ORIGINAL ARTICLE

Feasibility of Wind Power and Photovoltaics Replacing Nuclear Power

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Abstract: The paper studies the feasibility of using renewable energy (specifically wind power and photovoltaics) to replace nuclear power in terms of area acquisition, grid scheduling, and overall cost and benefit. The development of renewable energy in Taiwan is restricted by area availability. Assuming a power generation capacity of four nuclear power plants, the analysis finds that wind and photovoltaic (PV) power would respectively require about 33.7 and 88.5 times the area required for the nuclear power plants. The paper also studies operating reserve requirements to prevent power outages resulting from unexpected changes of wind or PV output, finding that at least 2 gas-fired power plants with the level of Da-tam power storage plant are required at a cost of about NT$565.5 billion. Furthermore, based on the scenario of My 2050 L-4 with a more active program, wind power and PVs replacement of nuclear power would only become feasible in 2035 and require a total investment of NT$2,590 billion, equivalent to about 9 times of construction costs of Taiwan's 4th nuclear power plant. Renewable energy is intermittent and unsteady and, as large-scale renewable energy is increasingly integrated into the power grid, providing a stable electricity supply will be a critical consideration in determining the future role of nuclear power in Taiwan.

Keywords: nuclear power, wind power, photovoltaics, opportunity cost

Introduction

Taiwan is heavily dependent on imported energy, but is unable to import electricity from the other countries due to topographical and political considerations.[1] Following oil crises in 1973 and 1979, the Taiwan government began to actively pursue policies to diversify the island's energy supply through the development of nuclear power alongside increases to fossil-fuel power plant capacity. Nuclear power has a higher energy density than conventional fossil fuels, and thus requires considerably smaller area for equivalent amounts of installed capacity.

However, nuclear power has become an extremely contentious political issue in Taiwan in recent years, resulting in the mothballing of an as yet incomplete 4th nuclear power plant (4th NPP).[2] Figure 1 illustrates the evolution of 4th NPP.

The 4th NPP was first proposed in the 1980s, but construction was suspended in May 1985 in response to strong local opposition. Over the next 25 years, the project was repeatedly restarted and halted in response to domestic and international events, including the 2011 Fukushima Daiichi disaster. As of writing, the project has been formally mothballed[2]. In response to climate changes, in 1992 the United Nations formulated the United Nations Framework Convention on Climate Change (UNFCCC) [3], [4] to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." This was followed by Kyoto Protocol, an international agreement linked to the UNFCCC, which commits its parties to set specific targets of emission reduction.

Taiwan's government has proposed a series of policies to respond to international calls for emissions reduction, including the expansion of renewable energy. However, the development of renewable energy in Taiwan is restricted by area acquisition. In addition, the variable

