Feasibility of Replacing Nuclear and Fossil Fuel Energy with Offshore Wind Energy: A Case for Taiwan

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Abstract: Adequate recognition of the offshore wind energy potential may help coastal states frame proper energy policies for replacing nuclear and fossil fuel energy. In this study, we examined the application potential of the offshore wind energy generated by 31 offshore wind farms designated by the Taiwanese government for future exploitation. Our findings indicate that offshore wind energy (through its substantial power generation volume and capacity factor) can play the most pivotal role in future power generation for Taiwan. A total of 59.3 TWh of electricity produced from offshore wind energy and solar photovoltaics (PVs) each year could replace the power generated from nuclear energy by 2025. Coal-fired power generation could be replaced by offshore wind energy and other renewables by 2032. The full exploitation of offshore wind farms as detailed in this study (103.4 TWh/year), together with other renewables, could reduce the share of liquefied natural gas-fired power generation to 5.6% of the total Taiwanese power supply by 2040. Realizing the ultimate target of 100% carbon-neutral power generation would rely mainly on a further decrease in electricity consumption per unit of gross domestic product and the expansion of offshore wind energy and geothermal energy.

Keywords: offshore wind farm optimization; WindSim; energy transition; low-carbon and non-nuclear power generation

1. Introduction

Offshore wind energy is regarded as a key energy source in the project of replacing domestic nuclear and fossil fuel energy with renewables in Taiwan. This policy is justifiable considering that there is excellent potential for offshore wind energy in the Taiwan Strait [1]. The current government in Taiwan is speeding up the exploitation of offshore wind energy and solar photovoltaic energy to achieve a low-carbon and non-nuclear electricity system.

The primary energy supply of Taiwan has been characterized by a reliance on fossil fuels and nuclear energy since the 1980s. In 2020, imported primary energy accounted for 97.8% of the total energy supply in Taiwan. The imported energy included oil, coal, and liquefied natural gas (LNG), which accounted for 44.1%, 30%, and 17.1%, respectively, of the total energy supply in Taiwan. Nuclear energy represented 6.6% of Taiwan’s total energy supply [2].

In 2020, coal- and LNG-fired power plants generated 45% and 35.7% of the total electricity produced in Taiwan, respectively (Figure 1). The electricity generated from nuclear energy accounted for 11.2% of the total electricity generation, and the electricity generated from renewable energy sources accounted for 5.5% of the total electricity generation. Solar photovoltaics (PVs) accounted for the highest proportion (40%) of the total electricity generated from renewable energy sources, followed by waste and hydropower (23% and 20%, respectively). Wind energy accounted for 15% of the generated renewable power. The main sectors of electricity consumption are the industrial, residential, and service sectors, which accounted for 55.6%, 18.5%, and 17.1%, respectively, of total electricity consumption.
in Taiwan in 2020. The power generated in Taiwan increased by 51.6% from 2000 to 2020 (Figure 1). During this period, the annual increase rate of power generation in Taiwan was 2.2% and that of electricity consumption was 2.3% [2].

The electricity policy in Taiwan was adjusted toward low-carbon fossil fuels and renewable energy after a new president was elected in 2016. The investment in future power generation is focused on natural gas and renewable energy. The exploitation of renewable energy will focus on offshore wind energy and solar PVs in the future. The construction of the first offshore wind farm in Taiwan was completed in November 2019. This farm has a capacity of 128 MW. The peak-hour power output from renewable energy was 3493 MW at 13:44 on 2 June 2016. At that time, the renewable energy generation was higher than the nuclear energy generation (3458 MW) for the first time in Taiwan. The total electricity consumption at that time was 34,120 MW. The main contributors to this historic milestone were hydropower and pumped-storage hydropower (outputs of 1719 and 1170 MW, respectively), followed by solar PV and onshore wind energy (outputs of 360 and 244 MW, respectively) [4].

Taiwan’s energy policy actively promotes the replacement of nuclear and fossil fuel energy with renewable energy. However, considerable challenges exist in achieving this energy transition. Whether the generated renewable energy can substitute for nuclear and fossil fuel energy in a timely manner is worth examination. In this study, we examined the potential of offshore wind energy for replacing nuclear and fossil fuel energy. The large-scale potential of offshore wind energy in Taiwan has been studied on a preliminary basis. Lin and Chen [5] evaluated the wind potential of a 10,000 km² economic zone in Taiwan with a power density of 10 MW/km² and capacity factor of 0.3. Yue and Yang [6] used a geographic information system and wind speed distribution map to evaluate the offshore wind energy potential in potential areas for wind turbine installation with a minimum annual wind speed of 6 m/s at a height of 50 m, a maximum distance of 30 km
from the coast, and water depths up to 40 m. Chen et al. [7] also used a wind speed distribution map to estimate the wind energy potential of offshore areas in Taiwan with wind speeds of at least 4 m/s at a height of 50 m and a maximum water depth of 40 m. The aforementioned studies have evaluated the offshore wind energy potential of exploitable areas by calculating the approximate wind energy per unit area or using a large-scale wind speed distribution map. A potential evaluation using uniform values of the capacity factor or yearly average wind speed distribution maps may be unable to account for the wind conditions in particular sea areas that may be affected by factors such as coastal terrain; moreover, such methods may not reflect the power output of various wind speed frequencies over the entire year, leading to inaccurate estimations of wind power. In addition, using wind speed at a height of 50 m may not be applicable for wind speeds at the hub heights of modern wind turbines (over 100 m).

In contrast to the aforementioned studies, in this study, data from offshore meteorological masts and the Modern-Era Retrospective Analysis for Research and Applications (MERRA) database at time intervals of 10 min and 1 h, respectively, were used. The combined use of these data may have enhanced the accuracy of wind power estimation by accounting for the wind conditions of particular sea areas (to increase spatial resolution) and the power output of specific wind speed frequencies (to increase temporal resolution). We also used the measure–correlate–predict (MCP) method to estimate the long-term power production of the wind farms, and thus improve the reliability of estimation. In addition, we used WindSim to evaluate wind resources and optimize the placement of turbine by maximizing energy yield. These measures may have enhanced the accuracy and reliability of wind power estimation.

The aim of this study was to estimate the potential contribution of power generated by 31 offshore wind farms designated by the Bureau of Energy of the Republic of China (BEROC) for future exploitation (to replace nuclear and fossil fuel energy and transition toward low-carbon, non-nuclear energy in Taiwan). This paper provides the following novel contributions to the field of offshore wind energy. First, a method for accurate evaluation of large-scale offshore wind farms is outlined; the method combines the use of data from offshore meteorological masts and the MERRA database. Estimating the long-term energy yield by using the MCP method improved the reliability of estimation, and evaluating wind resources and optimizing wind turbine placement by using WindSim maximized the annual energy production (AEP) and enhanced the accuracy of financial evaluations of wind farms. The total installation capacity of the offshore wind farms investigated in this study amounted to 26.5 GW, which can be used to generate 103.4 TWh of electricity per year. This electricity amount corresponds to 38.1% of the total electricity consumption of Taiwan in 2020. Second, a schedule for the replacement of nuclear energy and fossil fuels with offshore wind energy has been proposed, representing a means of implementing a concrete policy to realize a domestic carbon-neutral climate policy and avoid the risks of nuclear energy. The amount of electricity expected to be produced each year from offshore wind energy and solar PV energy by 2025 would be sufficient to replace the electricity currently generated by nuclear energy. Coal-fired power generation could be replaced in 2032 by offshore wind energy and other renewables. The full exploitation of the offshore wind farms outlined in this study, together with other renewables, would be able to reduce the share of LNG-fired power generation to 5.6% of the total power supply by 2040. The integration of electricity production from offshore wind energy with loads, the electrical grid, and energy storage systems was not discussed because it was not a priority of this study.

