

4.1. Analytical Program

In 2009, nine classes of power generation plant operated in Taiwan. They were coal-fired, gas-fired, oil-fired, nuclear, hydro, onshore wind, solar photovoltaic, biomass, and waste incineration. To ensure feasibility of implementation, the optimal power generating infrastructure for 2025 and 2030 will be based on these nine. Three emerging technologies—"Coal-fired + CCS (Carbon Capture and Storage)", "Gas-fired + CCS", and offshore wind power—will also be considered. To avoid any issues of technological threshold and uncertainties regarding some new power-generating facilities, less mature technologies are not considered. These include marine energy and geothermal, which are power-generating technologies that Taiwan has not yet planned to use.

For a given installed capacity of each type of power plant, the "total generation", "total emissions", "total reserve capacity ratio", and "total power generation cost" of the above 12 classes of power generation facility can be calculated using the proposed program. However, if the installed capacity of each kind of power plant is allowed to vary between given upper and lower bounds, to make the entire structure satisfy constraints on "total generation", "total emissions", "total reserve capacity ratio", and "total reserve capacity ratio", which are automatically calculated by the program, then the "total power generation cost" is the sum of the cost of power generation by each class of power plant with the lowest installed capacity.

If the installed capacity of each kind of power plant is allowed to vary between upper and lower bounds, then the program searches for three constraints on "total generation", "total emissions", and "total reserve capacity ratio" to be satisfied, according to following criteria. First, the installed capacity of each class of power plant will be set to yield the required "total generation", "reserve capacity ratio" and "total emissions". Basically, the calculations should satisfy the constraints as closely as possible, even if they are not totally satisfied, such that the "total power generation cost" of the optimal power generation structure can be determined.

4.2. Calculation of Total Generation

As predicted by the BOEMOEA in 2010, the required power supply in Taiwan in 2025 will be 352.86 billion kilowatt-hours, while the average annual growth rate of the power supply between 2008 and 2018 will be 2.53%. If this average annual growth rate is assumed to be unchanged, then the required power supply in 2030 will be 391.28 billion kilowatt-hours.

The above power development forecasts may be called the BAU scenario. This scenario considers only eight factors, which are economic growth rate, the relative importance of industrial sectors, population growth rate, temperature (climate), electricity prices, demand side management, large-scale development projects or plans, and the price of fuel for power generation. They do not take into account the possibility of a more aggressive policy to promote carbon emission abatement, such as by replacing gasoline-fueled vehicles with electric vehicles. Accordingly, these power supply forecasts for 2025/2030 must be amended.

According to the analysis of the energy supply and consumption in Taiwan, the electricity and oil that are used in the transportation sector are account for 41.9% and 10.8%, respectively, of domestic energy consumption. This study assumes that in the BAU scenario, these shares remain unchanged to 2025 and 2030. Based on the forecasts of the United States Argonne National Laboratory, McKinsey, Frost Sullivan, and other national and international agencies, concerning political targets for electric vehicles, the penetration of electric vehicles globally, in the United States, and in China will be 16%, 46%, and 62%, respectively, in the year 2030. Furthermore, France's automobile industry has estimated that 27% of vehicles in France will be electric in 2025.

No forecast of the domestic electric vehicle penetration in Taiwan is yet available. However, based on the above international trend, this study reasonably assumes domestic electric vehicle penetrations in 2025 and 2030 of 10% - 40% and 20% - 50%, respectively. Hence, for Taiwan in 2025 and 2030, 10% - 40% and 20% - 50% of the oil that is used in the transportation sector will be replaced by electricity.

Between 2004 and 2009, the gasoline supplied for Taiwan's vehicles increased from 13.08 MKLOE to 13.30 MKLOE, with an average annual growth rate of 0.33%. If this growth rate remains unchanged, then in the BAU scenario, the supply of gasoline for Taiwan's vehicles will reach 14.02 MKLOE in 2025 and 14.25 MKLOE in 2030. If 10% - 40% and 20% - 50% of these energies are provided by electric power, then based on heating value conversions, vehicles in Taiwan will consume 15.26 billion kilowatt-hours to 61.06 billion kilowatt-hours and 30.53 billion kilowatt-hours to 76.32 billion kilowatt-hours of electricity in 2025 and 2030, respectively.

