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Prospects of wind energy on Penghu Island, Taiwan

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Abstract. This study applied long-term wind speed data from Penghu and Dongjidao weather stations to simulate the wind energy production for eight onshore and one offshore wind farms at Penghu Island, Taiwan by a commercial software package, Wind Atlas Application Program (WAsP). In addition, the RET Screen software suite was also applied to analyze economic characteristics of these nine wind farms (WFs). The results show that the capacity factors (CFs) of the nine wind farms mentioned above are in the range of 44.5% to 49.1%. In addition, utilizing 1.8-MW wind turbines (WTs) for all onshore WFs was the most feasible selection among the four potential types of WTs (600, 900, 1,800 and 3,600 kW) considered. 3-MW WTs selected for the offshore WF can produce the most wind energy and the smallest wake loss among the three possible types of WTs (1, 2 and 3MW). As a consequence of implementing these WFs, the emission of about 680,977 tons carbon dioxide (tCO_2) into the local atmosphere in Penghu Island annually could be avoided. Finally, based on the payback periods achieved, the order of implementation of the considered WFs can be identified more clearly. Longmen WF should be the first priority, and the next one should be SiyuWF and so on. Besides, this study provides much useful information for WF planning on Penghu Island.

Keywords: wind energy; wind turbine; wind farm; carbon dioxide; Penghu Island

1. Introduction

In the past decade, the rapid development of renewable energy, such as hydropower, ocean energy, biomass energy, solar energy, and wind energy has demonstrated its significance for electric power systems. Of all these renewable energy sources, wind energy is the essential one. At the end of 2013, the annual installed capacity of wind turbines worldwide was about 35,301 MW and the global cumulative installed capacity was approximately 318,117 MW (Council 2014).

Recently, many researchers have become involved in the evaluation of renewable energy. For example, In the Kingdom of Saudi Arabia, there are many researchers focused on the profitable development of wind energy. The authors (Rehman *et al*. 2003) carried out a wind power cost assessment at twenty locations within the Kingdom of Saudi Arabia. The result shows that the minimum production cost about 0.0234 US$/kWh is at Yanbo by using 2,500-kW WTs while Shafiqur Rehman *et al*. (2011) analyzed and assessed the economic characteristics of a 20-MW

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WF. This WF could generate 59,037.7 MWh each year with CF of 33.7%.

In Algeria, there are many researchers carrying out wind energy evaluation over the country. Himri *et al*. (2008) presented that the CF at Adrar WF was the highest of 38%. In the southwestern region of Algeria, at a height of 17 m above ground level (AGL) the average wind speed over 7.5 m/s was found by using Wind Atlas Analysis and Application Program (WAsP) (Himri *et al*. 2009, Himri *et al*. 2010). In Tindouf, the emission of roughly 23,252 tons of carbon dioxide (tCO_2) into local atmosphere annually can be avoided if the installation of a 30-MW WF is completed (Himri *et al*. 2012).

Wind resource assessment at seven locations in Jordan was explored by building a 100-MW wind farm in each of these locations (Alsaad 2013).The research found that the annual mean wind speed of all locations was over 6.83 m/s. The impact of obstacles on small wind turbine analyzed based on neural network shelter model (Andrew and Lubitz 2011). Moreover, an onshore wind farm in Jiangsu, China was carried out by selection of Vestas V80-2MW wind turbines (Zhou *et al*. 2011). Lili *et al*. (2012) investigated wind characteristics of a strong typhoon in China. In Vietnam, the authors found by measurement that the annual wind power density is higher than 200 W/m^2. Huge wind energy resources located in Vietnam are described in (Nguyen 1996, Nguyen 2007, Do and Sharma 2011, Tran *et al*. 2012, Tran *et al*. 2013). Their results have pointed out that the windiest area is in Ninh-Thuan province and the average wind speed was found to be over 10 m/s at a hub height of 100 m AGL.

Numerous researchers have attempted to study and evaluate the wind energy in Taiwan. These researchers have come to conclude that there are abundant wind energy resources in Taiwan. The research in (Chang *et al*. 2003) concluded that the capacity factors of 25 selected sites are in the range of 45% to 64.2%.On the west coast and in the Penghu Archipelago is abundant wind energy. It mostly comes from the northeast direction with average wind speed above 10.5 m/s (Fang *et al*. 2013, Chen *et al*. 2012). Especially, the wind energy in Penghu Island is especially high in spring and winter seasons (Tran *et al*. 2012) due to the wind usually being strong in these seasons. The annual energy production of the Jhongtun WF was 19.87 GWh with CF over 40% (Wen *et al*. 2011).