2. Challenges of Energy Utilization in Taiwan

Numerous challenges exist in achieving energy transition in Taiwan: (1) the high electricity consumption in Taiwan; (2) the tight power supply during peak hours; (3) the local opposition to thermal power plants because of air pollution; and (4) the political
pressure to reconstruct the Lungmen Nuclear Power Plant, which has been temporarily sealed for safety reasons.

2.1. High Electricity Consumption

The annual growth rate of electricity consumption in Taiwan was 2.3% in 2000–2020. The increasing summer temperatures have resulted in increasing power consumption because air conditioners are being used for longer durations each year.

2.2. Tight Power Supply during Peak Hours

The lowest percent operating reserve in 2019 was 6.02% at 14:17 on 24 April. Moreover, the lowest percent operating reserve during the past three years was 2.89% at 13:37 on 29 May 2018. The percent operating reserve was lower than 6% for 104 days in 2017 [8]. Although the situation related to the percent operating reserve is currently manageable, there may be challenges related to the future power supply due to the increasing use of air conditioning during peak hours because of the worsening heat.

2.3. Local Opposition against Thermal Power Plants

Concerns related to air pollution have resulted in strong local pressure to reduce the load of thermal power plants, particularly the Taichung coal-fired power plant in central Taiwan, which had a capacity of 5788 MW and was the third-largest thermal power plant in the world in 2019. The Taichung City Government ordered the capacity of the Taichung Thermal Power Plant to be decreased by approximately 40–50% to reduce local air pollution. However, this measure could have the following consequences. First, it could affect Taiwan’s electricity supply considering the low percent operating reserve (less than 6%) during peak hours. Second, Taipower is currently installing new units to meet the increasing electricity demand of Taiwan. The increased power production is not planned to supplement the reduced power generation caused by the decrease in the capacity of the Taichung Thermal Power Plant. Third, the decrease in the capacity of the Taichung Power Plant could cause power shortages in central Taiwan, which would force other Taiwanese regions to offset this electricity shortage [9].

2.4. Political Pressure to Reconstruct the Lungmen Nuclear Power Plant

In 2020, the nuclear power generation capacity of Taiwan was 3872 MW. This power was generated by three active plants and six reactors. Moreover, the generated nuclear power accounted for 11.2% of the electricity generated in Taiwan in 2020. Nuclear accidents and nuclear waste are the major concerns of the Taiwanese people regarding the use of nuclear energy. The severe nuclear disaster in Fukushima, which was caused by an earthquake and a tsunami, led to considerable concern in Taiwan, where nuclear power plants have been constructed in coastal areas with high seismic activities. In the first published map of active seismic faults in Taiwan (published in 1975), the Shanshao Fault, located 7 and 5 km from the Chinsnash and Kuosheng Nuclear Power Plants, respectively, and the Hencun Fault, located 1 km from the nuclear island of the Maanshan Nuclear Power Plant, are not listed as active faults. These active faults had not yet been discovered when the nuclear power plants were constructed; thus, the aforementioned faults were not considered in the safety evaluation of the nuclear power plant designs. Considering the discoveries of new active faults in Taiwan since 1975, the seismic design coefficients of the three nuclear power plants in Taiwan might be too low [10]. In addition, the Chinsnash, Kuosheng, and Maanshan Nuclear Power Plants were analyzed to be within very high seismic hazard areas, as determined by the Global Seismic Hazard Assessment Program seismic hazard data [11].

The issue of the Lungmen Nuclear Power Plant has caused considerable controversy over Taiwan’s energy policy in the past two decades. The construction of the Lungmen Nuclear Power Plant began in 1999. The severe earthquake that occurred in central Taiwan in 1999 caused legislators to inspect the construction progress of this plant. They observed
problems such as rusty reinforcing bars and seawater seepage into the foundation of the plant [12]. Legislators of the Democratic Progressive Party called for halting the construction of the nuclear power plant in April 2000, which led to the suspension of construction in October 2000. Contractors were idled for 111 days. The temporary cancellation by the Taiwanese government and other project management difficulties caused significant delays in construction. In April 2014, the Taiwanese premier announced that the two reactors at the Lungmen Nuclear Power Plant would be mothballed amid the rising public outcry against nuclear power following the Fukushima nuclear disaster in Japan on 11 March 2011. The mothballing of the Lungmen Nuclear Power Plant was completed in July 2015, and the plant has remained mothballed since then [13].

Taiwan is one of the few areas worldwide where nuclear power plants are located close to areas with a high risk of earthquake disasters. This situation is extremely rare in the world. The three existing nuclear power plants are located within 8 km of active faults; thus, these plants face considerable risks. According to the current understanding of the geological conditions of the three nuclear power plants, all of them have been constructed on unsuitable sites. Thus, these nuclear power plants should be urgently decommissioned [10]. Article 23 of the Basic Environment Act, which was announced in 2002, stipulates that the Taiwanese government should establish plans to gradually achieve the goal of becoming a nuclear-free country [14]. Paragraph 1 of Article 95 of the Electricity Act also suggests that the nuclear energy-based power-generating facilities should be decommissioned by 2025 [15]. Thus, the Taiwanese government has planned the decommissioning of the existing three nuclear power plants and did not plan to resume the construction of the Lungmen Nuclear Power Plant.

The issue of nuclear energy was subjected to a referendum in Taiwan on 24 November 2018. The main text of Case 9 of the referendum was as follows: “Do you agree that the government should maintain the ban on imports of agricultural products and food from areas in Japan affected by the Fukushima Daiichi nuclear plant disaster on 11 March 2011?” Moreover, the main text of Case 16 was as follows: “Do you agree to abolish Paragraph 1 of Article 95 of the Electricity Act, that is, to abolish the article of ‘nuclear-energy-based power-generating facilities should be completely shut down by 2025’?” The referendum results for Case 9 indicated that 72% of the voters wished to maintain the import ban on food produced in areas affected by the Fukushima nuclear plant disaster. However, the referendum results for case 16 indicated that 54% of the voters agreed to continue the usage of nuclear power plants beyond 2025 [16]. Thus, 54% of the voters supported the continued use of nuclear energy, probably to ensure sufficient energy supply; however, some of them had concerns regarding the environmental impacts of nuclear energy. These findings are reasonable because pro-nuclear political parties and civil groups have promoted the narrative that there would be electricity supply shortages and electricity price hikes without nuclear power.