The energy efficiency of a small gasoline engine is approximately 17%, while that of small electric vehicle batteries is about 68%. If the wastage rates in gasoline transportation and power transmission are also considered, then the energy utilization factor of electrical energy from power plants to the kinetic energy of electric vehicles is 3.15 times that of gasoline energy from the oil refinery to the kinetic energy of traditional vehicles. Accordingly, if in 2025 and 2030, the electric vehicle penetration in Taiwan is 10% - 40% and 20% - 50% respectively, then the energies required in those years for those vehicles will be equivalent to between 4.84 billion kilowatt-hours and 19.38 billion kilowatt-hours and between 9.69 billion kilowatt-hours and 24.23 billion kilowatt-hours.

Based on the above calculations, the total power supply for 2025 should be amended to 352.86 + 4.84 = 357.7 billion kilowatt-hours (for 10% penetration of electric vehicles) to 352.86 + 19.38 = 372.24 billion kilowatt-hours (for 40% penetration of electric vehicles), while the total power supply for 2030 should be amended to 391.28 + 9.69 = 400.97 billion kilowatt-hours (for 20% penetration of electric vehicles) to 391.28 + 24.23 = 415.51 billion kilowatt-hours (for 50% penetration of electric vehicles).

The above "total power supply" specifies the electricity that is needed by the power clients (including cogeneration systems), but excluding transmission line loss and the power used by the power plants, themselves. Because Taiwan's power transmission line loss and average electricity used by power plants account for 4.2% and 4.8% of the total power supply, respectively, the "total power generation" (the actual power that is generated by all power plants) in 2025 will be 389.89 billion kilowatt-hours (for a 10% penetration of electric vehicles) to 405.74 billion kilowatt-hours (for a 40% penetration of electric vehicles), while the "total power generation" for 2030 will be 437.06 billion kilowatt-hours (for a 20% penetration of electric vehicles) to 452.91 billion kilowatt-hours (for a 50% penetration of electric vehicles).

4.3. Calculation of Total Carbon Emissions

According to the analysis of the GHG emission in Taiwan, the GHG emissions of the power sector and those from oil in the transportation sector account for 56.0% and 11.5% of domestic GHG emissions, respectively. In the BAU scenario, assumed herein, these shares remain unchanged till 2025 and 2030. If in 2025 and 2030, 10% - 40% and 20% - 50% of the oil used in the transportation sector are replaced by electricity, then the GHG emissions of Taiwan's power generation sector in the year 2025 will account for 57.15% - 60.6% of domestic carbon emissions, while in the year 2030, they will account for 58.3% - 61.75%. The remaining miscellaneous carbon emissions will be unable to be substituted with electricity and is beyond the scope of this study.

Based on prior description, further analysis reveals that if Taiwan's GHG emissions abatement targets for 2025 and 2030 of 9.5 ton-CO_2/yr/p (based upon "Sustainable Energy Development Guidelines") and 5.0 ton-CO_2/yr/p (proposed by "B1 scenario of IPCCC") are imposed, then the upper bounds on the annual emissions per capita of the power sector of Taiwan in 2025 and 2030 will be 9.5 ton-CO_2/yr/p × (57.15% - 60.6%) = 5.42 ton-CO_2/yr/p - 5.76 ton-CO_2/yr/p and 5.0 ton-CO_2/yr/p × (58.3% - 61.75%) = 2.92 ton-CO_2/yr/p - 3.09 ton-CO_2/yr/p.

5. Seven Optimal Combinations

Based on the various nuclear power generation capacities that could be installed in 2025 and 2030 in Taiwan, this study identifies seven major scenarios for Taiwan's power infrastructure in the future. Based on the availability of CCS and various penetration rates of electric vehicles, these scenarios are broken down into seven scenarios. Each scenario is optimized and analyzed using the "Taiwan's low-carbon power infrastructure optimization program" to identify Taiwan's best future low-carbon power infrastructure. This optimization program allows the capacities of all kinds of power plant to vary freely between their upper and lower bounds, and automatically discovers the best solution that satisfies the conditions on all kinds of power generation.

1) Scenario one: the service lives of nuclear power plants one to three will be extended and these plants will continue to run until 2025. Nuclear plant four will also be running on schedule, so the total nuclear power installed capacity in 2025 will be 7.84 GW. This scenario is consistent with the BAU scenario that is planned by the current energy administration, and so the installed capacities of all 12 kinds of power plant are the same.

