Chapter

# Evaluation of PV-Wind Hybrid Energy System for a Small Island

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## Abstract

Hybrid renewable energy system (HRES) consists of more than one type of renewable energy technology such as wind and solar. The main application of such energy systems is to provide electricity to remote areas such as villages and islands, where no other means of power generation are available. Present study includes the basic information about the working methodology and other characteristics of HRES. Furthermore, two case studies of HRES have also been included to demonstrate the practical working of such energy systems. In first case study the performance of a small HRES, consisting of photovoltaic (PV) panels and wind turbines installed at Deokjeokdo island in South Korea, has been analyzed using real time measured experimental data. Second case study deals with the techno-economic optimization of HRES designed for fulfilling yearly electricity consumption of Deokjeokdo island. Out of multiple HRES solutions, two systems were declared as the optimal solutions based on lowest net present cost (NPC) and lowest levelized cost of energy (LCOE).

**Keywords:** renewable energy, hybrid energy system, economic feasibility, lowest net present cost

## 1. Introduction

In order to develop an eco-friendly island, it is necessary to make electricity, heat and water independence using renewable energy as an energy source. Present study is aimed at developing a sustainable eco-friendly energy and water-independent community inside a small island called Deokjeokdo island—Incheon, South Korea. Considering the natural environment and geographical features with hills, a small communities called Urumsil town in Deokjeokdo island through eco-friendly energy sources based on a hybrid power system are developed. The hybrid power system consists of a small wind turbine, a photovoltaic panel, a pumped storage hydroelectricity and energy storage system. The renewable energy hybrid system can provide stable electricity and water to the island without greenhouse gas emission by fossil fuels. The Korea Institute of Civil Engineering and Building Technology (KICT) has signed a memorandum of understanding with Incheon city and is participating in the eco-island project centered on Deokjeokdo island. A local community in Deokjeokdo, Incheon city, was selected in 2013 to be developed as an environmentally-friendly energy and water independent community. A hybrid power system based on a small wind turbine, a photovoltaic panel, a pumped storage hydroelectricity and energy storage system was built. Through this arrangement, electricity is supplied to the community without diesel power generation.

### 1.1 Hybrid renewable energy system (HRES)

Hybrid renewable energy system (HRES) comprises of multiple sorts of sustainable power sources, for example, sun based and wind. The principle thought behind the idea of HRES is to give continues and maintainable supply of power to regions particularly far from primary terrains. A HRES can be associated with principle grid or it can likewise be an independent power producing unit, having its very own framework for storing surplus power, depending upon the nearby land conditions and some other monetary conditions. **Figure 1** demonstrates the working structure of a conventional HRES with pumped hydro storage (PHS) as energy storage system (ESS).

Recently, many case studies of installing HRES at a remote location have been conducted around the globe. For instance, Perez-Navarro et al. [1] designed a hybrid system consisting of wind-biomass in order to compensate and stabilize the power production of a 40 MW wind power plant in Spain. Apart from the main equipment, their designed HRES also consisted of other auxiliaries such as stand-by generators, separate ESS and biomass gasifier as well. The extra power generated by the biogas generator was used to compensate the low power production of wind farm. Borhanazad et al. [2] conducted a comprehensive study to investigate the wind conditions, solar radiations and hydro potential of multiple locations in Malaysia for rural electrification. Similarly, Zuberi et al. [3] estimated the biomass potential of Pakistan and concluded that biomass can contribute to generate almost 24% of the total electricity demand of the country. They covered biomasses such as municipal solid waste (MSW), bagasse and livestock in their study. They also presented an idea of stand-alone power generation system using biomass as raw fuel. Bhandari et al. [4] studied a very classic model of HRES for rural electrification, consisting of wind-PV-hydro as primary energy sources. They showed that installing such HRESs at very remote locations can be economically cheaper than connecting aforementioned areas with main grids. Mazzola et al. [5] designed a PV-biomass based HRES for a small town in India and conducted its economic feasibility as well. The authors mentioned that LCOE can be reduced up to 40% if

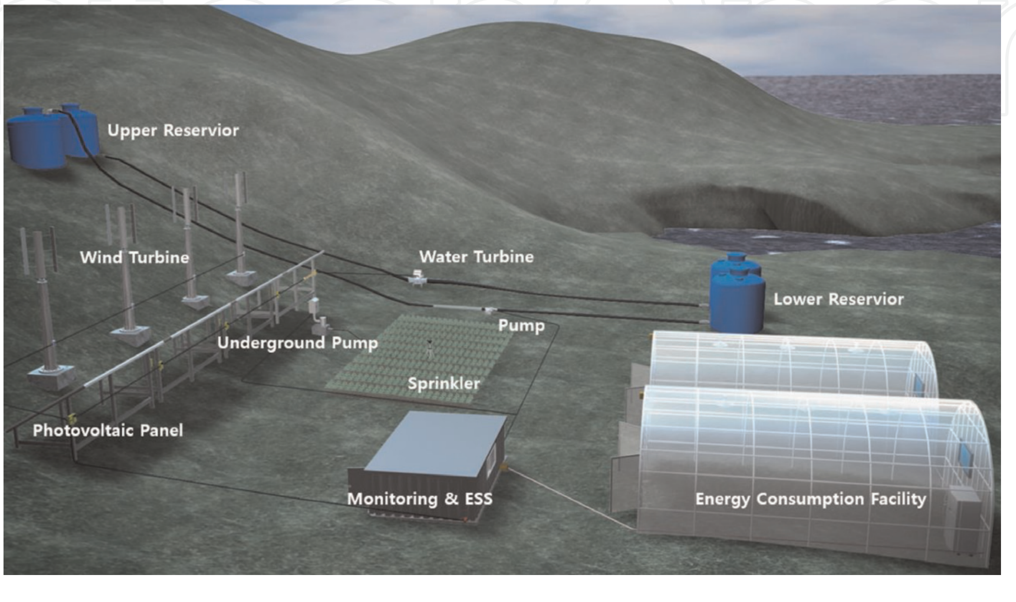


**Figure 1.**
*Conceptual design of HRES.*

compared with electricity generation from diesel generators. Ahmad et al. [6] investigated the HRES consisting of wind-PV-biomass as primary energy sources for electrification of a small town in Pakistan called the Kallar Kahar. The study was conducted for multiple load conditions and authors recommended the installation of HRES near aforementioned site on the basis of strong economical conclusions.

### 1.2 Deokjeokdo island in South Korea as test bed

Deokjeokdo island (latitude: 37.22°, longitude: 126.15°) is the biggest island in the Ongjin-kun area in South Korea, arranged 50 km far from Incheon ocean port. At the end of 2013, the total population of Deokjeokdo island was approximately 5000 and its area is 21 km$^2$. The island has a relatively large population engaged in