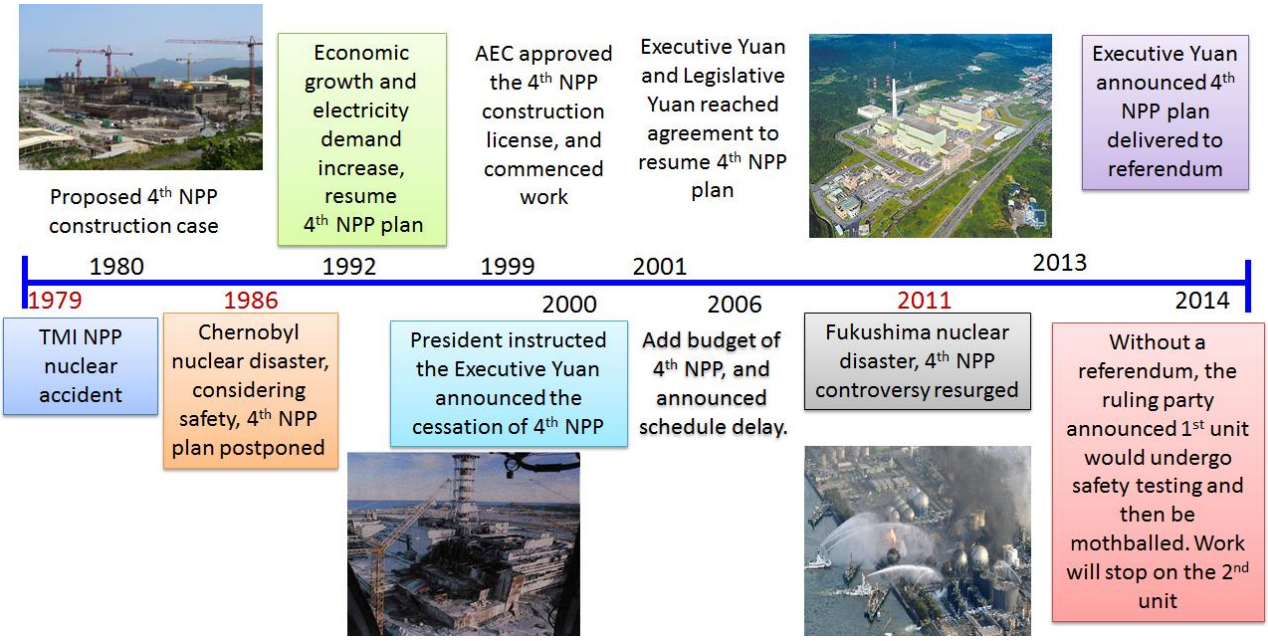

Figure 1. History chronicles of Taiwan's fourth nuclear power plant. [2]

and uncertain characteristics of renewable energy creates difficulties for integration with the power grid, along with additional costs [5].Renewable energy sources have long been discussed as a potential replacement for nuclear power. The paper conducts a short- and medium-term feasibility study of replacing nuclear power with wind power and photovoltaics in Taiwan, in terms of area acquisition, grid scheduling and cost. The remainder of the paper is organized as follows: the issue of area acquisition is analyzed first, followed by grid scheduling and cost/benefit for the development of renewable energy. Some important implications of these analyses are discussed, to generate conclusions and recommendations.

Area acquisition

Currently, wind power and photovoltaics are among the most popular forms of renewable energy. According to the Renewables 2015 Global Status Report [6], in 2014 global solar and wind installed capacity had respectively reached 177 GW and 370 GW. In 2013, Taiwan's installed capacity of nuclear power, photovoltaics and wind power are respectively 5,144 MW, 392MW, and 614MW, with corresponding power generation of 41.64, 0.34 and 1.64 billion kWh and capacity factors of 92.4%, 9.84%, and 30.49% [1]. Accounting for future improvements to manufacturing technology, this study assumes respective capacity factors for photovoltaics and wind power of 15% and 40% (Table 1).

This paper assumes four nuclear power plants[1] to calculate the area required for renewable energy to replace nuclear power. The area required for the four nuclear power plants are 2.45, 2.2, 3.54 and 4.8 km^2 respectively, for a total area of 13km^2, producing 63.5 billion kWh per year.

Taiwan has a high population density, with few sites suitable for onshore wind farms, thus we assume that future wind farm development will be largely offshore. In addition, the area off Taiwan's west coast is particularly well suited for offshore wind farms construction, thus it can be presumed that offshore wind power will provide an paper uses the specifications for offshore wind turbine to study the area required for offshore wind power to replace nuclear power. The fan diameter of a 5MW offshore U.S. NREL-5MW wind turbine is 126m. To prevent interference between turbines, individual turbines must be separated horizontally by at least 3 to 5 times the fan's diameter and about 4 to 6 times the fan's diameter

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[1] Currently, there have already been three nuclear power plants (1st ,2nd and 3rd NPPs) in operation commercially in Taiwan, and 4th NPP had been halted.

longitudinally [7]. Assuming that turbines will be placed 4 times and 5 times the fan's diameter in the horizontal and longitudinal direction, abundant power source in the future. Therefore, this respectively, this study finds that a total area of 1,151 km^2 is required for offshore wind power plants to replace the nuclear power generated by the four assumed nuclear power plants. Photovoltaics are assumed to require 0.01 km^2 per MW, thus requiring a total of 483 km^2 for photovoltaics to replace nuclear power. Therefore, replacing nuclear power with wind or photovoltaics would require about 33.7 and 88.5 times the area needed by nuclear power plants.