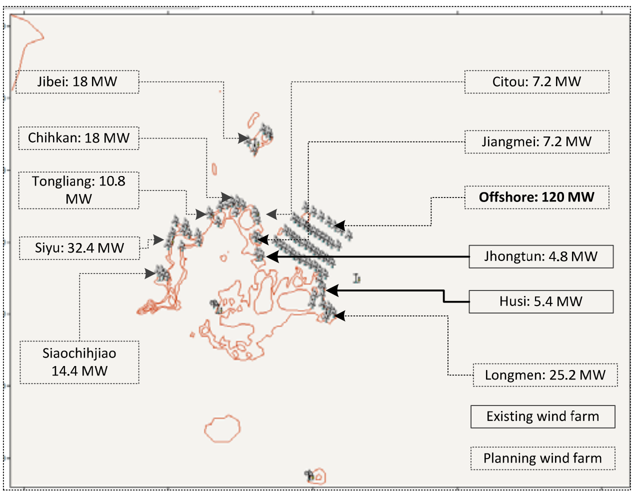


Fig. 1 Geographical distribution of potential wind farms in Penghu country

On the other hand, there are many researchers focusing on wind energy on Islands. For example, Calero and Carta (2004) presented the development of wind energy at Canary Island in Spain as well as wind resources in Bangladesh, on Kutubdia Island, where wind power potential was also assessed by using WAsP. The Repower 5-MW WT was used as a pilot test to analyze the feasibility of a wind farm at Young wang in Korea (Lee *et al*. 2013). Similarly, on Penghu Island, Taiwan, many researchers have investigated wind energy resources as well as the effects of wind farms on the power system (Yuan *et al*. 2011, Tran *et al*. 2012, Wu *et al*. 2013, Yuan *et al*. 2013). These researchers have showed that Penghu Island is an ideal Island for developing wind energy.

Based on the review of research literature on the wind energy development, this study focuses in more detail on wind energy assessment for Penghu Island with regard to eight onshore and one offshore wind farms. Fig. 1 presents the geographic location of each wind farm. The wind energy resource of the whole Island is investigated for practical potential locations by using WAsP as well as using RETscreen4 software to evaluate the economics of each wind farm. This study will recommend the installation priority of wind farms based on capital costs and payback periods.

2. Wind energy status in Taiwan

Taiwan is located in the tropical region, spread across a total land area of 35,980 km^2. It is a mountainous country with the hottest temperature in summer (about 38^{o}C from June to August) while the average temperature of the other months is nearly 25^{o}C. The population in Taiwan was estimated in December 2013 at 23,373,517, making it the sixteenth most densely populated country in the world with a population density of 646 people per km^2. Fig. 2 shows the installed capacity of Taiwan's power plants at the end of 2013: Most energy supplied comes from natural gas, coal and nuclear power plants with approximately 37%, 28% and 13% ratios, respectively while renewable energy makes up about 7%, of which wind energy occupied roughly 1.5% (614 MW). Fig. 3 presents the distribution of existing wind farms in Taiwan. Currently, the number of wind farms in Taiwan is growing. There are 23 wind farms with a total capacity 614 MW. The biggest one is located in Miaoli County with an installed capacity of 42 MW.

There are three wind farms located on remote islands: A Jin-Sha wind farm with rated capacity 12 MW is located in Kim-Men County. Husi and Jhongtun WFs are located in Penghu County. The Hu-Si wind farm with rated capacity of 5.4 MW is composed of six units of Enercon E44-900kW wind turbines. The Jhongtun wind farm has 4.8 MW rated capacity. The wind farm is composed of eight units of Enercon W40-600kW wind turbines.

Recently the Taiwan government has proposed a project to develop wind energy on Penghu Island by providing grand of 250 million New Taiwan Dollars (NTD) and a 50% equipment grant for developing wind farms with total rated capacity over 100 MW (Bureau of Energy). One of the targets of this project is to reduce carbon emission by 50% in 2015 and build 450 onshore and 600 offshore wind turbines with a total 4,200 MW rated capacity before 2030 (Wu *et al*. 2013).

At the present, the electric power supply for Penghu Island is predominantly from thermal power plants with 12 units of 10 MW each while wind energy makes up 10.2 MW of total installed capacity. This fact demonstrates that Penghu Island has abundant wind energy (Chen *et al*. 2010, Yuan *et al*. 2011, Tran *et al*. 2012, Yuan *et al*. 2013). Currently, the annual energy production is over 35,740 GWh with about 40% of CF (Wen *et al*. 2011). Therefore, Penghu Island is an ideal area to develop wind energy.