In line with the referendum results, the cabinet approved a proposal to abolish Paragraph 1 of Article 95 of the Electricity Act, thereby halting the policy of phasing out nuclear power by 2025. Moreover, the legislature approved the annulment of this paragraph on 7 May 2019. Although the 2025 deadline has been cancelled, the government’s goal of making Taiwan nuclear-free remains unchanged. The MOEA of Taiwan stipulated that the government will not delay the planned decommissioning of current nuclear power plants, nor will it resume the construction of the Lungmen Nuclear Power Plant. Authorities also aim to reduce the electricity production of coal-fired plants each year. The operating nuclear power plants will be decommissioned without delay because the government is focused on the development of renewable energy [17].

3. Methods

Offshore wind energy is expected to replace nuclear and fossil fuel energy in the future energy policy of Taiwan. We used the data measured with offshore meteorological masts and MERRA data to estimate the energy yield of the wind farms in the studied area.
economic feasibility of the wind farms was evaluated by calculating their net present values (NPVs) from the results of wind farm optimization. Finally, the potential of offshore wind energy in the studied area for replacing nuclear and fossil fuels energy in Taiwan was analyzed. The flowchart of this study is displayed in Figure 2.

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3.1. Datasets

The data used in this study were obtained from meteorological masts and the MERRA database. The masts are located in the Chunan and Changhua nearshore areas of Taiwan (Figure 3). The Chunan and Changhua masts are located 2 and 6 km from the coastline, respectively. Data from four MERRA sites were used for wind resource evaluation. The 31 offshore wind farms investigated in this study are the planned sites announced in 2015 by the BEROC for future wind resource exploitation after considering ecology-, military-, waterway-, and fishery-related concerns [18].

Figure 3. Geographic locations of the 31 studied offshore wind farms, two meteorological masts, and four MERRA sites [18].

The data used in this study are presented in Table 1. The cup anemometer and vane conforming to the International Electrotechnical Commission (IEC) 61400-12-1 Class 1 standard are used on the mast. The MERRA-2 data used in this study are composed of grid points with a spatial resolution of approximately 50 km × 50 km (Figure 3). The time
interval of the mast data was 10 min, and the MERRA data had an hourly resolution. In this study, hourly data were used to ensure a consistent resolution.

Table 1. Data used in this study.

| Data Source | Location      | Longitude (°E) | Latitude (°N) | Data Collection Height (m) | Data Collection Period       |
|-------------|---------------|----------------|---------------|----------------------------|------------------------------|
| Mast        | Chunan        | 120.831        | 24.706        | 90                         | 1 July 2017–30 June 2018     |
|             | Changhua      | 120.273        | 24.001        | 95                         | 1 July 2017–30 June 2019     |
| MERRA       | 1             | 120.625        | 25.000        | 62.5                       | 1 January 2009–31 December 2018 |
|             | 2             | 120.625        | 24.500        |                             |                              |
|             | 3             | 120.000        | 24.000        |                             |                              |
|             | 4             | 120.000        | 23.500        |                             |                              |

3.2. MCP Method

MCP is adopted to relate and adjust on-site measurements to a long-term reference. This method uses the linear least squares (LLS) to correlate target and reference wind speed data to obtain a scatter plot. The following equation is used to express the linear curve fit:

\[ y = mx + b \]  

The following equations are used to calculate the slope and intercept:

\[ m = \frac{S_{xy}}{S_{xx}} \]  

\[ b = \bar{y} - mx \]

where \( S_{xx} \) and \( S_{xy} \) are calculated by the following equations:

\[ S_{xx} = \sum_i (x_i - \bar{x})^2 \]  

\[ S_{xy} = \sum_i (x_i - \bar{x})(y_i - \bar{y}) \]

where \( x_i \) is the reference data, \( \bar{x} \) is the average of the reference data, \( y_i \) is the target data, and \( \bar{y} \) is the average of the target data.

MCP was conducted in this study to simulate historical wind conditions by using the short-term data measured by the mast, and long-term data obtained from MERRA. The power law was used to calculate the MCP data for a height of 140 m for the MHI 9500 wind turbine from the data obtained from masts and the MERRA database for the heights of 95 and 62.5 m, respectively. The simulation used hourly wind speeds and wind directions, because hourly data may be more suitable as long-term data than the 10-minute average wind data [19].

3.3. WindSim Model

In this study, the WindSim model was adopted to create the site terrain by using elevation and roughness data. The model uses computational fluid dynamics (CFD) to solve the following formula:

\[ \rho \frac{\partial \bar{u}_j}{\partial x_j} = \rho \bar{f}_i + \frac{\partial}{\partial x_j} \left[ -\bar{p} \delta_{ij} + \mu \left( \frac{\partial \bar{u}_j}{\partial x_i} + \frac{\partial \bar{u}_i}{\partial x_j} \right) - \rho \bar{w}_i \bar{w}_j \right], \]

where \( \rho \frac{\partial \bar{u}_j}{\partial x_j} \) is the change in the mean momentum of the fluid element, \( \rho \bar{f}_i \) is mean body force, \( \bar{p} \delta_{ij} \) is the isotropic stress due to the mean pressure field, \( \mu \left( \frac{\partial \bar{u}_j}{\partial x_i} + \frac{\partial \bar{u}_i}{\partial x_j} \right) \) represents the viscous stresses, and \( \rho \bar{w}_i \bar{w}_j \) denotes the Reynolds stress.
The elevation data for the study area were obtained from the ASTER GDEM v2 Worldwide Elevation Data, and the roughness data are from the GlobeLand30 dataset. The standard k–ε turbulence model (Table 2) involves two equations.

Table 2. Parameters used in this study to evaluate wind resources.

| Properties          | Categories                  | Parameters                  | Value     |
|---------------------|-----------------------------|-----------------------------|-----------|
| Wind fields         | Boundary conditions         | Boundary layer height       | 1000 m    |
|                     |                             | Speed above boundary layer height | 15 m/s   |
|                     |                             | Boundary condition at top   | No-friction wall |
| Physical models     | Potential temperature       | Disregard temperature       | 1.225     |
|                     | Air density                 |                             | 1.225     |
|                     | Turbulence model            | Standard k–ε                |           |
| Calculation parameters | Solvers                      | General collocated velocity |           |
| Wind resources      | Wind resource map           | Heights                     | 140       |

The following equation is used to express the turbulent kinetic energy $k$:

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \frac{\mu_t}{\sigma_{k}} \frac{\partial k}{\partial x_j} \right] + 2\mu_t E_{ij}E_{ij} - \rho \epsilon . \quad (7)$$

The following equation is used to express the dissipation $\epsilon$:

$$\frac{\partial (\rho \epsilon)}{\partial t} + \frac{\partial (\rho \epsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \frac{\mu_t}{\sigma_{\epsilon}} \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} \frac{\epsilon}{k} \frac{\partial k}{\partial x_j} E_{ij}E_{ij} - C_{2\epsilon} \rho \frac{\epsilon^2}{k} . \quad (8)$$

where $u_i$ is the velocity component in the $i$ direction, $\mu_t$ is the eddy viscosity, and $E_{ij}$ is the component of the rate of deformation.

