Design the Optimal Number of Components in a Grid-Connected Hybrid Power Generation System

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Abstract- Hybrid power generation systems are an effective solution for the variable generated power of renewable energy resources. In this paper, a grid-connected hybrid power generation system including wind turbines, solar panels, wave generators and power storage batteries for a village in the Chabahar Bay in southeastern of Iran is optimally designed. The purpose of selecting this region is to investigate the economic feasibility of using wave generators in hybrid power generation systems. In the design, during various operating scenarios simulated with Homer software, adding power generation resources to the village will provide part of the required power locally, which will reduce the cost of purchasing electricity from the power grid, and even profitability is also achieved with the sale of electricity to the power grid. On the other hand, the reliability of power grid is improved in terms of the Loss of Power Supply Probability (LPSP) index.

Keywords Hybrid Power System, LPSP, Homer, Sensitivity Analysis, Chabahar Bay.

1. Introduction

Electricity is the key to development and progress. Development of industries, growth of population and change in people's standard of living have led to an increase in energy demand. At present, the world's population is about 7 billion. According to predictions, the world's population will reach 9 billion in 2040, which will increase energy demand [1]. According to the International Energy Agency's forecast in 2013, energy consumption in 2040 will be 56% higher than the one in 2010. An increase in energy demand has led to an increase in energy prices [2].

One of the other issues in the field of electrical energy is the dependence of the world's energy structure on fossil fuels. The limited availability of fossil fuels and their rising prices, on the one hand, and environmental negative impacts, and global resolve and international organizations to reduce greenhouse gas emissions and the regulation of multiple documents in this area, on the other hand, has sparked glances towards the development and use of renewable energy as much as possible [3].

Moreover, electrification to remote and rural areas for development is important as one of the puzzle pieces of each country's development. Extending the power grid and expanding the electric power transmission lines to electrification these areas is impossible, time-consuming, and costly in many cases, and the use of renewable energy is a good solution to meet the increasing need of these regions for electrical energy [4].

Renewable energy sources such as wind, solar, wave, geothermal, etc. are sources that, unlike fossil fuels, have the same rate of production and consumption, and their consumption for electricity production is free. But the production of electrical energy from electric power sources is variable due to their natural nature and is dependent on environmental conditions.

In restructured power systems and the electricity market, electricity needs to be supplied at an affordable and consistently high quality and cost for profitability and maintaining consumer confidence and loyalty, and the volatility of renewable energies is a major challenge in using these energies [5]. Although the use of storage systems has solved a significant part of this problem, increasing the load can cause the inability of the renewable energy source to supply the load.

To solve this problem, the combination of renewable energy sources is considered as one of the new methods of generating power. In areas where there is potential for electric power generation from several renewable energy sources, a hybrid power generation system can be used to meet consumers' demand for electric power [6]. In hybrid power generation systems, two or more power supplies are combined with the energy storage system and serve the consumer. Power sources can be renewable or fossilized, such as diesel generators, and renewable sources are determined by the potential of each region [7].

Extensive researches have been conducted on hybrid power generation systems. Several papers have been presented on the analysis, modeling, control and optimization of the performance of hybrid systems [5, 8-12]. One of the important issues in the hybrid systems is the energy storage problem, which numerous studies have been carried out in this regard [12-14]. Economic optimization of hybrid power generation systems has been the subject of much research [15, 16]. Evaluation of reliability is a criterion for quality assessing the hybrid power systems, which has been studied in numerous articles [17-20]. One of the reliability indexes is the Loss of Power Supply Probability (LPSP), which indicates the ability of an electrical power system to continuously supply of the load. The LPSP is the ratio of the number of hours that an electric power system cannot handle in a given time period to the total number of hours of the time period which is between zero and one [20]. The lower the LPSP index, the electrical system has better performance in supply of consumer load.