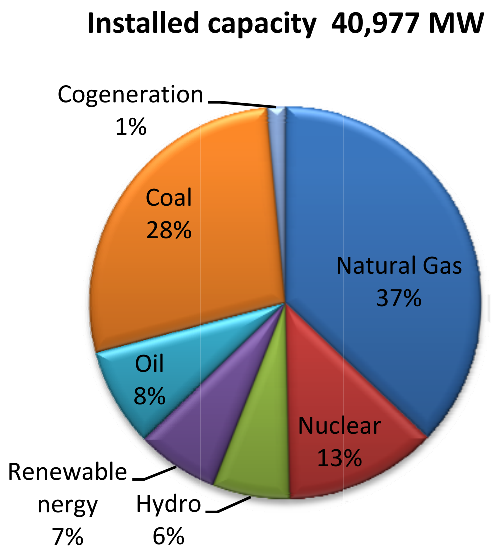


Fig. 2 Total installed capacity of Taiwan's power plants at the end 2012 (Taipower 2013)

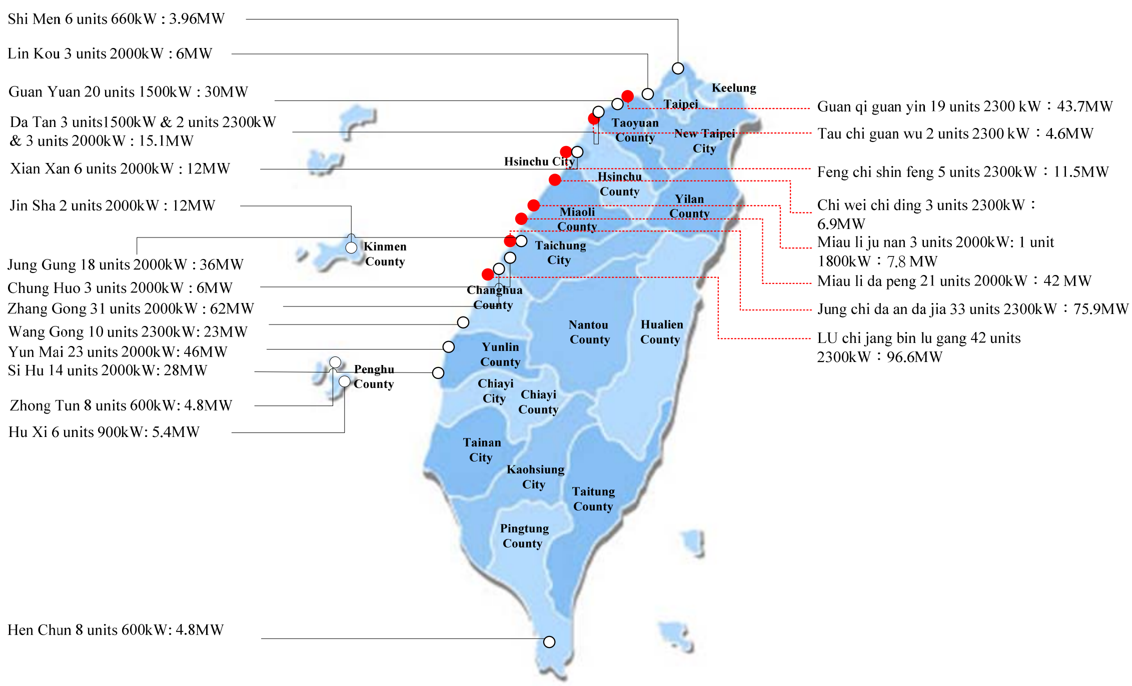


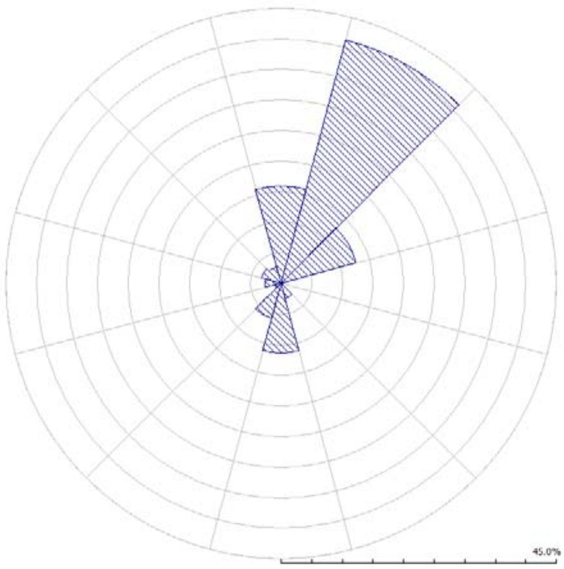
Fig. 3 Distribution of installed wind farms in Taiwan