3.4. Wind Turbine

Energy yield was evaluated by using the MHI Vestas Offshore V164-9.5 MW wind turbine. The technical specifications of the turbine are indicated in Table 3. A steel tube was used in the construction of the tower. The corrosion protection strategy for the tower is centered on the tower’s paint coating. The power curve of the turbine is illustrated in Figure 4. The turbine has a cut-in and cut-out wind speed of 3 m/s and 25 m/s, respectively. The rated wind speed is at 14 m/s.

Table 3. Technical specifications of the MHI Vestas Offshore V164-9.5 MW wind turbine [20].

| Properties          | Value                  |
|---------------------|------------------------|
| Rated power         | 9.5 MW                 |
| Wind class IEC S    |                        |
| Rotor               | Type 3-bladed, horizontal axis |
|                     | Diameter 164 m         |
|                     | Swept area 21,124 m²   |
|                     | Power regulation Pitch with variable speed |
| Tower               | Hub height 140 m (Site-specific) |
| Operational data    | Cut-in wind speed 3 m/s|
|                     | Nominal wind speed 14 m/s|
|                     | Cut-out wind speed 25 m/s|
| Generator           | Type Permanent magnet generator |
|                     | Frequency 50/60 Hz      |
3.5. Wind Farm Optimization

Wind farm optimization involves the reduction of energy production loss caused by the wake effect. The Jensen model was used in this study to calculate the wake effect of the wind turbine. This model assumes a linearly expanding wake with a velocity deficit that is based on the distance between the upstream turbine and the downstream turbine [21]. The wake model is derived by conserving the momentum downstream of the wind turbine. The velocity in the wake is given as a function of downstream distance from the turbine hub [22]. Vanluvanee [23] recommends that Jensen’s model be used for the energy predictions in offshore wind farms, as it gives a good tradeoff between prediction errors. In this study, the Park Optimizer module of WindSim was used to optimize the layouts of wind farms [24,25]. The decay coefficient \( k_d \) was set as 0.05 in the wake model for the offshore condition [26].

3.6. AEP

The AEP is calculated as follows:

\[
AEP = N_h \sum F(v) \times P(v),
\]

where \( N_h \) is the number of hours in a year (=8760), \( F(v) \) is the Weibull distribution, and \( P(v) \) is the power output.

3.7. Economic Evaluation

We used \( NPV \) to evaluate the economic feasibility of investing in offshore wind farms. The economic feasibility of the wind farms was evaluated by calculating their \( NPV \)s by using the wind farm optimization results. The following equation is used to calculate \( NPV \):

\[
NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_{Total}
\]

where \( C_t \) is the net cash inflow during the time period \( t \), \( C_{Total} \) is the total initial investment costs, and \( r \) is the discount rate.

In this study, the equation can be expressed as follows:

\[
NPV(t) = -C_0 - C_{1n} - C_{2n} + \sum_{t=1}^{T} (1 + r)^{-t}E((P_t) - OC_t(n))
\]
where \( C_0 \) represents the fixed costs such as the external road, grid connection, and transformer; \( C_1 \) represents the turbine costs; \( C_2 \) represents the variable costs such as internal roads and foundation; \( n \) is the number of turbines; \( E(n) \) is the energy production; \( P_t \) is the revenue from power sales; and \( OC(n) \) represents the operational costs.

4. Estimation of the Offshore Wind Energy Potential

4.1. Validation of the Data and MCP Method

After the wind resource measurements were collected, the wind speed data were examined to ensure that only valid data were used in the subsequent analyses and that the data were as accurate as possible. Figure 5 illustrates the scatter plot of the wind speeds measured with wind masts at heights of 95 and 50 m in the Changhua offshore area. The correlation coefficient for the aforementioned data was 0.892, indicating that the data had suitable accuracy.

Figure 5. Scatter plot of the wind speeds measured with wind masts at heights of 95 and 50 m in the Changhua offshore area from July 2017 to June 2019 (\( R^2 = 0.892 \)).

The power law was used to obtain the wind data for a height of 140 m for the MHI 9500 wind turbine from the data obtained from masts and the MERRA database for the heights of 95 and 62.5 m. The power law can be expressed as [27,28]:

\[
\frac{V_2}{V_1} = \left( \frac{h_2}{h_1} \right)^\alpha
\]

(12)

where \( V_2 \) is the projected wind speed at the desired height \( h_2 \), \( V_1 \) is the observed wind speed at the measurement height \( h_1 \), and \( \alpha \) is the wind shear (power law) exponent.

The correlation coefficients of the wind speed and wind direction data for a height of 140 m between the Changhua mast and MERRA data from July 2017 to June 2019 were 0.855 and 0.905, respectively (Table 4); thus, the data from the masts and MERRA database had a close relationship.
Table 4. Correlation and RMSE of the wind speed and correlation of the wind direction between the mast and MERRA data and between the MCP and MERRA data.

|                | Wind Speed   | Wind Direction |
|----------------|--------------|----------------|
|                | R² (%)       | RMSE (m/s)     | R² (%)         |
| Mast vs MERRA  | 85.5         | 5.68           | 90.5           |
| MCP vs MERRA   | 98.4         | 0.38           | 99.3           |

The MCP method was adopted in this study to estimate the long-term power production of wind farms by using short-term mast data and long-term MERRA data. The MCP data for a height of 140 m were then calculated using the power law. The accuracy of the wind data obtained using the MCP method was examined. The correlation coefficients of the wind speed and wind direction at a height of 140 m between the MCP and MERRA data from January 2009 to December 2018 were 0.984 and 0.993, respectively (Table 4), which indicated that the wind speed and wind direction data obtained using the MCP method had a close relationship with those obtained from the MERRA database. The root mean square error (RMSE) of the wind speed between the MCP and MERRA data (0.38 m/s) was smaller than that between the mast and MERRA data (5.68 m/s) (Table 4), indicating that the errors between the MCP and MERRA data were significantly lower than those between the mast and MERRA data.

4.2. Wind Farm Optimization

The wind data obtained from the masts in Chunan and Changhua indicated that the wind resources of the offshore areas of Taiwan could be principally characterized by two periods. During the winter from October to January, the wind speeds were high due to the northeast monsoon (Figure 6). During the remainder of the year, the wind speeds were relatively low. Overall, the wind speed distributions in Chunan in the northern offshore area were relatively even, whereas those in Changhua in the central offshore area fluctuated significantly.

Figure 6. Time series of the wind speed measured using masts from 1 July 2017 to 30 June 2018 at heights of 90 and 95 m in Chunan (above) and Changhua (below).
The site terrain was first created in WindSim by using elevation and roughness data. Elevation data were established by using the ASTER GDEM v2 Worldwide Elevation Data. The roughness data were obtained from GlobeLand30. These two data were imported into the Global Mapper to establish a GWS file to import into WindSim. The terrain elevation and the optimized layouts of wind farms are illustrated in Figure 7. Notably, the elevations in the offshore areas were always 0 m, whereas the elevations in the coastal land areas where wind farms were situated increased gradually.