2) Scenario two: scenario two is the same as scenario one, except that the "gas-fired power generation" and "renewable energy power generation" capacities are significantly increased to three times those in the BAU scenario after 2010. The installed capacities of "coal-fired power generation", "oil-fired power generation", and "waste power generation" do not exceed those in the BAU scenario. In scenario two, "gas-fired power generation" and "renewable energy power generation" are increased to meet power generation requirements; otherwise, the calculations are as in the BAU scenario (Scenario one).

3) Scenario three: the service lives of nuclear power plants one to three will be extended to 2025, but nuclear power plant four will stop running, so the total installed nuclear capacity will be only 5.14 GW. The other constraints are the same as in scenario two, but scenario three allows the installed capacities of "gas-fired power generation" and "renewable energy power generation" to be increased significantly to three times those in the BAU scenario. However, the installed "coal-fired power generation", "oil-fired power generation", and "waste power generation" capacities are still below their highest values in the BAU scenario. Nuclear power plant four was originally planned to become commercially operational at the end of 2012, but this date will definitely be postponed. If some security-related or political issue prevent nuclear power plant four from coming into service and the three existing nuclear power plants continue to operate with extended service lives, then the total nuclear power capacity will be reduced to 65.6% of that in the BAU scenario. In scenario three, "gas-fired power generation" and "renewable energy power generation" capacities are reasonably increased to ensure that the "generation" requirements in 2025/2030 are met without the operation of nuclear power plant four.

4) Scenario four: nuclear power plants one to three will be out of service before 2025, but nuclear power plant four will operate on schedule, so the total installed nuclear capacity will be only 2.7 GW. With other conditions as in scenario two, scenario four allows the installed capacities of "gas-fired power generation" and "renewable energy power generation" to increase significantly to three times those in the BAU scenario. However, the installed "coal-fired power generation", "oil-fired power generation", and "waste power generation" capacities will remain below their highest values in the BAU scenario. In this scenario, nuclear power plants one, two, and three are scheduled to be out of service in 2019, 2021, and 2025, respectively. In the BAU scenario, the service lives of all three of these plants are extended. If nuclear power plants one to three are removed from service as originally planned, but nuclear power plant four becomes commercially operational as planned, then the nuclear power generation capacity will be reduced to 34.4% of that in the BAU scenario. Reasonable increases in "gas-fired power generation" and "renewable energy power generation" capacities are allowed under the condition that only one nuclear power plant (nuclear power plant four) is operational, and whether the requirements

for 2025/2030 can thus be met is determined.

5) Scenario five: nuclear power plants one to three will be out of service before 2025, and nuclear power plant four will also not be operational, so the total installed nuclear capacity will be zero. Under the other limitations in scenario two, scenario five allows the installed "gas-fired power generation" and "renewable energy power generation" capacities to be increased significantly up to three times those in the BAU scenario. However, the installed "coal-fired power generation", "oil-fired power generation", and "waste power generation" capacities cannot exceed their upper bounds in the BAU scenario. Owing to extreme safety concerns or significant changes in energy policy, nuclear power generation may be completely eliminated. In this scenario, "gas-fired power generation" and "renewable energy power generation" capacities are allowed to increase reasonably, and whether the requirements for 2025/2030 can be met without any nuclear power plant is determined.

6) Scenario six: like scenario five, scenario six involves zero nuclear power, but all fossil fuel power plants are shut down, and replaced by renewable energy power plants. The power generation that can be achieved using all renewable energy sources is less than 50% of the maximal reserve that was estimated in the "Assessment of Renewable Energy Reserves in Taiwan" (Chen *et al.*, 2010) but it is not less than the lowest value in the BAU scenario. The installed "waste power generation" capacity does not exceed the highest value in the BAU scenario. Fossil-fueled power plants—including coal-fired, gas-fired, and oil-fired power plants—can partially replace the nuclear power plants, but because of their high carbon emissions, they are not ideal power generation facilities. The calculation in scenario six aims to elucidate whether power generation with zero nuclear energy and zero fossil fuel still can still meet demand in 2025/2030 by an extreme program of constructing "renewable energy power plants".