3. Wind data and site description

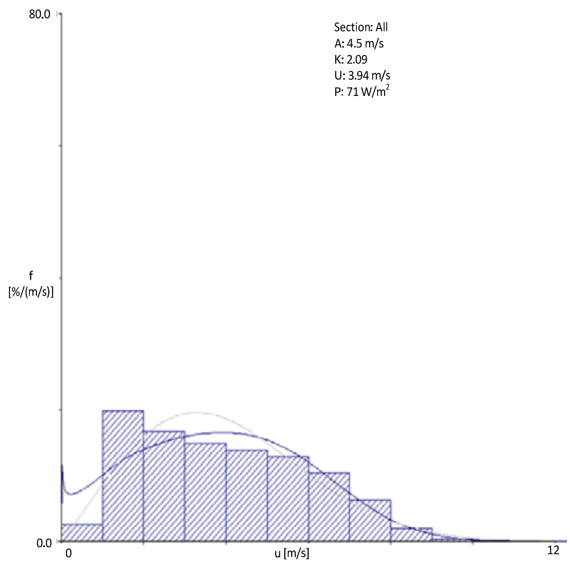
Central Weather Bureau (CWB), the Ministry of Transportation and Communications, R.O.C. supported this research by providing daily wind speed data. Dongjidao is a small island of Penghu county with an average elevation of around 10 m above sea level and has little surface roughness at the meteorological station. Therefore, the measured wind data is not much affected by surrounding obstacles. The Penghu meteorological station is located near a densely populated area; therefore, obstacles around the station do affect wind data.

The wind rose and wind speed frequency distribution were generated by using WAsP software. Fig. 4 shows the wind rose at Penghu station. The major direction of wind origin is from the northeast with 42% of wind coming from the N.E. The average wind speed and wind density are 3.94 m/s and 71 W/m^2, respectively. Fig. 5 summarizes the wind climate of this station. It can be observed that wind speed and wind power density are proportional with hub height. The numbers for wind decreases when roughness length increases from zero to 1.5 m.

At the Dongjidao station, the most wind energy comes from the north and northeast directions with 39% and 29%, respectively. The average wind speed and wind power density are 7.74 m/s and 535 W/m^2, as shown in Fig. 6. Wind climate for the Dongjidao station is summarized in Fig. 7. The wind speed increases when the height gains from 10 m to 200 m. Otherwise, wind speed decreases when roughness length increases from 0 m to 1.5 m.



(a) Wind rose



(b) Wind distribution

Fig. 4 Wind rose and wind distribution in Penghu station

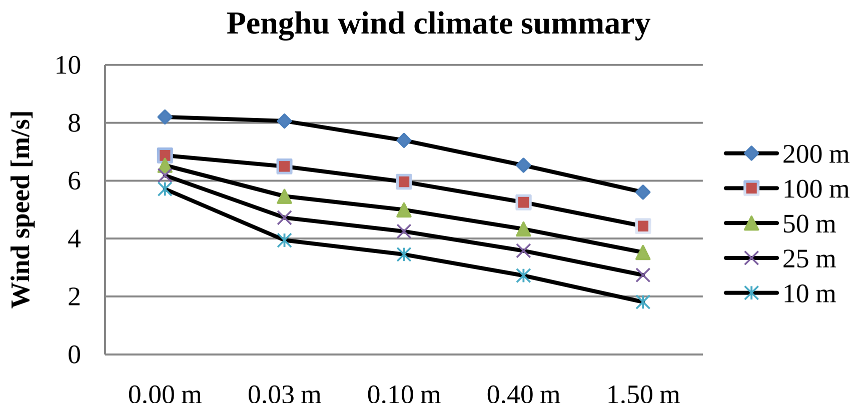
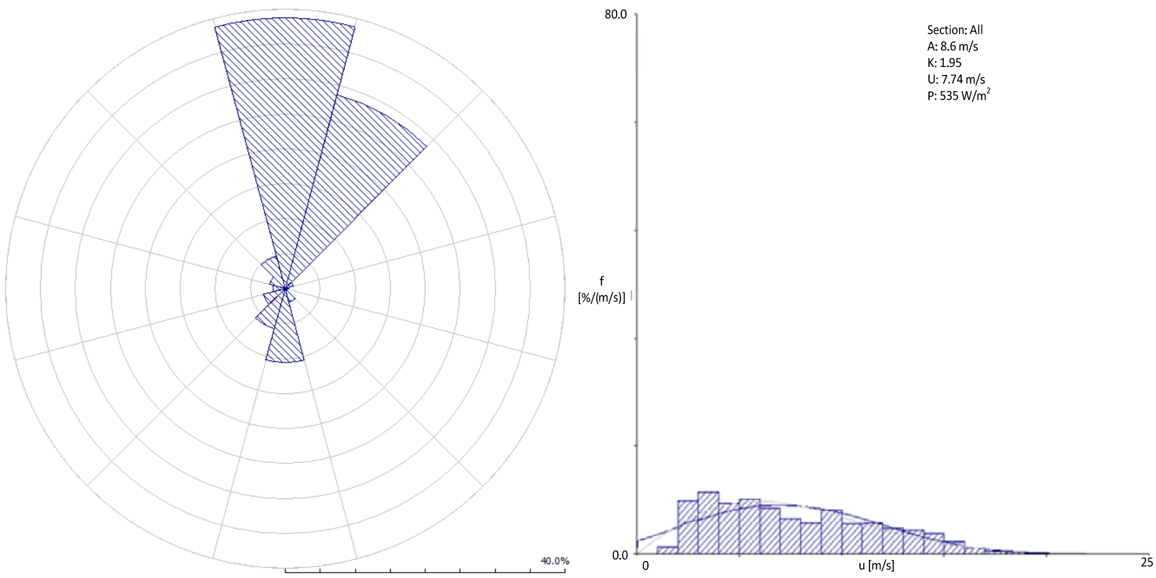