![Elevation of the terrain of the nearshore area and the optimized layout of wind farm 1 (left) and wind farm 3 (right). The triangle and the circle represent the wind turbine and the meteorological mast, respectively.](image)

After the establishment of the terrain model, MCP data were imported into WindSim to create a wind resource map of the calculated area by the Wind Resources Module. The wind resource map of wind farms 24–30 is illustrated in Figure 8. Most of the wind farms 24–30 had annual average wind speeds between 8.3 and 8.9 m/s, with only a small part in the southeast between 7.7 and 8.3 m/s.

An energy map was then generated using the Park Optimizer module of WindSim, and wind speed data were combined with the power curve of the selected wind turbine. The energy map of wind farms 24–30 is illustrated in Figure 9 by using wind speed data and the power curve of the selected Vestas Offshore V164-9.5 MW turbine. The energy map indicated the wind resource potential before conducting the layout optimization of the wind farm. The area where turbines were to be positioned in wind farms 24–30 allowed for an annual average energy production of 4050–4450 kW. Similar to the situation in the wind resource map (Figure 8), a small part in the southeast had a lower annual average energy compared to other areas.

The wind resource and energy maps were then used as input to conduct wind farm layout optimization by using the Park Optimizer module of WindSim. The layouts of wind farms were optimized based on the wind resource maps (Figure 7). Approximately 55 and 125 turbines can be erected in wind farm 1 and wind farm 3, respectively.
Data. The roughness data were obtained from GlobeLand30. These two data were imported into the Global Mapper to establish a GWS file to import into WindSim. The terrain elevation and the optimized layouts of wind farms are illustrated in Figure 7. Notably, the elevations in the offshore areas were always 0 m, whereas the elevations in the coastal land areas where wind farms were situated increased gradually.

Figure 7. Elevation of the terrain of the nearshore area and the optimized layout of wind farm 1 (left) and wind farm 3 (right). The triangle and the circle represent the wind turbine and the meteorological mast, respectively.

After the establishment of the terrain model, MCP data were imported into WindSim to create a wind resource map of the calculated area by the Wind Resources Module. The wind resource map of wind farms 24–30 is illustrated in Figure 8. Most of the wind farms 24–30 had annual average wind speeds between 8.3 and 8.9 m/s, with only a small part in the southeast between 7.7 and 8.3 m/s.

Figure 8. Wind resource map of wind farms 24-30 obtained using WindSim.

An energy map was then generated using the Park Optimizer module of WindSim, and wind speed data were combined with the power curve of the selected wind turbine. The energy map of wind farms 24–30 is illustrated in Figure 9 by using wind speed data and the power curve of the selected Vestas Offshore V164-9.5 MW turbine. The energy map indicated the wind resource potential before conducting the layout optimization of the wind farm. The area where turbines were to be positioned in wind farms 24–30 allowed for an annual average energy production of 4050–4450 kW. Similar to the situation in the wind resource map (Figure 8), a small part in the southeast had a lower annual average energy compared to other areas.

Figure 9. Energy map of wind farms 24–30.

The wind resource and energy maps were then used as input to conduct wind farm layout optimization by using the Park Optimizer module of WindSim. The layouts of wind farms were optimized based on the wind resource maps (Figure 7). Approximately 55 and 125 turbines can be erected in wind farm 1 and wind farm 3, respectively.

4.3. Economic Evaluation

The economic feasibility of the wind farms was evaluated by calculating their NPVs using the wind farm optimization results. The NPV and NPV of including an additional turbine with different numbers of turbines for the wind farms are illustrated in Figure 10. For wind farms 24–30, the NPV of including an additional turbine began to decline approximately after the 700th turbine; however, the total NPV continually increased until the 746th (last) turbine. The investment for the turbines after the 700th one might be weighed when considering the total economic effectiveness of wind farm exploitation.
4.3. Economic Evaluation

The economic feasibility of the wind farms was evaluated by calculating their NPVs using the wind farm optimization results. The NPV and NPV of including an additional turbine with different numbers of turbines for the wind farms are illustrated in Figure 10. For wind farms 24–30, the NPV of including an additional turbine began to decline approximately after the 700th turbine; however, the total NPV continually increased until the 746th (last) turbine. The investment for the turbines after the 700th one might be weighed when considering the total economic effectiveness of wind farm exploitation.

![Figure 10. NPV and NPV of including an additional turbine with different numbers of turbines for wind farms 24–30 (dNPV: additional NPV; dn: additional turbine). In general, dNPV/dn decreases gradually. In some circumstances, the number of repeat operations is insufficient with a certain number of turbines, which leads to an increase in dNPV/dn after adding an additional turbine.](image)

4.4. Total Power Generation Potential of Offshore Wind Farms

By optimizing the wind farm layout, the total power generation potential of the 31 offshore wind farms could be estimated. Table 5 presents the estimated power generation potential of the 31 wind farms. A total of 2792 wind turbines with a combined power generation potential of 103.4 TWh per year can be erected at the 31 farms. The capacity factors of the wind farms were between 41.2% and 50.2%, with a mean capacity factor of 44.5%.

Table 5. Estimated power generation potential of the 31 wind farms.

| Wind Farm | Number of Turbines | Installation Capacity (MW) | Power Generation (GWh/y) | Capacity Factor (%) |
|-----------|--------------------|-----------------------------|--------------------------|-------------------|
| 1         | 55                 | 522.5                       | 2293.7                   | 50.1              |
| 2         | 28                 | 266                         | 1170.0                   | 50.2              |
| 3         | 125                | 1187.5                      | 5218.4                   | 50.2              |
| 4         | 30                 | 285                         | 1031.8                   | 41.3              |
| 5         | 51                 | 484.5                       | 1754.0                   | 41.3              |
| 6         | 92                 | 874                         | 3405.2                   | 44.5              |
| 7         | 91                 | 864.5                       | 3368.2                   | 44.5              |
| 8         | 89                 | 845.5                       | 3294.1                   | 44.5              |
| 9         | 61                 | 579.5                       | 2257.8                   | 44.5              |
| 10        | 94                 | 893                         | 3479.2                   | 44.5              |
| 11        | 102                | 969                         | 3775.3                   | 44.5              |
| 12        | 104                | 988                         | 3849.3                   | 44.5              |
| 13        | 99                 | 940.5                       | 3664.3                   | 44.5              |
| 14        | 91                 | 864.5                       | 3368.2                   | 44.5              |
| 15        | 102                | 969                         | 3775.3                   | 44.5              |
| 16        | 71                 | 674.5                       | 2627.9                   | 44.5              |

The electricity generation potential of the offshore wind farms investigated in this study can be further examined according to their geographic location (Table 6). The capacity factors of the northern wind farms (1–3) were higher than 50%, corresponding to their high average energy in the energy map. The capacity factors of the wind farms in the remaining areas were between 41.2% and 44.5%. The total installation capacity reached 26.5 GW, which can yield 103.4 TWh of electricity per year. This electricity amount corresponds to 38.1% of the total electricity consumption of Taiwan in 2020 (271.1 TWh) [2].
Table 5. Estimated power generation potential of the 31 wind farms.