7) Scenario seven: not only do nuclear power plants one to four run continuously until 2025, but also the capacities of nuclear generator units are maximized at the original sites of the power plants, yielding a total installed nuclear capacity of 22.4 GW. Under the other limitations in scenario one, the installed capacity of each kind of power plant in this scenario does not exceed the installed capacity in the BAU scenario. Under the prerequisites that no new power plants are constructed, nuclear or otherwise, scenario seven aims to determine whether maximizing the capacities of nuclear generator units at the original plant sites can meet demand in 2025/2030.

8) Comparison of scenarios: To compare the advantages and disadvantages of the scenarios, **Tables 4** and **5** list the optimal power generation infrastructure and the value of each index in each scenario for 2025 and 2030, respectively. These tables only refer to the most important and more technically feasible scenarios: "all renewable energy" and "with CCS" are therefore excluded. As shown in **Table 4**, in 2025, "generation" meets demand in all scenarios. However, only scenario two (BAU + enhanced gas and renewable energy) and scenario seven (nuclear generation capacity of 22.4 GW) meet the standard for "reserve capacity ratio" set by the Executive Yuan, while scenario three (nuclear generation capacity of 5.14 GW) and scenario four (nuclear generation capacity of 2.7 GW) are close to meeting this standard. The "reserve capacity ratio" in scenarios one (BAU) and five (zero nuclear energy) are significantly lower than required. In all scenarios except scenario seven (nuclear generation capacity of 22.4 GW), "emissions" significantly exceed the standard. In scenario seven, "emissions" do not exceed the standard. Except when the "reserve capacity ratio" falls far short of the required, as it does in scenario one (BAU), the average annual "power generation costs" are all similarly varying by only about 5% from each other; in all these cases, the cost is about 40% higher than that in scenario one.

As shown in **Table 5**, "generation" in all scenarios meets demand in 2030. However, only scenarios two (BAU + enhanced gas and renewable energy) and seven (nuclear generation capacity of 22.4 GW) fully meet the standard for "reserve capacity ratio" set by the Executive Yuan; scenarios three (nuclear generation capacity of 5.14 GW) and four (nuclear generation capacity of 2.7 GW) almost meet this standard. The "reserve capacity ratio" in scenarios one (BAU) and five (zero nuclear energy) are significantly lower than required. "Emissions" in all seven scenarios are significantly higher than the standard. The comparison of "power generation costs" reveals that except when the "reserve capacity ratio" is far below the standard, as it is in scenario one (BAU), "power generation costs" vary little (by no more than 8%); the cost in all of these cases is 40% - 55% higher than in scenario one.

6. Conclusions

This study is a response to the global warming crisis that is being caused by GHG emissions due to human activities, and the carbon dioxide emissions standards that have been formulated by the Taiwan's government for 2025 and by IPCC for 2030. This study analyzes the GHG emissions and energy infrastructure of Taiwan. Data on Taiwan's energy use and plans for developing power generation that have been announced by the BOEMOEA are considered. The values of parameters that optimize Taiwan's low-carbon power generation infrastructure are determined.

According to the results, the following important conclusions are drawn.

Table 4. Comparison among the optimal power generation structures of the major scenarios for the year 2025, when CCS is still unavailable. Installed capacities of various types of power plants and the performance indexes are shown (emissions abatement standard: Sustainable Energy Development Guidelines).