Fig. 5 Regional wind climate summary Penghu station



(a) Wind rose (b) Wind distribution

Fig. 6 Wind rose and wind distribution in Dongjidao station

4. Wind resource in Penghu Island

4.1 Eight onshore wind farms

The energy yield from the 10 onshore wind farms was obtained by using WAsP software. For each wind farm, we adopted four types of wind turbines (600 kW, 900 kW, 1.8MW and 3.6 MW) to estimate the annual energy productions of the wind farms. Figure8 presents the annual energy productions with the highest and lowest annual energy productions of 1.8 MW and 600 kW wind turbines for all wind farms, respectively. For example, Longmen wind farm produces 112.988 GWh when using 1.8 MW wind turbines; however, the number decrease to 67.535 GWh when using 600 kW wind turbines. The most important finding is that employing 1.8 MW wind turbines is the optimal choice.

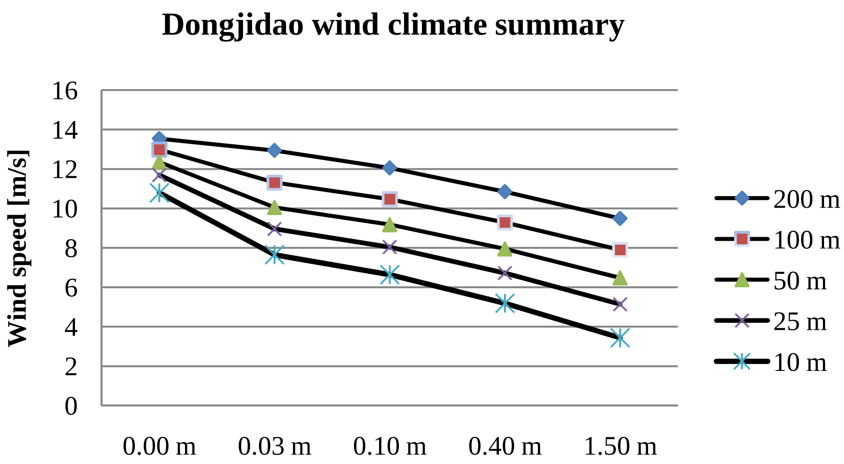
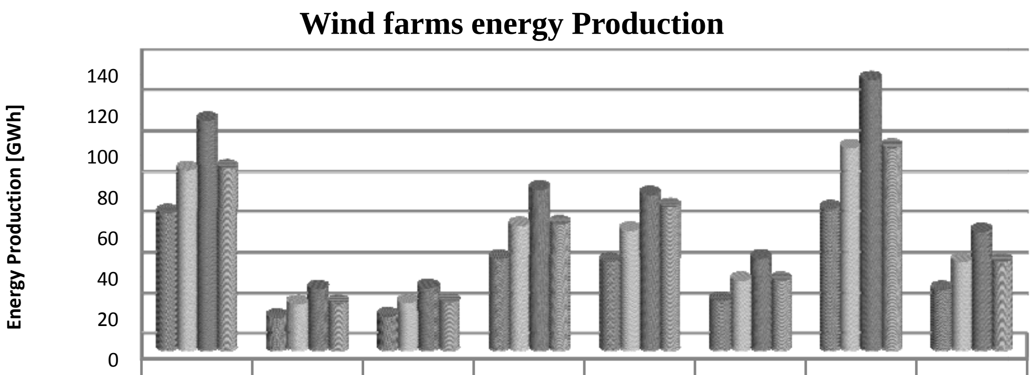
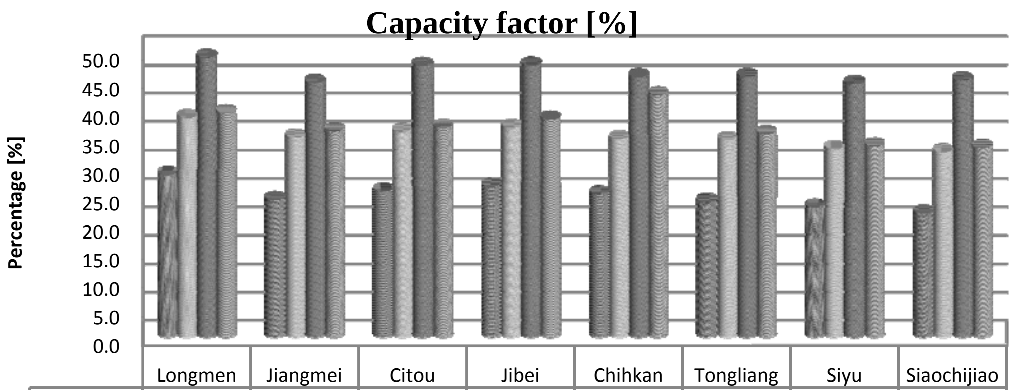