In this paper, the optimal number of renewable energy sources of wind, solar, wave, and energy storage batteries is determined in a grid-connected hybrid power generation system. According to many works have been done in optimal design of hybrid systems, there are two basic methods for design: first, mathematical modelling and using of optimization methods [12, 16, 20] and second, simulation and optimal design with Homer or LINGO software [4, 15, 21-22]. In this paper, the second method is used for optimal design. The study area is located far away from the main electrical grid and located on the shore and therefore a village located on the shore of Chabahar Bay in Iran has been selected for this purpose. The purpose of this site is to investigate renewable energy potential in Chabahar Bay and economic feasibility of different renewable energy resources in a hybrid system. Also, the economic feasibility of using wave generators in hybrid power generation systems and their impact on the whole system is evaluated in this region. The hybrid system supplies the need of the village's electricity requirement, which consists of 15 homes connected to the main power grid, but due to its low capacity and weakness, the grid has a high probability of power failure in this area. In the scenarios, we plan to provide part of the required power locally by adding the sources of power to the village, thereby reducing the cost of purchasing electricity from the main grid and even benefiting from the sale of electricity to the main grid. On the other hand, the reliability of this area is improved in terms of the LPSP index.

In the second section, the specification of the study area and the hybrid power system used are presented and in the third section, different scenarios are simulated and analyzed by Homer software. In Section 4, the analysis of sensitivity to wind speed, the price of a turbine wave and the price of energy sales are presented and finally, a conclusion is made in the Fifth Section.

2. Specifications of the Study Area and Hybrid Power System

2.1. The Study Area

Sistan&Baluchestan province is located in the southeastern part of Iran, with an area equal to 11 percent of the area of Iran with an area of 180726 square kilometers and a population of 2534327. The province has a border with Pakistan and Afghanistan with a total border of 1100 km and the border with the Oman Sea and the free waters in the south of the province.

The geographical situation of Sistan&Baluchestan province is such that it is possible to extract a variety of renewable energies. The altitudes of Sistan&Baluchestan Province are among the mountainous regions of central Iran, and include three young Taftan and Bazman volcanoes. The existence of these three young volcanoes is a very rich source of geothermal energy. The north and south of the province have an excellent wind direction to produce wind energy, and in the south of the province lies the open waters of the Oman Sea, and has a very good potential for producing waves and tides. In all parts of the province, the sun's radiation is very good all year round and solar energy can be extraordinarily high.

In the south of this province lies the Chabahar Bay, adjacent to the Oman Sea and the free waters. The Chabahar Bay is the largest Iranian bay in the Oman Sea, with a total area of 290 square kilometers, with a coastline of more than 265 kilometers. Its latitude is northern $25^{o}39'20''$ and its longitude is eastern $57^{o}47'27''$.

The study area in this paper is a village located on the shore of Chabahar Bay. The village has 15 homes and is connected to the main power grid, but because of the low capacity and weakness of the main network, the probability of power failure in this village is high. The average values of annual irradiance, wind speed, altitude and period of wave for the studied village are shown in Figs. 1 to 4, respectively.

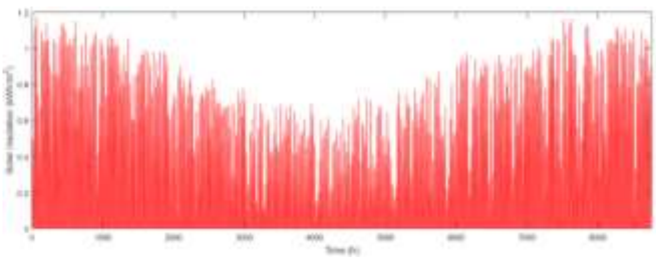

Fig. 1. Annual average of sun irradiance.