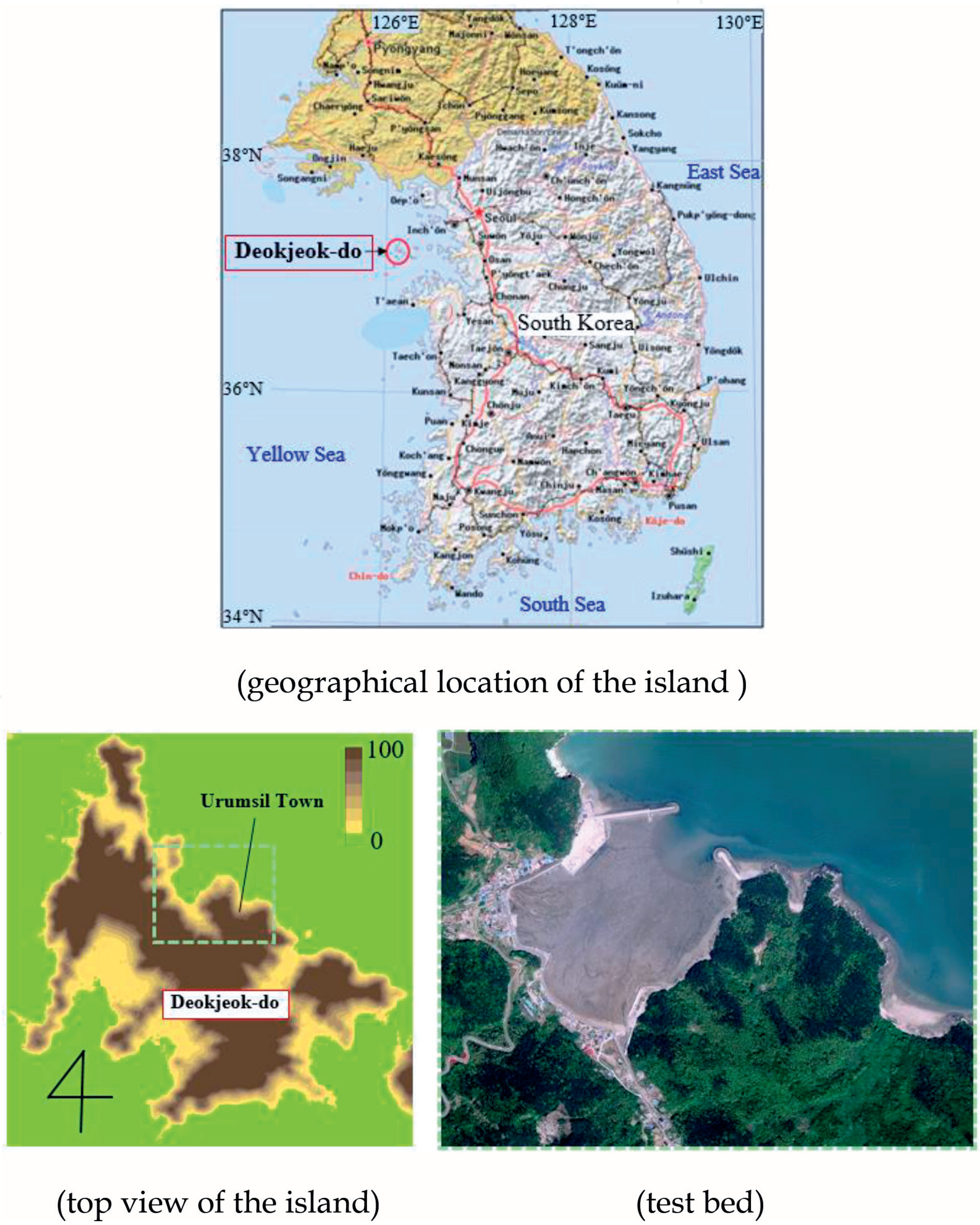


**Figure 2.**
*Geographical location of Deokjeokdo island in South Korea.*

agriculture and tourism, rather than fishing, and is actively developing tourism resources as Green Island. This island is excessively long way from primary land of South Korea, so it is not monetarily suitable to associate it with main framework for power transmission. Subsequently, this island has its very own power generation system fueled by diesel. In any case, the local government has demonstrated its enthusiasm to make Deokjeokdo island, a green island as far as power generation is concerned. Present study investigates the sustainable power source potential at the mentioned site and after that recommends an ideal HRES dependent on economic assessments.

**Figure 2** demonstrates geographical details of the Deokjeokdo including the Urumsil town and test bed of the hybrid renewable energy system.

## 2. Analysis of experimental HRES installed at Deokjeokdo island

Experimental HRES facility installed at Deokjeokdo island is shown in **Figure 3**. The experimental HRES consists of two Darrieus type vertical axis wind turbines (VAWT) and photovoltaic (PV) panels. The total capacity of this system is 24 kW, with each wind turbine rated at 1.5 kW and solar panels of 3 kW capacity, respectively. In order to record the wind conditions such as wind speed and wind direction, a vertical tower called the "wind master" has been installed at the local site, as shown in **Figure 3**. Anemometer and anemoscope are attached on wind master to record wind speed and wind angle, respectively. Solar panels are inclined at 30° to capture the maximum radiations from sun. This system was being monitored for two consecutive years, i.e., 2016 and 2018.

### 2.1 Wind potential estimation

Prior to assessing the power production from HRES, specifically from wind turbine, it is of immense importance to analyze the wind conditions of local site at first place. In current case, the wind data used for this purpose come from measured by wind master as mentioned above. **Figure 4** shows the season wise plots of wind characteristics in the form of wind rose. It is clear from the figures that prevailing wind direction is south-west (180–270°); with most frequent wind speeds are in the range from 2 to 3 m/s and spring is the "windiest" season. It is to be noted that wind data were measured at 10 m height.

Weibull probability density function (PDF) and cumulative density function (CDF) are two classical tools to study the wind characteristics of a region. Both functions can be defined as follows, respectively:

$$PDF = f(v) = (k/c)(v/c)^{k-1} \exp\left[-(v/c)^k\right] \ (v > 0; k, c > 0) \quad (1)$$

$$CDF = F(v) = 1 - \exp\left[-(v/c)^k\right] \quad (2)$$

where $k$, $c$ and $v$ are Weibull shape parameter, Weibull scale factor and wind speed, respectively. Shape factor and scale parameters are the defining parameters for Weibull distribution [7] and they determine the abscissa scale and the width of wind speed data distribution plot, respectively. There are many mathematical approaches to calculate $k$ and $c$ like graphical, maximum likelihood, empirical, power density and moment method [8]. Empirical method and method of Justus and Mikhail [9] will be used in this present study to estimate $k$ and $c$.