Type of power plant	Scenario one: installed capacity planned by BOEMOEA for 2025 (GW)	Scenario two: scenario one + enhanced gas-fired and renewables (GW)	Scenario three: nuclear power plants one to three in operation + enhanced gas-fired and renewables (GW)	Scenario four: only nuclear power plant four in operation + enhanced gas-fired and renewables (GW)	Scenario five: zero nuclear energy + enhanced gas-fired and renewables (GW)	Scenario seven: scenario one + maximal nuclear energy: 22.4GW (GW)
Coal-fired	28.25	24.11 - 26.54	26.50 - 28.25	28.25	28.25	19.39 - 22.55
Coal-fired + CCS	--	--	--	--	--	--
Gas-fired	18.32	*25.45	*25.45	*25.45	*25.45	18.32
Gas-fired + CCS	--	--	--	--	--	--
Oil-fired	2.87	2.87	2.87	2.87	2.87	2.87
Nuclear	7.84	7.84	5.14	2.70	--	*22.40
Hydro	2.50	*3.63	*3.63	*3.63	*3.63	2.24
Wind (onshore)	1.06	*2.30	*2.30	*2.30	*2.30	0.31
Wind (offshore)	1.95	*5.85	*5.85	*5.85	*5.85	--
Solar PV	2.00	*5.98	*5.98	*5.98	*5.98	0.42 - 0.01
Biomass	0.03	*0.04	*0.04	*0.04	*0.04	0.03
Waste energy	1.37	0.41 - 0.79	0.79 - 1.37	1.37	1.37	0.79 - 0.41
Performance index						
Total generation (kWh/person-day)	44.87 - 46.67	44.87 - 46.67	44.87 - 46.67	44.87 - 46.67	44.87 - 46.67	44.87 - 46.67
Insufficient generation rate	0%	0%	0%	0%	0%	0%
Total emissions (ton/person-yr)	8.14 - 8.67	6.48-7.00	7.13 - 7.65	7.72-8.24	8.37 - 8.89	05.42 - 5.75
Emission excessive rate	50% - 51%	20% - 22%	32% - 33%	42%-43%	54% - 55%	0%
Average annual cost for 2010-2025 (billion NTD)	131.7-132.1	176.0 - 185.5	183.4 - 194.1	189.7-191.8	187.1 - 188.2	181.4 - 190.4
Reserve capacity ratio (Executive Yuan standard: 16%)	4% - 8%	16%	15% - 16%	11% - 16%	7% - 11%	16%

*The required installed capacity is larger than that planned by BOEMOEA, but still within the upper bound set by the present study.

6.1. Power Generation Structure Planned by BOEMOEA Does Not Meet Future Requirements

Analyzing the power generation infrastructure for each of the installed power generation capacities (including estimates based on linear extrapolation) that are planned in the "2009-2018 Long-Term Load Forecast and Development of Power Supply Summary Report" and "Annual Renewable Energy Targets and Penetration" that were released by the BOEMOEA in February and March 2010, yields the following findings.

The "generation" provided by Taiwan's power generation infrastructure in 2025 will meet demand; "emissions" will exceed the standard (set in the "Sustainable Energy Development Guidelines) by up to 50% - 51%; the "reserve capacity ratio" will be only 4% - 8%—well below the required 16%.

The "generation" provided by Taiwan's power generation infrastructure in 2030 will meet demand; "emissions" will exceed the standard (set in the B1 scenario of the IPCC) by 224% - 225%; the "reserve capacity ratio" will be −1% - 3%—far below the standard of 16%.

6.2. CCS Is the Key Technology for Achieving Carbon Abatement Goal

CCS is the most critical technology for ensuring that the Taiwan power infrastructure will simultaneously satisfy the requirements of "generation", "emissions", and "reserve capacity ratio" in the future. If by the year 2025, CCS technology is mature and commercially viable, and CCS power plants can be constructed within the range set by the upper and lower bounds in this study, then regardless of the operational nuclear power generation capacity, "generation" and "reserve capacity ratio" in the

Table 5. Comparison among the optimal power generation structures of the major scenarios for the year 2030, when CCS is still unavailable. Installed capacities of various types of power plants and the performance indexes are shown (emissions abatement standard: B1 scenario of the IPCC).

Type of power plant	Scenario one: installed capacity planned by BOEMOEA for 2030 (GW)	Scenario two: scenario one + enhanced gas-fired and renewables (GW)	Scenario three: nuclear power plants one to three in operation + enhanced gas-fired and renewables (GW)	Scenario four: only nuclear power plant four in operation + enhanced gas-fired and renewables (GW)	Scenario five: zero nuclear energy + enhanced gas-fired and renewables (GW)	Scenario seven: scenario one + maximal nuclear energy: 22.4 GW (GW)
Coal-fired	31.47	28.54 - 31.34	31.47	31.47	31.47	26.47 - 29.27
Coal-fired + CCS	--	--	--	--	--	--
Gas-fired	19.44	*28.79	*28.79	*28.79	*28.79	19.44
Gas-fired + CCS	--	--	--	--	--	--
Oil-fired	2.37	2.37	2.37	2.37	2.37	2.37
Nuclear	7.84	7.84	5.14	2.70	--	*22.40
Hydro	2.50	*3.63	*3.63	*3.63	*3.63	2.50
Wind (onshore)	1.16	*2.60	*2.60	*2.60	*2.60	1.16
Wind (offshore)	3.30	*9.90	*9.90	*9.90	*9.90	3.30
Solar PV	2.50	*7.48	*7.48	*7.48	*7.48	2.50
Biomass	0.03	*0.04	*0.04	*0.04	*0.04	0.03
Waste energy	1.37	0.79	1.37	1.37	1.37	0.41
Performance index						
Total generation (kWh/person-day)	50.31 - 52.14	50.31 - 52.14	50.31 - 52.14	50.31 - 52.14	50.31 - 52.14	50.31 - 52.14
Insufficient generation rate	0%	0%	0%	0%	0%	0%
Total emissions (ton/person-yr)	9.47 - 10.0	7.23 - 7.76	7.88 - 8.41	8.46 - 9.00	9.11 - 9.64	5.98 - 6.51
Emission excessive rate	224% - 225%	148% - 151%	170% - 172%	190% - 191%	212% - 213%	105% - 111%
Average annual cost for 2010-2030 (billion NTD)	136.3 - 136.7	193.1 - 201.9	200.4 - 205.2	200.7 - 202.7	197.5 - 197.9	203.2 - 212.1
Reserve capacity ratio (Executive Yuan standard: 16%)	−1% - 3%	16%	13% - 16%	9% - 13%	6%-9%	16%