Fig. 7 Regional wind climate summary at Dongjidao station



	Longmen	Jiangmei	Citou	Jibei	Chihkan	Tongliang	Siyu	Siaochijiao
600 kW	67.535	15.946	16.574	45.008	43.535	24.344	69.455	29.681
900 kW	88.679	22.657	23.199	61.219	58.806	34.165	99.456	43.451
1800 kW	112.988	30.051	30.592	79.056	76.406	45.154	133.011	58.238
3600 kW	89.52	22.838	23.529	61.918	70.528	34.169	99.792	43.35

Fig. 8 Summary of energy productions for onshore wind farms



	Longmen	Jiangmei	Citou	Jibei	Chihkan	Tongliang	Siyu	Siaochijiao
600 kW	28.5	24.1	25.6	26.5	25.1	23.8	22.8	21.8
900 kW	38.5	35.1	36.1	36.8	34.8	34.6	33.0	32.5
1800 kW	49.1	44.7	47.7	47.7	45.7	45.7	44.5	45.1
3600 kW	39.4	36.1	36.8	38.2	42.5	35.7	33.5	33.2

Fig. 9 Capacity factors of the proposed onshore wind farms

Fig. 9 summarizes the CFs of the intended wind farms. It can be observed that the Longmen wind farm possesses the maximum CF of 49.1% when employing1.8-MW wind turbines while the minimum CF is at Siaochihjiao wind farm of 21.8% using 600-kW wind turbines. The results indicated that the wind farms should be developed as a good source of electricity and as the way to reduce CO_2 production.

4.2 Offshore wind farm 120 MW

In the offshore wind farm, the observed wind climate was interpolated from Penghu and Dongjidao stations. An interpolator 2.2 tool in WAsP software was used to estimate the wind climate in offshore wind farms. Figure10 shows the result of the combination of wind roses of three wind farms. It is observed that most wind energy at the intended offshore wind farms comes from the northeast direction.

For the offshore wind farm, three types of wind turbine with 1, 2 and 3 MW rated capacities are applied to estimate the annual energy productions of the proposed offshore wind farm. In Fig. 11, there is a clear trend of increasing energy production when the size of WT increases from 1 MW to 3 MW. The gross AEP is 514.203 GWh and 355.854 GWh when using 3-MW and 1-MW WT, respectively. In addition, the wake loss is the lowest when using 3-MW WT. An important finding is that using 3-MW WT for this offshore wind farm will get the most energy production and least wake loss.

5. Wind energy economic analysis

In this section, we analyze the economics of each wind farm by using RETScreen software (RETScreen 2013). The Vestas V100-1.8MW wind turbine is used for all onshore wind farms while the VestasV90-3MW WT is used for the offshore wind farm. Recently, in Taiwan, one MWh of electric power energy produces 0.624 tCO_2 .Table 1 provides financial input parameters for economic analysis. The parameters include the inflation rate, debt ratio, debt interest rate and the life cycles of the project wind farms. In Taiwan, the capital cost of onshore and offshore wind farms are estimated 1,500 and 2,000 $/kW, respectively (Taipower 2013). In addition, for this offshore wind farm there will be a grant of US$10,333,333 from the Energy Promotion Project by the Bureau of Energy, Ministry of Economic Affairs, R.O.C. (Bureau of Energy).