**Figure 3.**
*Experimental HRES at Deokjeokdo island.*

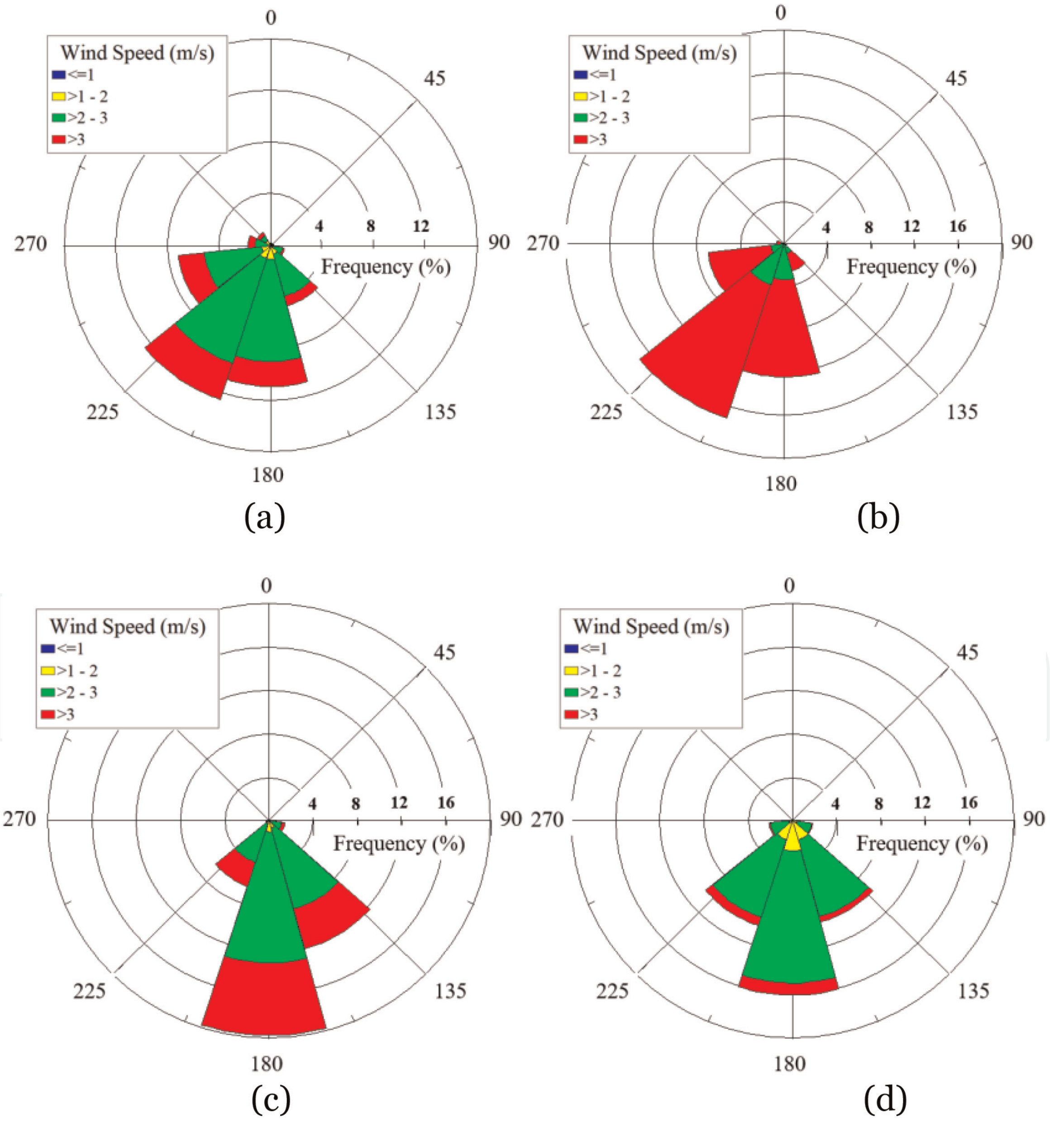


**Figure 4.**
*Wind rose at Deokjeokdo island (a) winter (b) spring (c) summer (d) fall.*

$$v_m = \frac{1}{n}\left[\sum_{i=1}^{n} v_i\right] \tag{3}$$

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(v_i - v_m)^2 \tag{4}$$

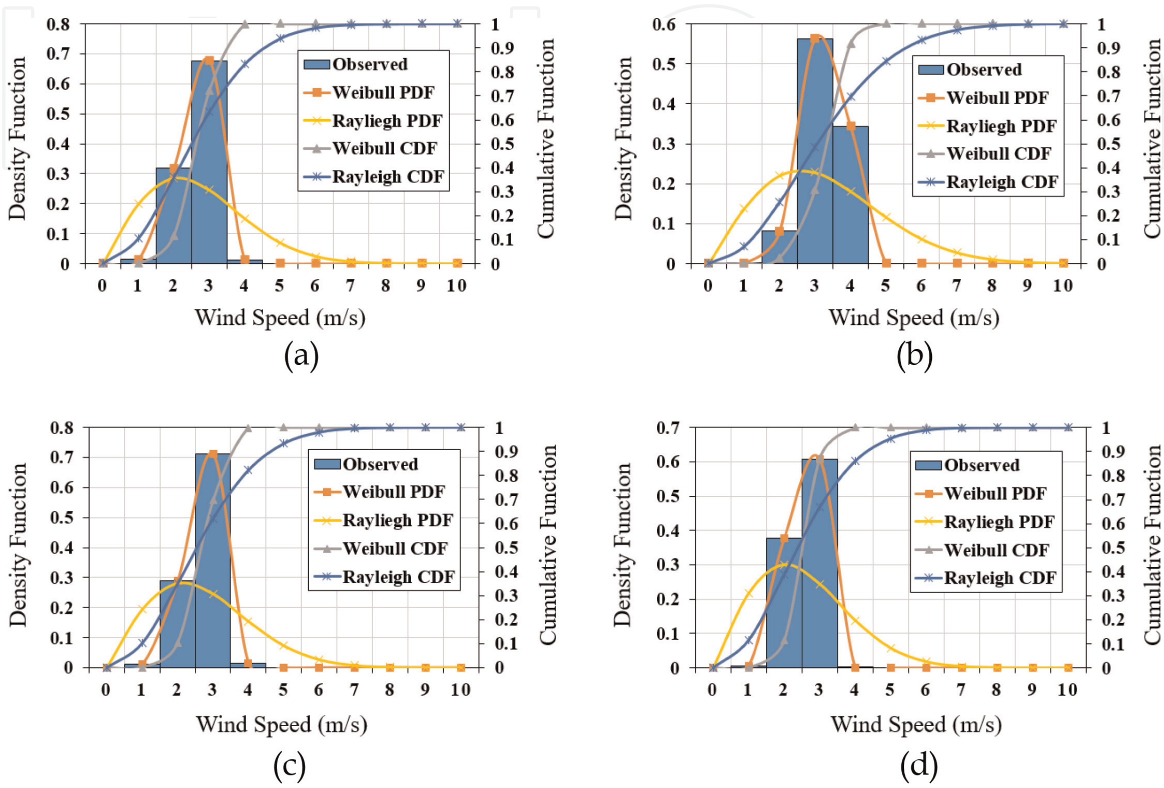


**Figure 5.**
*Weibull plots at Deokjeokdo island (a) winter (b) spring (c) summer (d) fall.*

| Angle range [°] | Percentage of total wind occurrence | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| [0–30] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| [30–60] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| [60–90] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| [90–120] | 2 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 2 | 1 | 1 | 1 |
| [120–150] | 8 | 4 | 2 | 3 | 5 | 14 | 12 | 14 | 15 | 8 | 9 | 5 |
| [150–180] | 23 | 18 | 13 | 23 | 29 | 43 | 43 | 36 | 36 | 24 | 28 | 17 |
| [180–210] | 32 | 36 | 33 | 47 | 46 | 35 | 36 | 35 | 34 | 37 | 36 | 28 |
| [210–240] | 26 | 31 | 35 | 24 | 19 | 6 | 7 | 12 | 12 | 24 | 20 | 26 |
| [240–270] | 8 | 10 | 15 | 3 | 2 | 0 | 0 | 1 | 1 | 6 | 5 | 14 |
| [270–300] | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 4 |
| [300–330] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 |
| [330–360] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 1.**
*Monthly variation in percentages of total wind speed according to wind direction ranges.*

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \quad (1 \leq k \leq 10) \tag{5}$$

$$c = \frac{v_m}{\Gamma(1 + 1/k)} \tag{6}$$

**Figure 5** shows the season wise Weibull plots for Deokjeokdo island prepared using 2 years measured data (2016 and 2017). These figures also show the curves for Rayleigh distributions (PDF and CDF), which are essentially Weibull distributions at $k = 2$. **Figure 5** reveals that the most frequently occurring wind during all the seasons is 3 m/s and spring has high wind speeds, as it was also concluded above from **Figure 4**.

**Table 1** explains the distribution of wind coming from different directions on monthly basis. **Table 1** also concludes the same as **Figure 4** that prevailing wind direction is south-west.