*The required installed capacity is larger than that planned by BOEMOEA, but still within the upper bound set by the present study.

years 2025 and 2030 will meet demand, and the excess "emissions" over the target rate will be far lower than those achieved without CCS.

Without CCS technology, even though the "generation" requirements will be met, in no scenario (with one exception) will the emission reduction targets be met, and the shortfalls will be large, regardless of whether the standards are those set by Taiwan for 2025 or set by IPCC for 2030. The exception is the scenario in which the nuclear power generation capacity is 22.4 GW, in which the emissions targets for 2025 will be met.

6.3. "Zero Nuclear Energy" Does Not Enable Power Demand to Be Met, Whereas a Nuclear Generation Capacity 22.4 GW Is an Excellent Option

In the absence of CCS and nuclear power, if the power generation of gas-fired and renewable is increased, then in 2025 and 2030, although total power supply will meet demand, the "reserve capacity ratios" will be only 7% - 11% and 6% - 9%—considerably short of the standard of 16% that has been set by the Executive Yuan. Accordingly, zero nuclear power is not a feasible scenario.

If no CCS is used, but nuclear generator units are extended to a maximum capacity of 22.4 GW at the sites of nuclear power plants one to four, and the gas-fired and renewable power generation capacity is not increased, then the "generation", "emissions", and "reserve capacity ratio" requirement can be all met in both 2025 and 2030, with the exception that "emissions" will exceed standard in 2030, in which year the "power generation cost" will be similar to those in all other scenarios.

However, although nuclear power generation capacity of 22.4 GW satisfies the requirements of carbon emissions and cost, the so-called "external costs" of a large amount of nuclear waste and doubts about nuclear safety may be much greater than in the other scenarios. These issues involved are beyond the scopes of this study.

6.4. "Renewable Energy Power Generation" Is the Most Important Factor in Ensuring the Stability of Power Supply in the Future

In the scenarios with nuclear power generating capacities of 2.7 GW, 5.14 GW and 7.84 GW, "power supply" and "reserve capacity ratio" fall far short of requirements in 2025 and 2030 unless capacity increases above those in the BAU are made. In such a case, Taiwan could suffer a power supply crisis at any time. Based on technological feasibility and societal concerns, increases to "gas-fired" and "renewable" power generation capacities are favored over the construction of "CCS power plants" and "nuclear power plants".

This study establishes the need to upgrade the installed capacity of "gas-fired" and "renewable energy" plants to three times those in the BAU, to provide the required reserve capacity ratio. At present, the renewable energy installed capacity in Taiwan is very low, if increasing the renewable power generation capacity to 2025 is targeted, then the ratios between the renewable power generation capacity in 2009 and the target capacity in 2025 will be hydropower: 1/1.8; biomass power generation: 1/2; onshore wind power generation: 1/5; solar PV: 1/600 and offshore wind power: 0.

Given that the feasibility of CCS technology is still unclear and substantial increases in nuclear power generation capacity may not be feasible, the rapid growth of installed renewable power generation capacity (and wind power and solar power in particular) over the next decades will be critical to the success or failure of power planning in Taiwan.

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