| Wind Farm Number | Amount of Turbines | Installation Capacity (MW) | Power Generation (GWh/y) | Capacity Factor (%) |
|------------------|--------------------|-----------------------------|--------------------------|---------------------|
| 1                | 55                 | 522.5                       | 2293.7                   | 50.1                |
| 2                | 28                 | 266                         | 1170.0                   | 50.2                |
| 3                | 125                | 1187.5                      | 5218.4                   | 50.2                |
| 4                | 30                 | 285                         | 1031.8                   | 41.3                |
| 5                | 51                 | 484.5                       | 1754.0                   | 41.3                |
| 6                | 92                 | 874                         | 3405.2                   | 44.5                |
| 7                | 91                 | 864.5                       | 3368.2                   | 44.5                |
| 8                | 89                 | 845.5                       | 3294.1                   | 44.5                |
| 9                | 61                 | 579.5                       | 2257.8                   | 44.5                |
| 10               | 94                 | 893                         | 3479.2                   | 44.5                |
| 11               | 102                | 969                         | 3775.3                   | 44.5                |
| 12               | 104                | 988                         | 3849.3                   | 44.5                |
| 13               | 99                 | 940.5                       | 3664.3                   | 44.5                |
| 14               | 91                 | 864.5                       | 3368.2                   | 44.5                |
| 15               | 102                | 969                         | 3775.3                   | 44.5                |
| 16               | 71                 | 674.5                       | 2627.9                   | 44.5                |
| 17               | 89                 | 845.5                       | 3294.1                   | 44.5                |
| 18               | 125                | 1187.5                      | 4626.6                   | 44.5                |
| 19               | 99                 | 940.5                       | 3664.3                   | 44.5                |
| 20               | 69                 | 655.5                       | 2553.9                   | 44.5                |
| 21               | 84                 | 798                         | 3109.1                   | 44.5                |
| 22               | 78                 | 741                         | 2887.0                   | 44.5                |
| 23               | 63                 | 598.5                       | 2331.8                   | 44.5                |
| 24               | 118                | 1121                        | 4320.5                   | 44.0                |
| 25               | 100                | 950                         | 3661.4                   | 44.0                |
| 26               | 85                 | 807.5                       | 3112.2                   | 44.0                |
| 27               | 130                | 1235                        | 4775.2                   | 44.1                |
| 28               | 100                | 950                         | 3661.4                   | 44.0                |
| 29               | 106                | 1007                        | 3881.1                   | 44.0                |
| 30               | 107                | 1016.5                      | 3917.7                   | 44.0                |
| 31               | 154                | 1463                        | 5278.4                   | 41.2                |
| Total            | 2792               | 26,524                      | 103,407.4                | 44.5                |

Table 6. Power generation potential of the 31 offshore wind farms according to their geographic locations.

| Wind Farm Number | Average Energy (kW/yr) | Amount of Turbines | Installation Capacity (MW) | Gross AEP (GWh/y) | AEP with Wake Losses (GWh/y) | Wake Loss (%) | Capacity Factor (%) |
|------------------|------------------------|--------------------|-----------------------------|-------------------|-------------------------------|---------------|---------------------|
| 1–2              | 5180                   | 83                 | 788.5                       | 3533.1            | 3463.7                        | 1.96          | 50.1                |
| 3                | 5500                   | 125                | 1187.5                      | 5338.6            | 5218.4                        | 2.25          | 50.2                |
| 4–5              | 4370                   | 81                 | 769.5                       | 2893.7            | 2785.8                        | 3.73          | 41.3                |
| 6–23             | 4580                   | 1603               | 15,228.5                    | 61,007.4          | 59,331.6                      | 2.75          | 44.5                |
| 24–30            | 4450                   | 746                | 7087                        | 28,126.8          | 27,329.5                      | 2.83          | 44.0                |
| 31               | 4350                   | 154                | 1463                        | 5530.3            | 5278.4                        | 4.55          | 41.2                |
| Total            | 2792                   | 26,524             | 106,429.9                   | 103,407.4         | 2.84                          | 44.5          |                     |

5. Potential of Offshore Wind Energy to Replace Nuclear and Fossil Fuel Energy in Taiwan

In this section, the potential of offshore wind energy to aid the transition to a more sustainable power supply in Taiwan is examined. The assumptions of future power supply planning are listed in Table 7 mainly according to the National Electricity Supply and Demand Report [29]. The 2020–2040 cumulative renewable power generation capacity and total electricity generation were projected as follows. The National Development Council (NDC) projected the average annual gross domestic product (GDP) growth rate to be 2.44%
from 2020 onward [30]. The Taiwan Bureau of Energy’s Electricity Division estimated that power consumption per GDP unit will decrease by 2%/year from 2020 onward [29]. Based on these projections, 2020–2040 electricity demand could be estimated.

Table 7. The assumptions of future power supply planning.

| Category       | Assumption                                                                 |
|----------------|----------------------------------------------------------------------------|
| Socioecon. cond.| Domestic population of 22.5 million in 2040 [31]                           |
|                | Average annual gross domestic product (GDP) growth rate of 2.44% from 2020 onward [30] |
| Demand         | Decrease in electricity consumption per GDP unit of 2%/year from 2020 onward [29] |
| Supply Renewal | Cumulative installation capacity of onshore wind energy of 1.2 GW by 2025 [29] |
|                | Cumulative installation capacity of offshore wind energy of 5.7 GW by 2025 that increases by 1.5 GW/year thereafter [29] |
|                | Cumulative installation capacity of solar PVs of 20 GW by 2025 that increases by 1 GW/year thereafter [29] |
|                | Capacity factor for new installation of solar PV energy of 25% from 2020 onward [32] |
|                | Cumulative installation capacity of hydropower of 2.2 GW by 2030 [33] |
|                | Capacity factor of hydropower of 25.2% from 2020 onward (by using the average of the capacity factor from 2000 to 2020) |
|                | Biomass reserves of 4.55 kWh/day/person (with a conversion to electric power of 1.82 kWh/day/person) [7] |
|                | Cumulative installation capacity of geothermal energy of 13.4 GW by 2040 with a capacity factor of 75% [34,35] |
| Nuclear        | Suspension of nuclear power generation by 2025 according to the national non-nuclear energy policy [29] |
| Fossil fuels   | Share of LNG-fired power generation in total power generation of 50% in 2025 that decreases thereafter until complete replacement by renewables [29] |
|                | Coal-fired power generation supplies only power demand that cannot be met by renewable and LNG-fired power generation [29] |

According to the National Electricity Supply and Demand Report [29], the cumulative installation capacity of offshore wind energy is targeted to be 5.7 GW by 2025, and then an additional 1.5 GW/year thereafter. Following this schedule, installation capacity is projected to grow to 20.7 GW in 2035 and 26.7 GW in 2039, which is more than the potential installation capacity of offshore wind energy of 26.5 GW estimated in this study. The capacity in 2039 is assumed to be 26.5 GW when possible delays due to factors such as supply chain disruptions and construction timing are considered. The year 2040 is thus used as a target in this study to analyze the portfolio of energy sources for electricity generation. The electricity generated by offshore wind energy from 2020 onward can be calculated using the capacity factor of 0.445 estimated in this study. The Bureau of Energy has set the cumulative installation capacity of onshore wind energy to be 1.2 GW by 2025 and has disregarded further expansion because the land area for onshore wind energy development will no longer be readily available [29]. The electricity generated by onshore wind energy was calculated to be 2.9 TWh/year from 2025 onward by using a capacity factor of 0.28 in 2020.