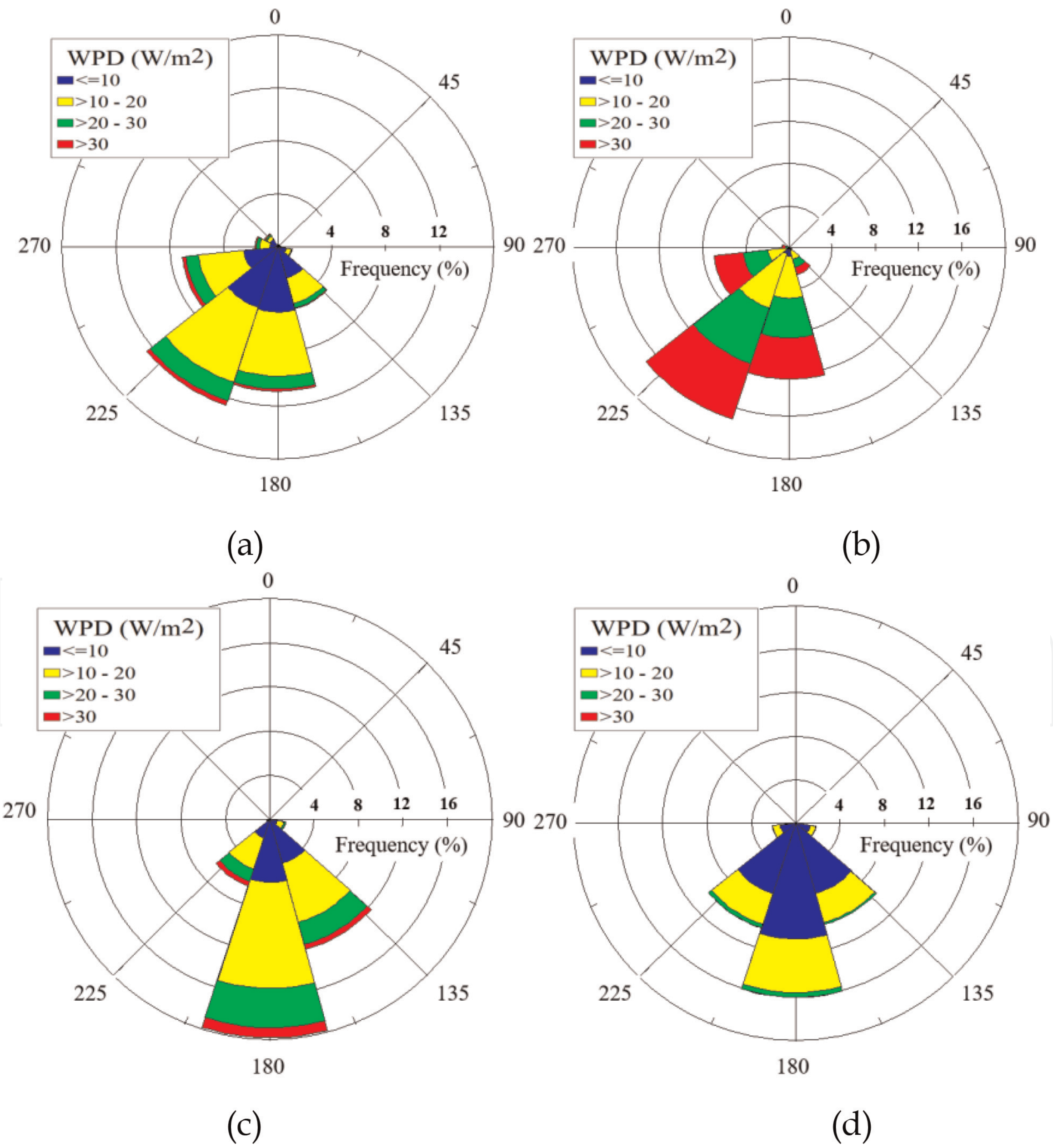


**Figure 6.**
*Observed WPD at Deokjeokdo island (a) winter (b) spring (c) summer (d) fall.*

**Figure 6** shows the wind power density (WPD) on the basis of seasons. The patterns being observed in **Figure 6** are very much identical to patterns of **Figure 4**.

### 2.2 Solar potential estimation

**Figure 7** shows the average solar radiations ($W/m^2$) over different major cities of South Korea. Daejeon has the highest solar radiations value (175 $W/m^2$) whereas Seoul has the lowest (145 $W/m^2$).

Similarly, **Figure 8** shows the average values of daily solar radiations and clearness index over Deokjeokdo island, on monthly basis.

### 2.3 Estimation of power production from wind turbine

This section presents the results such as power production from small Darrieus VAWT. **Table 2** summarizes the important details about the wind turbine whereas **Figure 9(a)** shows the geometrical dimensions and **Figure 9(b)** shows the power curve of wind turbine installed at Deokjeokdo island. The blade height and chord of the turbine rotor are 3 and 0.2 m, respectively. Design blade section profile is NACA0015, while the rotational diameter of the turbine rotor is 2 m. Rated wind speed and rotor rotational speed are 13.5 m/s and 300 rpm, respectively.

**Figure 10** shows diagram for data acquisition system to obtain experimental data from the wind turbine and the wind master. Turbine performance data is measured between turbine and power transducer, thus contains power generator loss. Power output is stored in battery bank first, then supplied to users after converting to AC voltages.

The commercial code, SC/Tetra, has been employed in the present numerical simulation. It solves the governing fluid dynamics equations, which consist of

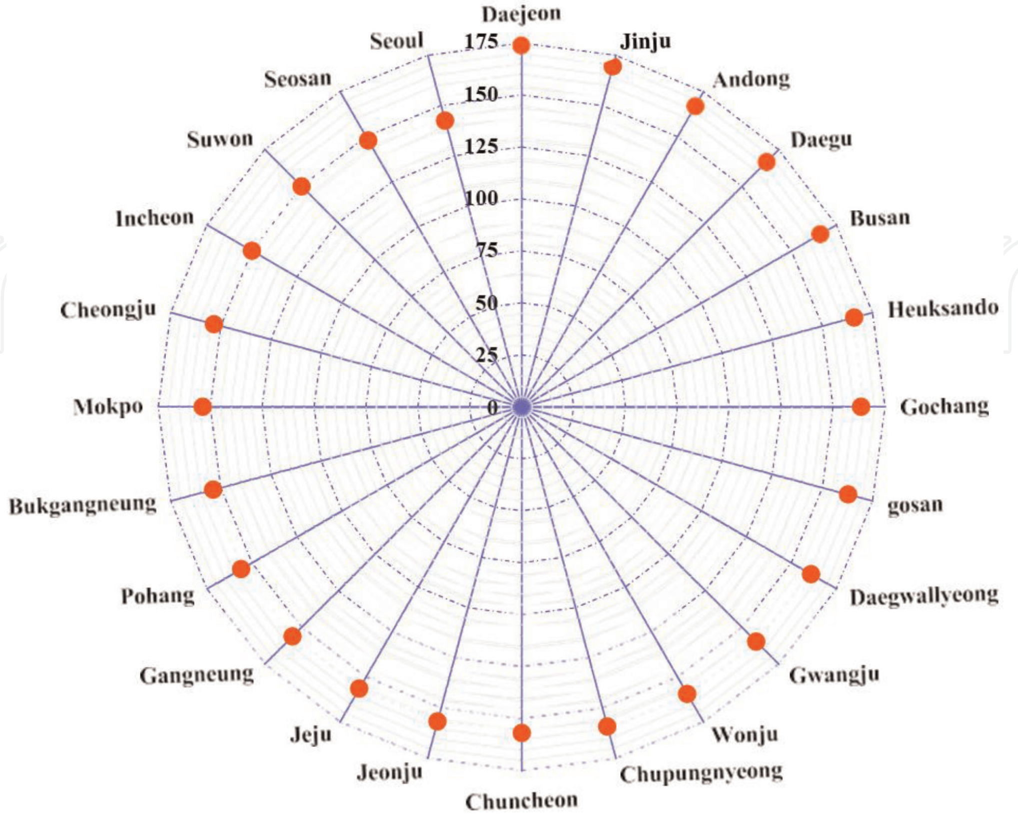


**Figure 7.**
*Solar radiations over different cities of South Korea ($W/m^2$) [10].*

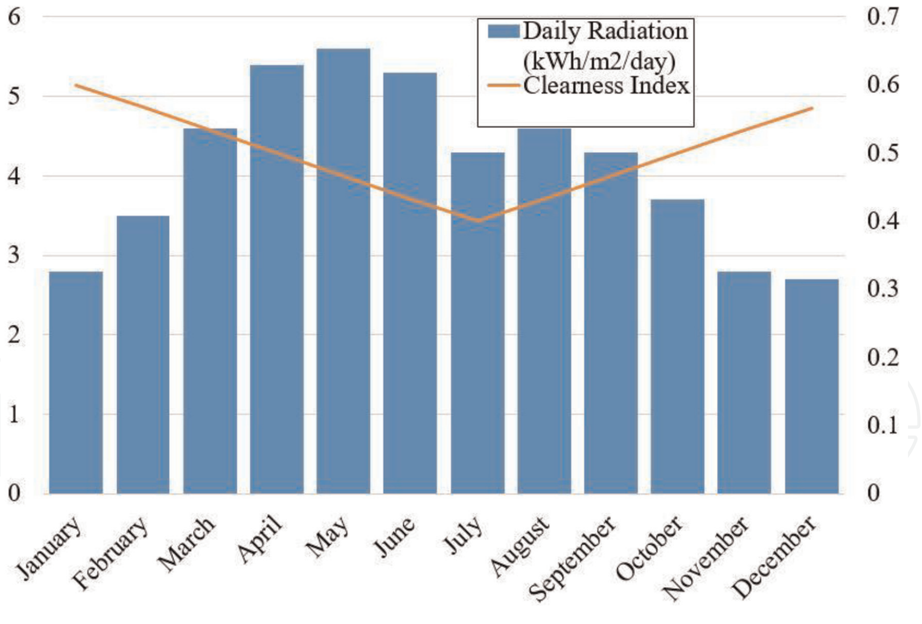


**Figure 8.**
*Solar radiations over Deokjeokdo island [10].*

| Parameter | Value |
|---|---|
| Rated power, kW | 1.5 |
| Rated wind speed, m/s | 13.5 |
| Rated rotational speed, RPM | 300 |
| Cut-in wind speed, m/s | 3 |
| Chord length, m | 0.2 |
| Blade length (height), m | 3 |
| Rotational diameter, m | 2 |
| Blade profile | NACA0015 |