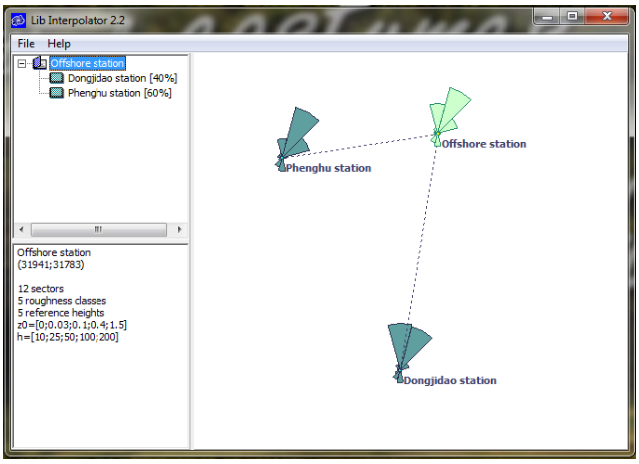
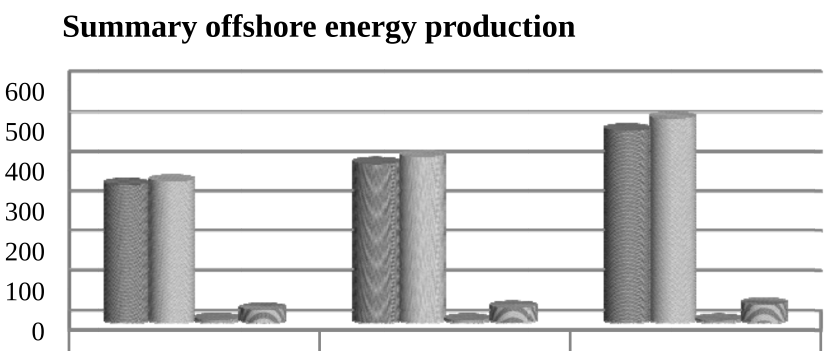


Fig. 10 Observed wind climate of the offshore wind farm



	1 MW	2 MW	3 MW
Net AEP [GWh]	346.854	400.002	484.355
Gross AEP [GWh]	355.854	417.651	514.203
Wake loss [%]	7.59	6.345	5.8
PCF [%]	33.00	38.05	46.08

Fig. 11 Summary of energy production of intent offshore WF

Table 1 Input parameters for economic analysis (Rehman *et al*. 2003, Ertürk 2012)

Items	**Unit**	**Parameters**
Inflation rate	%	3
Project life	yr	25
Debt ratio	%	100
Debt interest rate	%	5
Debt term	yr	25
Onshore WF cost	$/kW	1,500
O&M annual cost	$/kW	25
Offshore WF cost	$/kW	2,000

The analysis is also carried out to reduce greenhouse gas (GHG) emission entering into the atmosphere when using wind to generate electricity. Fig. 12 shows the annual GHG emission reductions for each WF. The results value point out that655,131 tCO_2 per year can be avoided which shall make Penghu Island a green and clean island.

Fig. 13 presents the annual saving and income from wind farms. Three wind farms, such as the offshore, Siyu and Longmen wind farms gain the most income of US $66,097, 16,840 and 14,740, respectively. The total electricity and GHG reduction income for all wind farms is US $139,831 million.

In the analysis, the financial viability is pointed out in terms of the Pre-tax internal rate of return (IRR) and simple payback period. As shown in Fig. 14, Longmen has highest Pre-tax IIRR with 30.25% and shortest simple payback in 3 years, which are important factors to consider when doing priority planning for installing winds farms.