Regarding solar PV energy, the Bureau of Energy set the cumulative installation capacity of solar PV to be 20 GW by 2025, with the expectation that it will increase by
1 GW/year thereafter [29]. According to the 2021 National Electricity Supply and Demand Report [32], the capacity factor for new installation is set to increase from 20% to 25% because the power generation performance of new installations has been better than expected. The electricity generated by solar PV from 2020 onward can be estimated by using the capacity factors of cumulative and new installations.

The exploitation of biomass energy is based on the potential evaluation of Chen et al. [7]. From 2020 to 2040, the electricity generated from biomass energy is projected to increase with the annual growth rate such that the total potential (1.82 kWh/day/person) will have been fully exploited by 2040. The Bureau of Energy and the Environmental Protection Administration set the cumulative installation capacity of hydropower to be 2.2 GW by 2030 [33]. The electricity generated by hydropower from 2020 onward can be estimated using the 2000–2020 average capacity factor of 25.2%. The total potential of geothermal energy in Taiwan has been estimated to be 33.6 GW [34]. The installation capacity of geothermal energy is projected to increase from 2020 to 2040 with the annual growth rate such that a potential of 13.4 GW (40% of the total potential) will have been exploited by 2040. The electricity generation is estimated by using the average capacity factor of 75% based on the performance parameter provided by the Intergovernmental Panel on Climate Change [35].

Based on the National Electricity Supply and Demand Report [29], offshore wind energy and solar PV are set to become the investment priorities for future power generation in Taiwan from 2020 onward. The renewable power generation capacity of Taiwan is projected to increase from 9.5 GW in 2020 to 81.2 GW in 2040, as illustrated in Figure 11. During the aforementioned period, the installation capacity of offshore wind energy is expected to increase from 0.128 to 26.5 GW and the annual power generation is expected to increase from 0.7 to 103.6 TWh. The share of renewable power in total generated power is projected to increase from 5.5% in 2020 to 94.4% in 2040. Offshore wind power will increase its share from 0.2% of total generated power in 2020 to 34.3% in 2040, thereby becoming the most notable contributor to domestic power supply in Taiwan, followed by geothermal energy at 29.3% and solar PV at 23.3%.

![Projections of cumulative renewable power generation capacity and total electricity generation](image)

**Figure 11.** Projections of cumulative renewable power generation capacity (left) and total electricity generation (right) in Taiwan by 2040 with a highlighted contribution of the offshore wind energy [2,29,36].

Offshore wind energy is set to play a central role in Taiwan’s future power generation. Although the installation capacity of offshore wind energy is projected to be only 73.6%
of that of solar PV energy in 2040, the amount of electricity generated from offshore wind energy will reach an estimated 1.5 times that generated from solar PV energy because the capacity factor of offshore wind energy (44.5%) is 2.0 times that of solar PV energy (22.8%). Financially, the average capital cost of offshore wind energy (USD 5504/kW) is 3.2 times that of solar PV energy (USD 1698/kW) in Taiwan [37]. The expansion of offshore wind energy exploitation and the localization of component production would enable a reduction in the costs of offshore wind energy in the future.

According to the National Electricity Supply and Demand Report in Taiwan [29], 59.3 TWh of electricity is expected to be produced annually from offshore wind and solar PV energy sources by 2025, and these renewables would be able to replace the electricity presently generated by nuclear sources (31.4 TWh in 2020). Additionally, in 2032, coal-fired power generation could be replaced mainly by offshore wind energy and solar PV. Furthermore, the full exploitation of the offshore wind farms detailed in this study (103.4 TWh/year), together with other renewables, would be able to reduce the share of LNG-fired power generation to 5.6% by 2040. Accomplishing the ultimate target of a 100% carbon-neutral power supply would rely primarily on further reductions in electricity consumption per unit of GDP and the expansion of offshore wind energy and geothermal energy. In addition to the current focus on offshore wind energy and solar PV expansion, national energy policy that directs considerably greater attention than before toward the active exploitation of geothermal energy is crucial.

6. Conclusions

In this study, we used data measured with offshore meteorological masts and MERRA data to apply the MCP method for estimating the AEP of 31 offshore wind farms in Taiwan through the WindSim tool. The novel findings of this study are as follows:

- A method for the accurate evaluation of large-scale offshore wind farms has been outlined; this was achieved by using the data from offshore meteorological masts and the MERRA database, adopting the MCP method for the estimation of the long-term power production of wind farms (thus improving the reliability of estimation), and using WindSim to evaluate wind resources and optimize wind turbine placement, thereby maximizing the AEP and enhancing the accuracy of wind farm financial evaluation.

- The total installation capacity of the 31 offshore wind farms investigated in this study amounted to 26.5 GW, which can be used to generate 103.6 TWh of electricity per year. Offshore wind power will increase its share from 0.2% of total generated power in 2020 to 34.3% in 2040.

- The offshore wind energy can play the most pivotal role in future power generation for Taiwan through its substantial power generation volume and capacity factor (between 41.2% and 50.2% with an average of 44.5%).

- The amount of electricity expected to be produced each year from offshore wind energy and solar PV energy by 2025 would be sufficient to replace the electricity currently generated by nuclear energy. Coal-fired power generation could be replaced in 2032 by offshore wind energy and other renewables. The full exploitation of the offshore wind farms outlined in this study, together with other renewables, would be able to reduce the share of LNG-fired power generation to 5.6% of the total power supply by 2040.

Many countries around the world are committed to the development of offshore wind energy to reduce carbon dioxide emissions in the wake of increasingly severe climatic catastrophes. Here, we propose a method to accurately evaluate large-scale offshore wind farms; the method combines the use of data from offshore meteorological masts and the MERRA database to enhance the accuracy of wind power estimation by accounting for the wind conditions of particular sea areas. Evaluating wind resources and optimizing wind turbine placement by using WindSim maximized the AEP and enhanced the accuracy of
financial evaluations of wind farms. These scientific and technical contributions may be used to facilitate the development of global offshore wind energy.

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**References**

1. 4C Offshore, Global Wind Speed Information Database. 2020. Available online: https://www.4coffshore.com/windfarms/windspeeds.aspx/ (accessed on 24 April 2021).

2. Bureau of Energy of the Republic of China (BEROC). Energy Statistics Handbook 2020. 2021. Available online: https://www.moeaboe.gov.tw/ECW_WEBPAGE/FlipBook/2020EnergyStaHandBook/index.html#p= (accessed on 22 April 2021).