**Table 2.**
*Specifications of test Darrieus wind turbine.*

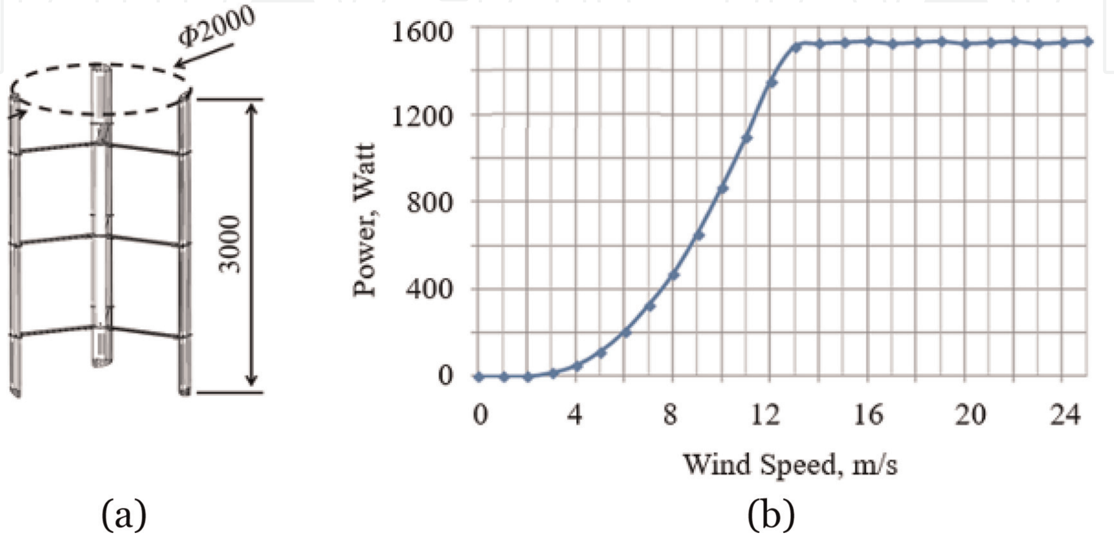


**Figure 9.**
*Darrieus wind turbine installed at Deokjeokdo island (a) rotor dimensions (b) power curve.*

continuity and unsteady Reynolds averaged Navier-Stokes (URANS) equations. The computational domain which consists of rotational and stationary domains, is shown in **Figure 11**. Tetrahedral, prism and pyramid elements have been used overall but mostly only tetrahedral element type is employed. The total number of meshing elements is around 13 million, whereas the total number of nodes is approximately 3.5 million in complete domain. Shear stress transport (SST) model with a scalable wall function is employed to estimate eddy viscosity. In terms of the boundary conditions, a velocity of 5 m/s is specified at the inlet, and natural outflow condition is imposed at the outlet.

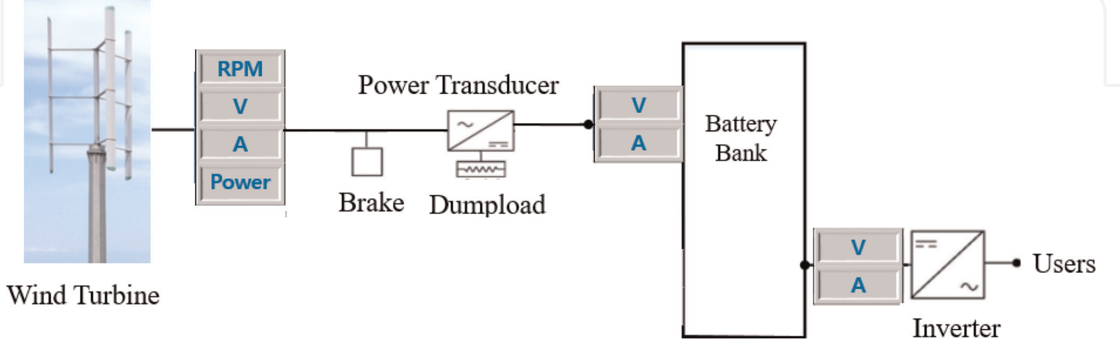


**Figure 10.**
*Diagram for data acquisition system.*

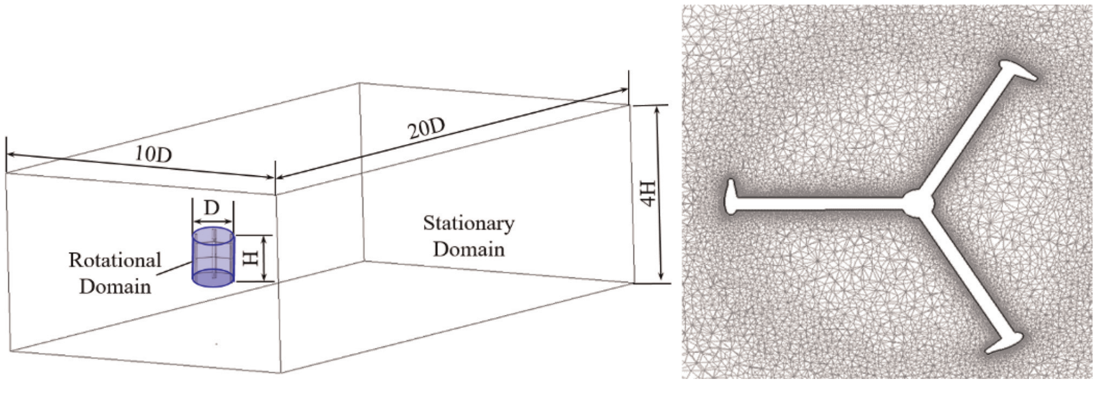


**Figure 11.**
*Computational domain (left) and grid system around turbine rotor (right).*

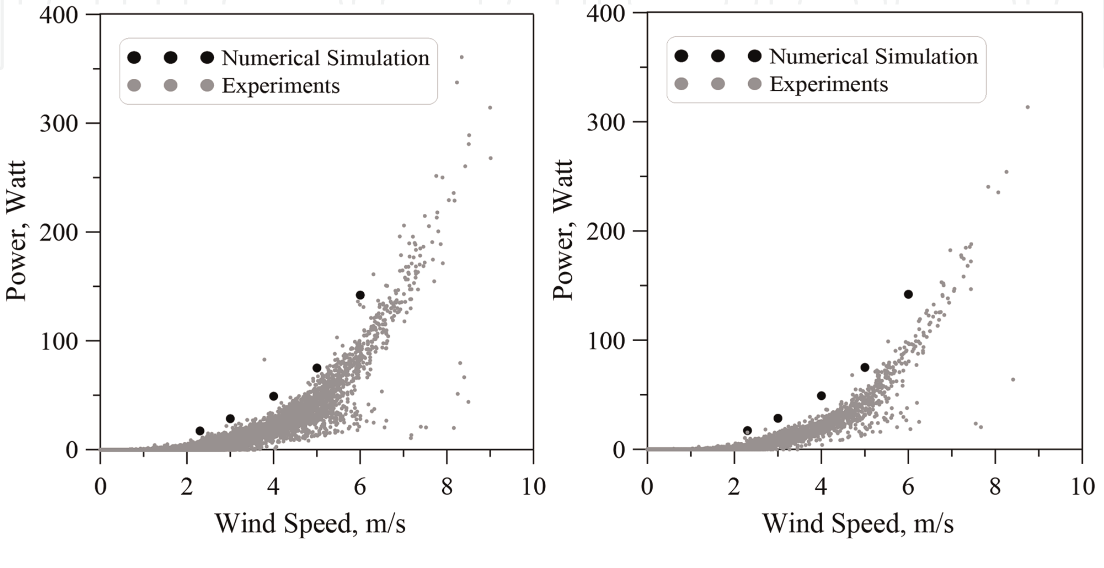


**Figure 12.**
*Comparisons of turbine power between numerical simulation and experimental measurement for 10-min average (left) and 30-min average (right).*