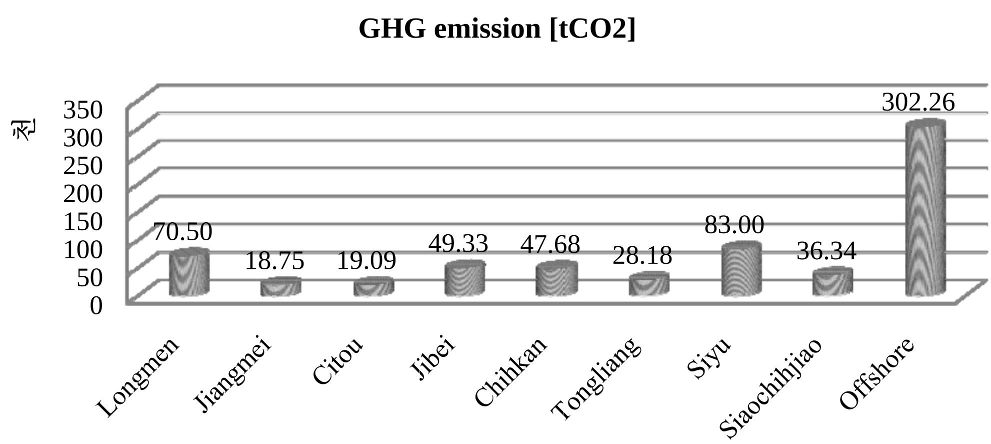


Fig. 12 Greenhouse gas emission reduction of the proposed wind farms

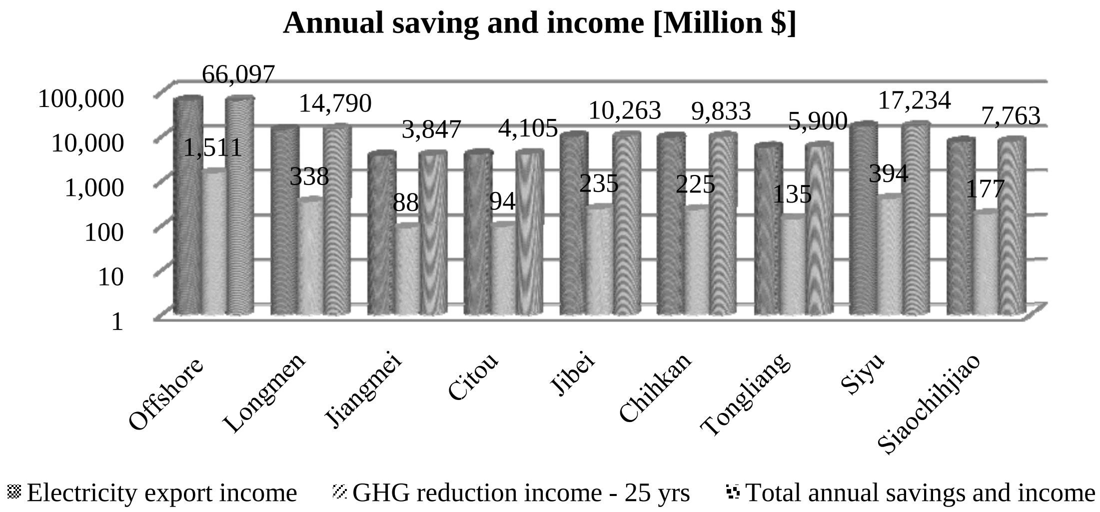


Fig. 13 Annual saving and income of wind farms

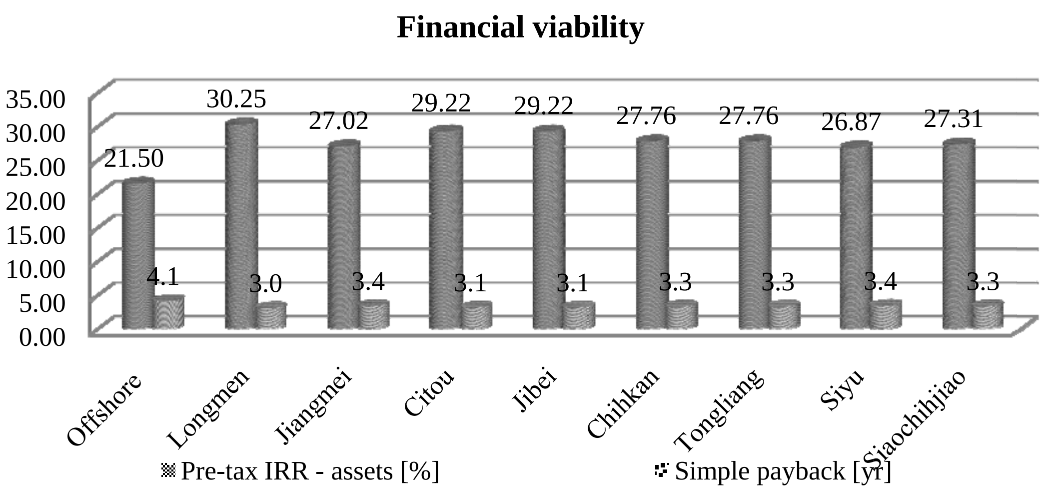


Fig. 14 Financial viability of wind farms

6. Conclusions

The wind data used in this study were from two stations, Penghu station with 12 years (2001-2013) data and Dongjidao station with 5 years (2009-2013) data. The study utilizes practical wind speed and geography to simulate the energy productions and perform economic analysis for all proposed wind farms by WAsP and RETScreen software, respectively. The study draws the following conclusions:

- At 100 m height AGL with roughness length of 0.03 m, the average wind speeds are 6.49 m/s and 11.31 m/s at the Penghu and Dongjidao stations, respectively.
- The largest wind energy comes from the northeast and the north. These 2 directions account for north direction of 42% and 39% of the wind at Penghu and Dongjidao stations, respectively.
- In the onshore wind farm, 1.8-MW wind turbine is the **most feasible selection** among the potential types discussed for producing wind energy.
- The highest capacity factor of 49.1%is obtained at Longmen wind farm.
- In the offshore wind farm, 3-MW wind turbine will generate the most electric energy and produce the least wake loss. The CF of this wind farm is 46.08%. The offshore WF could produce 346.854 GWh of electricity annually.
- If all wind farms are developed and operated, the amount of 655,131-tCO2 GHG annually emission entering into the Penghu environment can be avoided.
- The annual saving and income of all wind farms from electricity export and GHG reduction is about US $139,831 million.
- Longmen wind farm has maximum Pre-tax internal return rate of 30.25% and the minimum simple payback in 3 years.

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