3. Bureau of Energy of the Republic of China (BEROC). Energy Statistics Information. Available online: https://www.moeaboe.gov.tw/wesnq/Views/B01/wFrmB0101.aspx (accessed on 22 June 2021).

4. Huang, P.-J. Power output from renewable energy outnumbered that from nuclear for the first time. Liberty Times Net, 2 June 2016. Available online: https://features.ltn.com.tw/spring/article/2015/paper/996432 (accessed on 2 March 2021).

5. Lin, L.F.; Chen, C.X. Analysis of new renewable energy in Taiwan. In Nuclear Energy Institute Reports (INER-5848); Atomic Energy Commission: Taoyuan, Taiwan, 2008.

6. Yue, C.-D.; Yang, M.-H. Exploring the potential of wind energy for a coastal state. Energy Policy 2009, 37, 3925–3940.

7. Chen, F.; Lu, S.-M.; Tseng, K.-T.; Lee, S.-C.; Wang, E. Assessment of renewable energy reserves in Taiwan. Renew. Sustain. Energy Rev. 2010, 14, 2511–2528.

8. Taipower. Information of Power Supply in the Past. Available online: https://www.taipower.com.tw/tc/page.aspx?mid=210&cid=341&ccid=ae51e573-e600-4a77-bc48-9e8d8f1b70c1 (accessed on 14 July 2021).

9. China Post. Taipower Warns of Power Shortage Risks. 2019. Available online: https://chinapost.nownews.com/20190428-556578 (accessed on 14 August 2021).

10. Citizen of the Earth (CET). Decommissioning of Aged Nuclear Power Plants Close to Faults Should not Be Delayed. 2019. Available online: https://www.cet-taiwan.org/node/3370 (accessed on 14 May 2021).

11. Cochran, T.B.; McKinzie, M.G. Global Implications of the Fukushima Disaster for Nuclear Power; Natural Resources Defense Council: Washington, DC, USA, 2011.

12. Chiu, Y.-T. Activists ask for delay of nuke plant. Taipei Times, 29 October 1999. Available online: https://www.taipeitimes.com/News/local/archives/1999/10/29/0000008580 (accessed on 14 May 2021).

13. Chiu, Y.-T. Activists ask for delay of nuke plant. Taipei Times, 29 October 1999. Available online: https://www.taipeitimes.com/News/local/archives/1999/10/29/0000008580 (accessed on 14 May 2021).

14. Chiu, Y.-T. Activists ask for delay of nuke plant. Taipei Times, 29 October 1999. Available online: https://www.taipeitimes.com/News/local/archives/1999/10/29/0000008580 (accessed on 14 May 2021).

15. Ministry of Economic Affairs (MOEA). The Electricity Act; MOEA: Taipei, Taiwan, 2017.

16. Wang, T.-I. An overview of the results of referendum. United Daily News, 24 November 2018. Available online: https://udn.com/news/story/12539/3491368#prettyPhoto[pp_gal]/2/ (accessed on 14 April 2021).

17. Lin, J.H.; Luo, C.Y.; Lee, S.F. Ministry of Economic Affairs decided that the construction of the fourth nuclear power plant will not be resumed, nor will the decommissioning of nuclear power plants be delayed. Liberty Times Net, 2 February 2019. Available online: https://news.ltn.com.tw/news/focus/paper/1265570 (accessed on 14 March 2021).
18. Bureau of Energy of the Republic of China (BEROC). Essentials of Application for Offshore Wind Power Planning Site; BEROC: Taipei, Taiwan, 2015.
19. Bowen, A.J.; Mortensen, N.G. WASP Prediction Errors due to Site Orography; Risø National Laboratory: Roskilde, Denmark, 2004.
20. Vestas. Technical Specifications of the V164-9.5 MW Wind Turbine. Available online: https://www.vestas.com/en/products/offshore/V164-9-5-MW (accessed on 6 November 2021).
21. Jensen, N.O. A Note on Wind Generator Interaction; Risø National Laboratory: Roskilde, Denmark, 1983.
22. Shakoor, R.; Hassan, M.Y.; Raheem, A.; Wu, Y.-K. Wake effect modeling: A review of wind farm layout optimization using Jensen’s model. Renew. Sustain. Energy Rev. 2016, 58, 1048–1059.
23. VanLuvanee, D.R. Investigation of Observed and Modelled Wake Effects at Horns Rev Using WindPRO. Master’s Thesis, Department of Mechanical Engineering, Technical University of Denmark, Kongens Lyngby, Denmark, 2006.
24. Meissner, C. WindSim: Getting Started; WindSim AS: Tønsberg, Norway, 2019.
25. Meissner, C.; Vogstad, K.; Welle-Strand Horn, U. Park optimization using IEC constraints for wind quality. In Proceedings of the European Wind Energy Conference, Brussels, Belgium, 14–17 March 2011.
26. Hwang, C.; Jeon, J.H.; Kim, G.H.; Kim, E.; Park, M.; Yu, I.K. Modeling and simulation of the wake effect in a wind farm. J. Int. Counc. Electr. Eng. 2015, 5, 74–77.
27. Brower, M. Wind Resource Assessment: A Practical Guide to Developing a Wind Project; John Wiley & Sons: New York, NY, USA, 2012.
28. International Electrotechnical Commission (IEC). International Standard. IEC 61400-1, Wind turbines—Part 1: Design Requirements; IEC: Geneva, Switzerland, 2005.
29. Bureau of Energy of the Republic of China (BEROC). National Electricity Supply and Demand Report in Taiwan; BEROC: Taipei, Taiwan, 2021.
30. National Development Council (NDC). Middle- and Long-Term Projection of Social and Economic Parameters for Greenhouse Gas Phase Control Targets; NDC: Taipei, Taiwan, 2018.
31. Council for Economic Planning and Development (CEPD). Projection of Population from 2010 to 2060 in Taiwan; CEPD: Taipei, Taiwan, 2010.
32. Sun, W.-L. Solar PV will increase according to the National Electricity Supply and Demand Report 2019–2020. News of Environmental Information Center, 13 May 2021. Available online: https://e-info.org.tw/node/231060 (accessed on 24 March 2021).
33. Environmental Protection Administration (EPA). National Communication of Taiwan under the UNFCCC. 2018. Available online: https://ghgrule.epa.gov.tw/report/report_page/33 (accessed on 14 July 2021).
34. Jacobson, M.Z.; Delucchi, M.A.; Cameron, M.A.; Mathiesen, B.V. Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes. Renew. Energy 2018, 123, 236–248.
35. IPCC. Renewable Energy Sources and Climate Change Mitigation; Special Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK, 2012.
36. Ministry of Economic Affairs (MOEA). Report of Demand and Supply of Domestic Electricity in 2018; Ministry of Economic Affairs: Taipei, Taiwan, 2019.
37. Bureau of Energy of the Republic of China (BEROC). Minutes of the Second Conference of the Year 2021 for Examining the Feed-in-Tariff of the Electricity Generated by Renewable Energy Sources. Available online: https://www.moeaboe.gov.tw/ECW/renewable/content/ContentLink.aspx?menu_id=778 (accessed on 24 March 2021).