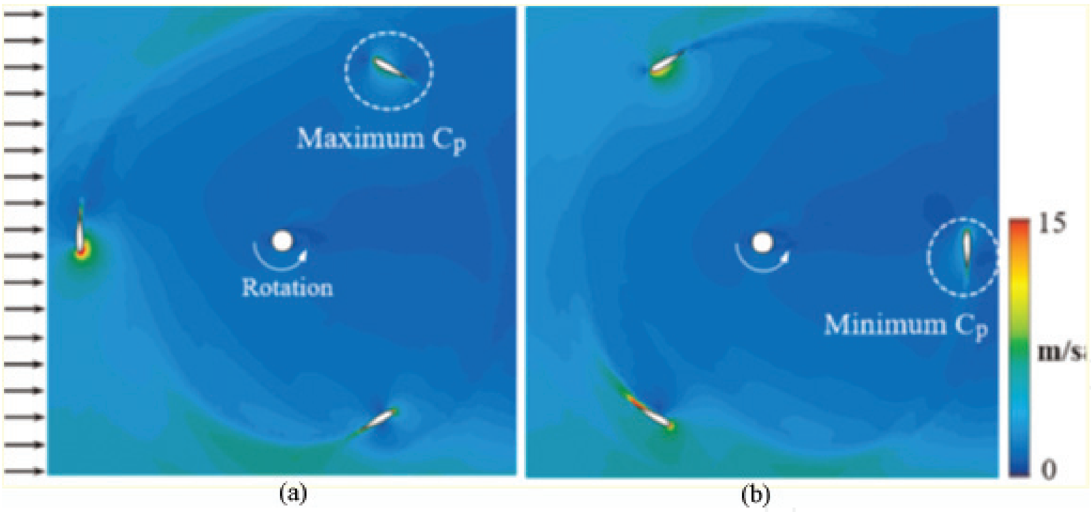


**Figure 13.**
*Wind speed around turbine rotor with wind speed of 5m/s (a) Rotor orientation for maximum $C_P$ (b) Rotor orientation for minimum $C_P$.*

**Figure 12** shows the comparisons of turbine power between numerical simulation and experimental measurement for two time averages. In the figure, turbine power obtained by numerical simulation has similar trend to the experimental result. Especially turbine power determined by 10-min average is more similar to the results of numerical simulation compared to 30-min average. This is considered that 10-min average step having lower SD is more effective to analyze the performance of a small vertical wind turbine. From the above comparisons, it can be said that turbine power obtained by numerical simulation is correctly analyzed.

**Figure 13** shows contours of wind speed around turbine rotor at two different rotation positions, where maximum and minimum values of power coefficient ($C_p$) occurred, during one complete revolution. Blade having maximum power surrounded by dashed line in the left side is located at the blade rotation angle of 240° where maximum wind velocity around the blade is occurred without large separation flow along the blade surface. An increase in linear speed of the blade leads to increase the rotational speed of rotor and eventually overall power output is enhanced. Larger separated flow is observed at the blade having minimum power because inflow in front of turbine rotor directly interfaces to the blade surface.

## 3. Optimal design of HRES

This section describes an optimum HRES for Deokjeokdo island based on lowest net present cost (NPC) and levelized cost of energy (LCOE) using HOMER pro software model. Hybrid optimization model for electric renewables (HOMER) pro software can efficiently model and optimize renewable energy plans for a specific region. The optimum HRES must fulfill hourly and annual electricity demand of the island, which corresponds to approximately 7.296 MWh/year without any external assistance such as grid, etc.

### 3.1 Input data for HOMER pro

Before starting energy simulations in HOMER pro, one must define pre requisites such as electric load, equipment such as wind turbines, PV panels and other essential details like interest rate and project life.

#### *3.1.1 Electric load*

In order to optimally design a HRES, electric load information such as peak load, daily average electricity consumption and hourly load profile are of critical importance. The maximum availability of load information enables designing a more compact HRES. In the present case, the load data were not collected from any official government source (because of unavailability of such data), but from a previous study on Deokjeokdo island [11]. The average daily load was found to be approximately 24,720 kWh with peak load of 2292 kW typically occurring during winter season and total annual electricity consumption corresponds to a value of 7.296 GWh. The electricity consumption during winter season is higher than rest of the seasons due to the extensive use of space heating equipment powered by electricity. **Figure 14** shows the daily and monthly electricity consumption at Deokjeokdo island.

#### *3.1.2 Equipment selection*

**Table 3** presents all technical and economic details about the selected equipment for the study. It is to be noted that all the equipment have been selected by default by HOMER pro except wind turbine; which has been selected after a detailed analysis of wind characteristics at Deokjeokdo island by same authors in Ali et al. [12].

#### *3.1.3 HOMER pro model*

**Figure 15** shows the HOMER pro model built for current study with two electric transmission lines, i.e., DC and AC. Basically, the electricity generated from each energy source is stored in the battery based on the DC line. This is because, in comparison with AC, small-scale power generation systems can reduce losses due to electricity conversion. Electric load is used after converting it to AC by using the converter as shown in the figure.

**Table 4** displays the values of all the sensitivity variables considered in current study. First values of all sensitivity variables in **Table 4**, makes the default case.

### 3.2 Optimum HRES solutions

This section presents the characteristics and analysis of the most optimal HRESs recommended for Deokjeokdo island on the basis of techno-economic evaluations.

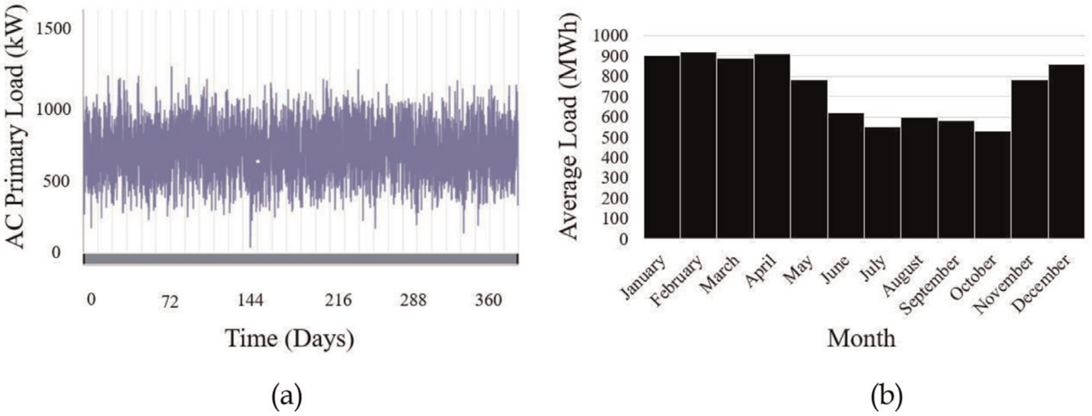


**Figure 14.**
*Total AC electric load at Deokjeok island (a) daily load (b) monthly load.*

**(a) Converter**

| Model | Capital ($/kW) | Replacement ($/kW) | O&M ($/year) | Lifetime (years) | Inverter efficiency (%) | Rectifier capacity (%) | Rectifier efficiency (%) |
|---|---|---|---|---|---|---|---|
| Leonics MTP-413F 25kW | 800 | 800 | 10 | 10 | 96 | 80 | 94 |

**(b) Battery**

| Model | Capital ($/battery) | Replacement ($/battery) | O&M ($/year) | Lifetime (years) | Initial state of charge (%) | Nominal voltage (V) | Nominal capacity (kWh) |
|---|---|---|---|---|---|---|---|
| Surrette 6CS25P (kinetic) | 250 | 250 | 1 | 20 | 100 | 6 | 6.91 |