Table 1. Comparison of land required in different generation technology.

	Nuclear Power	Offshore wind power	PV
Capacity in 2013 (MW)	5144	614 (onshore)	392
Generation in 2013 (billion kWh)	41.64	1.64 (onshore)	0.34
Capacity for replacing nuclear power (MW)	7,844	18,120	48,319
Capacity Factor (%)	92.4	40	15
Capacity per area (MW/km^2)	604	16	100
Area for replacing nuclear power (km^2)	13	1,151	483

The development of offshore wind farms raises issues including channel safety, marine ecological preservation, marine engineering and the sequential maintenance [2]. For large-scale PV power plants, it is difficult to obtain the enough area and long-term usage rights. Therefore, in 2013, the BOE launched the Million Rooftop PV Promotion Project which prioritizes rooftop PV installation [8]. However, even covering every rooftop in Taiwan with PVs would not produce sufficient power to replace nuclear power. PVs could be installed on fallow agricultural land in southern Taiwan, but the cost of doing so is still being evaluated.

Grid scheduling

In Taiwan, solar and wind resources are unevenly distributed. Although the Taiwan Power Company (TPC) has introduced many types of advanced technology to compensate for this uneven distribution, power dispatching is still inevitable. For offshore wind power, Taiwan's government is actively promoting the development of demonstration projects, but these entail massive investments for the installation for undersea cables and offshore substations to deal with the rated power output. The grid must be designed to accommodate a large-scale offshore wind power plant. Failure to do so will raise problems linking offshore wind power plants to the grid, resulting in power wastage; such problems have impeded the development of wind power in Germany.

Significantly increased sun exposure has resulted in the majority of Taiwan's PV capacity being located in Taiwan's southern region, but power consumption is concentrated in the northern region. To improve power system stability, more long transmission lines are required to link southern area to northern area. In addition, the cost of the extra transmission capacity needed by solar and wind power is difficult to estimate. The requirement of cost for different penetrations of renewable energy is also quite different. However, based on the results in [5], it needs more than 40% cost for per installed capacities of wind turbine and photovoltaics. Investments in the improvement of local distribution systems to allow integration of renewable energy sources should also be taken into consideration.

On the other hand, both wind and solar energy are characterized by intermittence and uncertainty of supply, raising another key challenge for large-scale grid integration. As shown in Fig. 2, Taiwan's wind power resources peak in winter, while demand peaks in summer. PVs cannot generate power at night. Thus, balancing power supply and load demand is a critical engineering consideration for the use of renewable energy. In addition, Taiwan is an island, and is thus restricted from importing electricity generated in countries. To compensate for anticipated and unanticipated reduction in power supply from wind or solar sources, we estimate that at least 2 gas-fired power plants with the level of Da-tam power storage plant will be needed to provide adequate operating reserve at an estimated cost of about NT$565.5 billion. Such improvements will increase of power system stability, and the development of renewable energy will also enhance Taiwan's energy self-sufficiency and energy security, while also promoting the development of related industries. However, sufficient energy storage devices will be required to absorb excess power generation from large-scale wind or photovoltaics plants, and cross-border grids may need to be constructed to lower the risk of mismatch between load shedding and power generation. These are issues which require both technological and political solutions.

Overall cost and benefit

Table 2 summarizes the current potential of

[2] Because the available area for onshore wind farm is quite few, the issues of development encountered are not discussed in the paper.

renewable energy in Taiwan. Construction costs per MW for wind power plants, rooftop PVs and land PVs are NT$142, 65 and 56 million, respectively (see Table 3) [9]. These estimated construction costs assume maximizing renewable energy usage, along with other strong assumptions regarding the feasibility of land acquisition and deregulation, making such plans currently difficult to achieve. The information for costs and the energy development plan are mainly based on ITRI's 2050 Calculator L-4.