**(c) PV panel**

| Model | Capital ($/kW) | Replacement ($/kW) | O&M ($/year) | Lifetime (years) | Derating factor (%) | Rated capacity (kW) | Efficiency (%) |
|---|---|---|---|---|---|---|---|
| CS6X-325P | 1500 | 1500 | 30 | 25 | 88 | 50 | 17 |

**(d) Wind turbine [10]**

| Model | Capital ($/wind turbine) | Replacement ($/wind turbine) | O&M ($/year) | Lifetime (years) | Hub height (m) | Wake loss (%) | Other losses (%) | Rated capacity (kW) |
|---|---|---|---|---|---|---|---|---|
| STX 93/2000 | 2,869,747 | 2,869,747 | 110,375 | 25 | 80 | 5 | 10 | 1500 |

**Table 3.**
*Selected equipment.*

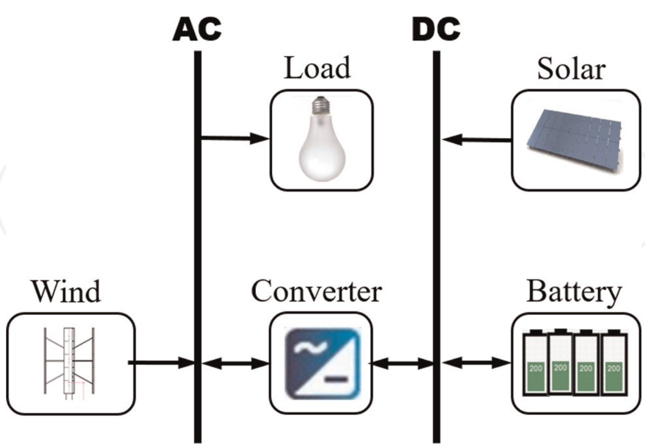


**Figure 15.**
*HOMER pro model constructed for current study.*

HOMER simulations generated a total of 551,035 alternatives, out of which only 232,683 solutions were found to be feasible. **Figure 16** shows the breakdown of all the solutions generated and it also specifies the multiple reasons for omitted solutions.

Out of the 232,683 feasible solutions, only following two HRESs were finalized as the most suitable options.

- System A: HRES with lowest overall net present cost (NPC)
- System B: HRES with lowest overall levelized cost of energy (LCOE)

**Table 5** shows the basic characteristics of both of the optimized system solutions. It is to be noted that both systems have batteries as default option for storing surplus electricity. System A has the lowest overall NPC (11.3 million $) whereas LCOE is lowest in case of system B ($ 0.123). **Table 5** also displays the values of

| Average load (kWh/day) | Discount rate (%) | Project lifetime (years) |
|---|---|---|
| 24,720 | 8 | 25 |
| 20,000 | 6 | 20 |
| 30,000 | 4 | 15 |

**Table 4.**
*Sensitivity variables.*

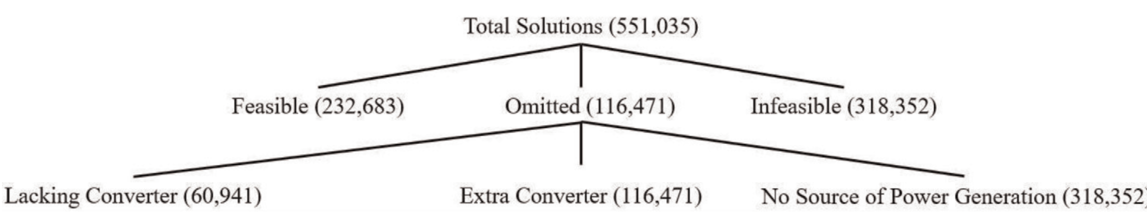


**Figure 16.**
*Breakdown of multiple solutions obtained from HOMER simulations.*

| Variable | Unit | System A | System B |
|---|---|---|---|
| NPC | Million $ | 11.3 | 17.61 |
| LCOE | $/kWh | 0.158 | 0.123 |
| Total load scaled average | kWh/day | 20,000 | 20,000 |
| Nominal discount rate | % | 8 | 4 |
| Project lifetime | years | 15 | 25 |

**Table 5.**
*Basic information about both system solutions.*

| Component | Model | Unit | Size (system A) | Size (system B) |
|---|---|---|---|---|
| PV panels | Canadian Solar Max Power CS6X-325P | kW | 2504 | 3157 |
| Battery | Surrette 6 CS 25P | Strings | 7197 | 6269 |
| Wind turbine | STX 93/2000 | ea. | 1 | 1 |
| System converter | Leonics MTP-413F 25 kW | kW | 1006 | 1009 |
| Dispatch strategy | HOMER cycle charging | N/A | N/A | N/A |

**Table 6.**
*Systems architecture.*

sensitivity variables at which optimal system solutions have been obtained. Project life of system A (15 years) is less than that of system B (25 years), which is also one of the reasons for low NPC of system A.

**Table 6** displays the selected size of each component for both systems. Both systems consist of one wind turbine and system converter of almost 1000 kW size. PV panel size for system B (3,157 kW) is higher than system A (2,504 kW), that is why NPC of system B is higher than system A. By selecting an appropriate model of wind turbine according to the wind conditions of Deokjeokdo island, both system architectures might be different from present cases. But, a right choice of wind

| Pollutant | Unit | Quantity (system A) | Quantity (system B) |
|---|---|---|---|
| Carbon dioxide | kg/year | 795 | 700 |
| Carbon monoxide | kg/year | 8.83 | 7.77 |
| Unburned hydrocarbons | kg/year | 0 | 0 |
| Particulate matter | kg/year | 0 | 0 |
| Sulfur dioxide | kg/year | 0 | 0 |
| Nitrogen oxides | kg/year | 5.52 | 4.86 |

**Table 7.**
*Pollutants emission.*

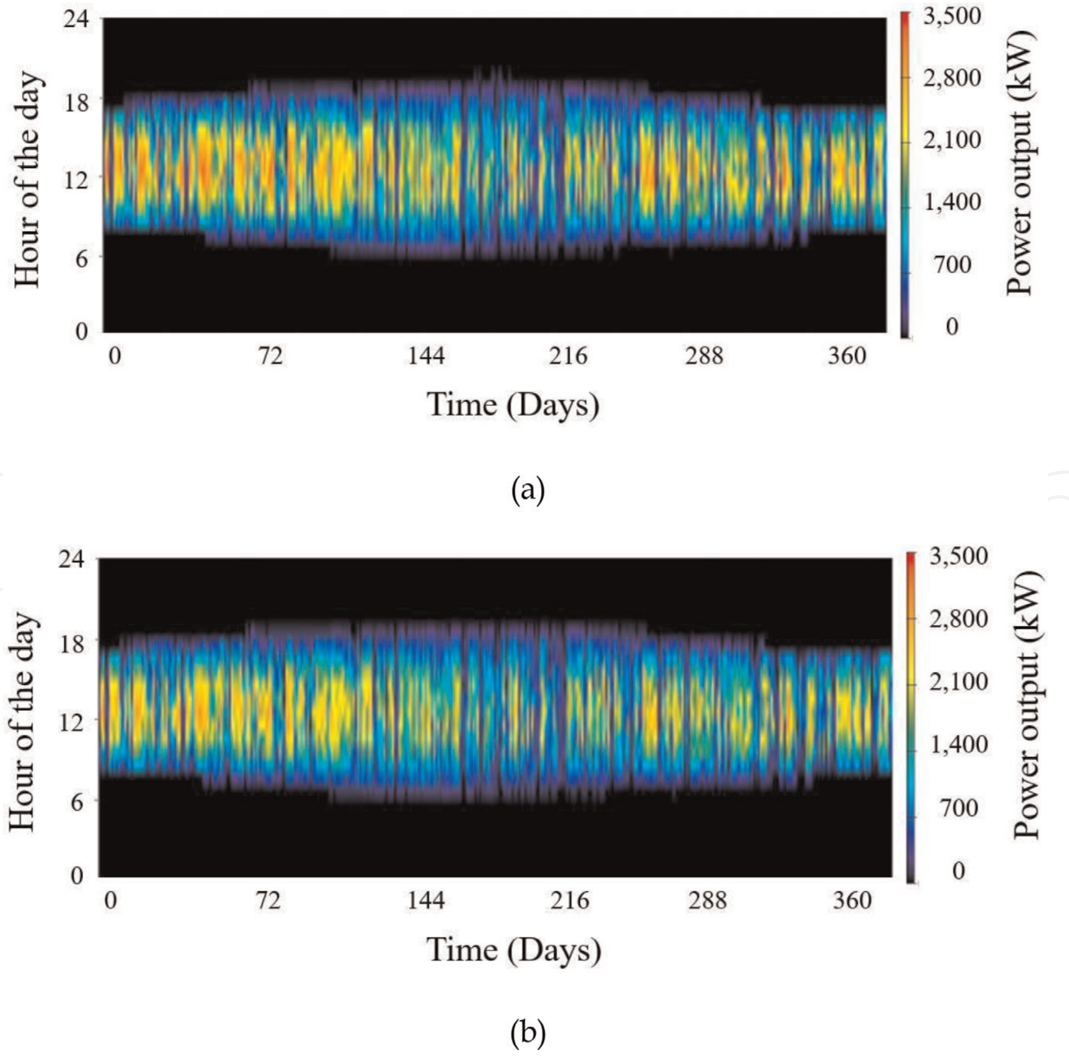


**Figure 17.**
*Daily PV power output for both systems (a) system A (b) system B.*

turbine depends on the detailed wind data analysis of local site, which is beyond the scope of current study; therefore not performed here.

Finally, **Table 7** shows the annual amount of pollutant gases emissions due to operation of both systems.

**Figure 17** displays the graphical representation of power produced by PV panels in both cases. Both the images of **Figure 17** indicate that summer is the ideal season for harvesting energy from sun in South Korea, as the average day-time is almost 14–15 hours in Deokjeokdo island. The average hourly power generated by PV panels in case of system A is 425 kWh whereas this value corresponds to 536 kWh for system B.

### 3.3 Sensitivity cases

Although the most optimal system solutions have already been explained in detail in above sections. But it is also of critical importance to briefly explain some

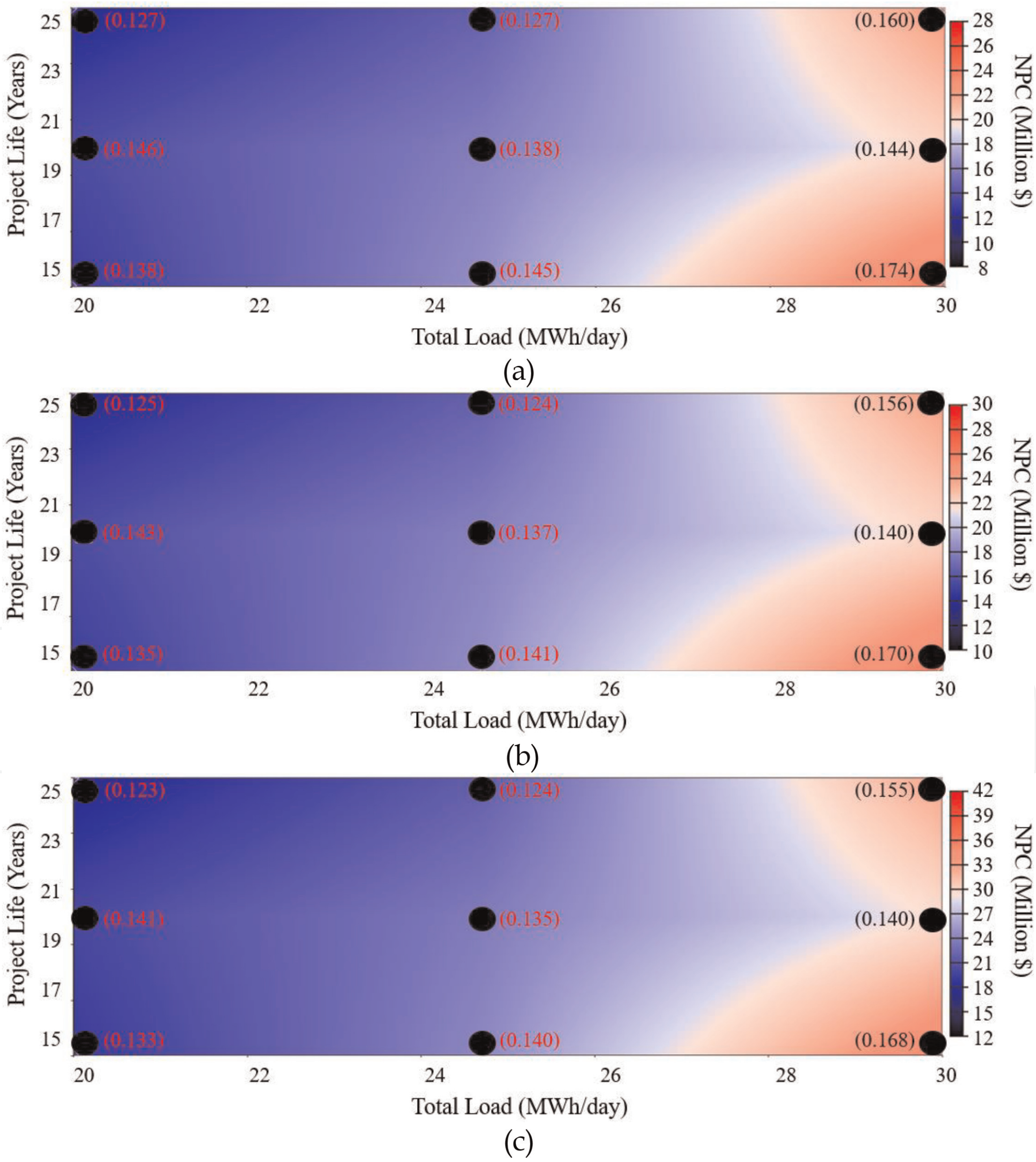


**Figure 18.**
*Multiple system solutions with LCOE superimposed over NPC (a) discount rate = 4% (b) discount rate = 6% (c) discount rate = 8%.*

of the other alternate system solutions on the basis of economic evaluations. In order to achieve this goal, **Figure 18** has been prepared which shows multiple system solutions obtained by superimposing NPC over LCOE.

**Figure 18** shows a total of 27 optimal system solutions obtained by varying the values of all sensitivity variables mentioned in **Table 4**.

## 4. Conclusions

The present study provides a basic information about the working methodologies of a hybrid renewable energy system (HRES) consisting of wind and solar as primary energy resources. Two case studies of HRES have also been included to further clarify the economic aspects of such energy systems.

First case study deals with the analysis of a small HRES consisting of wind turbines and PV panels with batteries as energy storage system (ESS). This small HRES is being installed at Deokjeokdo island in South Korea and its performance have been monitored for two consecutive years (2016 and 2017). Analysis showed that the prevailing wind direction at Deokjeokdo island is either north-east or south-west, with mean wind speed of 3.6 m/s at 10 m height. Similarly, average value of daily solar radiations was estimated to be 4.13 kWh/$m^2$ with mean clearness index of 0.5. The total capacity of this small HRES is 6 kW; with two Darrieus VAWTs of 1.5 kW size each and 3 kW size of PV panels.

Second case study finds an optimum HRES to fulfill the yearly electricity demand of Deokjeokdo island, which corresponds to approximately 7.296 MWh/year. Over 8760 simulations were performed to find out two optimum HRESs based on lowest NPC (system A) and lowest LCOE (system B), respectively. The overall NPC of system A was calculated to be 11.29 million USD, whereas for system B, it was 17.61 million USD. On the other hand, LCOE for system A was slightly higher than system B as it was 0.158 $/kWh for system A and 0.123 $/kWh for system B. Both systems can independently provide electricity to Deokjeokdo island throughout the year without any external assistance such as grid, etc.

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## Conflict of interest

The authors declare no actual or potential conflicts of interest.

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