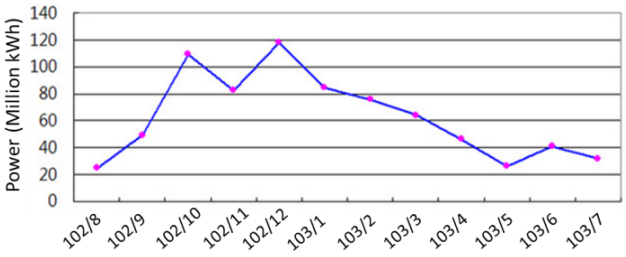

Figure. 2. Profile of the wind power during August, 2013 and July, 2014.

Table 2. 2030 Taiwan estimated wind power and solar power.

	Energy technology	Capacity (GW)	Generation (billion kWh)
Existing plan (2030)	Wind	4.0	14.02
	PV (rooftop)	3.0	3.89
	PV (land)	5.7	7.49
My 2050 L-4 (2030)	Wind	5.9	20.84
	PV (rooftop)	10.2	13.39
	PV (land)	4.6	6.00
My 2050 L-4 (2035)	Wind	10.9	38.19
	PV (rooftop)	10.6	13.90
	PV (land)	3.0	10.51

Current power generation plans anticipate annual renewable generation of 25.45 billion kWh (14.02 + 3.89 + 7.49 = 25.45 in Table 2), equivalent to 40.1% of nuclear power capacity. The total investment cost is about NT$1090 billion. The more aggressive My 2050 L-4 [9] program assumes a larger investment to develop renewable energy. According to this plan, wind power and photovoltaics could replace nuclear power by 2035, requiring an investment of NT$2,590 billion, equivalent to about 9 times the construction cost of 4th NPP. However, such a solution would resolve the current political impasse regarding the use of nuclear power, and also address issues related to nuclear waste processing and storage. However, current economic conditions make such large investments difficult to budget using public funds, and relying on private capital is also complicated by the need to ensure private investors with an attractive return on capital.

Discussion

In summary, to avoid extending the lifespan of the 1st, 2nd, and 3rd NPP from 2018 to 2025, and to replace nuclear power with wind power and PVs, the following conditions and the costs should be considered.

1. All the associated infrastructure construction should be completed before 2025.
2. The required investment is estimated to exceed NT$2,500 billion (equivalent to NT$10,000 per capita annually for 10 years).
3. To compensate for the intermittence and instability of renewable energy, at least 2 gas-fired power plants will be required at a cost of more than NT$500 billion.
4. The power grid must be strengthened to handle the increase in power transmission, particularly local distribution systems to allow integration of renewable energy. Land for and construction of energy storage devices will also be required at considerable expense.
5. Excessive public spending on renewable energy infrastructure will require cutbacks to other critical efforts including national infrastructure spending, social welfare, national defense and education.

Table 3. Investment costs for wind power and photovoltaics.

	Energy technology	Investment cost of plant, NT$ (billion)	Total investment cost, NT$ (billion)	Proportion of nuclear power (%)
Existing plan (2030)	Wind	570	1090	40.1%
	PV (rooftop)	200		
	PV (land)	320		
My 2050 L-4 (2030)	Wind	840	1,760	63.4%
	PV (rooftop)	660		
	PV (land)	260		
My 2050 L-4 (2035)	Wind	1,550	2,590	95.0%
	PV (rooftop)	690		
	PV (land)	350		

Conclusion

This paper studies the feasibility of using wind power and photovoltaics to replace nuclear power in Taiwan. Based on the most pessimistic My 2050 L-4 scenario, such a program could be accomplished by 2035, but will require an investment of at least NT$2,500 billion for direct construction and land acquisition costs, but does not include additional costs, such as those required for the reinforcement of the local distribution system, installation of energy storage devices and associated land acquisition. The future large-scale integration of intermittent and unsteady renewable energy sources with Taiwan's grid will raise critical problems for ensuring reliable electrical supplies in Taiwan.

Acknowledgment

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