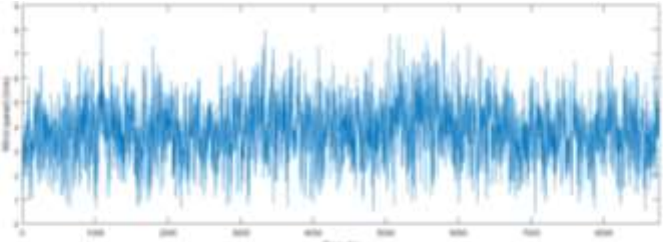

Fig. 2. Annual average of wind speed.

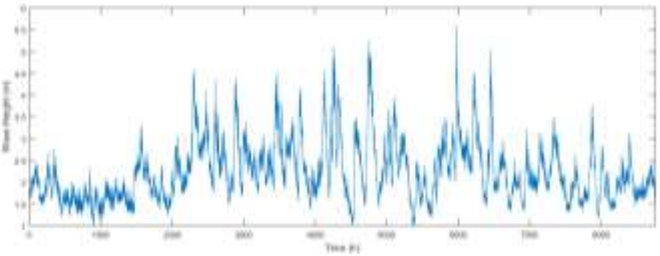

Fig. 3. Annual average of wave height.

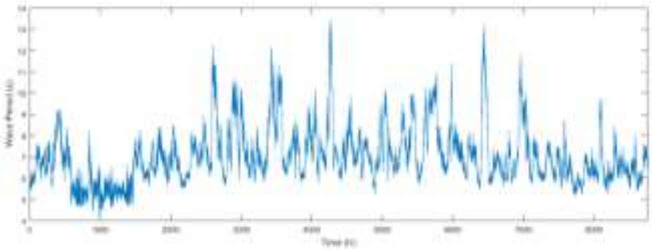

Fig. 4. Annual average of wave period.

In the study area, the cost of energy purchases for each home follows the structure presented in Table 1. If we show the monthly energy consumption of each home with a parameter E_{bm}, depending on the number of homes in the study set, we will have:

$$E_{bm} = \frac{\sum_{t \in M} e_b(t)}{15} \tag{1}$$

Where $e_b(t)$ is the monthly energy consumption of the village. According to the computational structure presented in Table 1, the monthly energy cost of the entire set is obtained using Eq. (2):

$$C_m = \begin{cases} 15(0.1196 E_{bm}) & E_{bm} \le 50 \\ 15(50 \times 0.1196 + 0.2649(E_{bm} - 50)) & 50 < E_{bm} < 75 \\ 15(10 \times 0.1196 + 65 \times 0.2649 + 0.4402(E_{bm} - 75)) & 75 \le E_{bm} \end{cases} \tag{2}$$

The total annual cost of the studied village for purchasing energy from the power grid is calculated as follows:

$$C_a = \sum_{m=1}^{12} C_m \tag{3}$$

For each of the village homes, the average monthly average consumption per month is considered in Fig. 5. In addition, due to the weakness of the main power grid, the availability of power in this village is modelled with a normal probability density function with a mean of 39 kilowatts and variance of 20. By generating random numbers based on this probability density function, the available power of grid at any time of the day is as shown in Fig. 6.

Table 1. Structure used to calculate monthly energy cost.

Monthly consumption (kWh)	Consumption interval (kWh)	Price ($\$/kWh$)
Less than 75	0 to 50	0.1196
	50 to 75	0.2649
More than 75	0 to 10	0.1196
	10 to 75	0.2649
	More than 75	0.4402

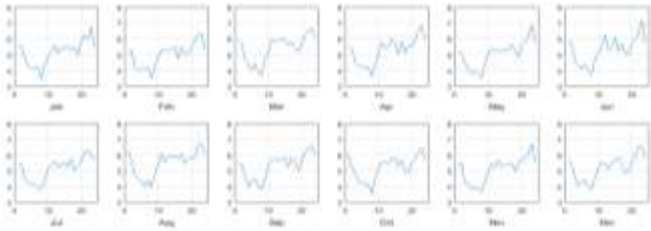

Fig. 5. Average monthly consumption of each home in kilowatts.

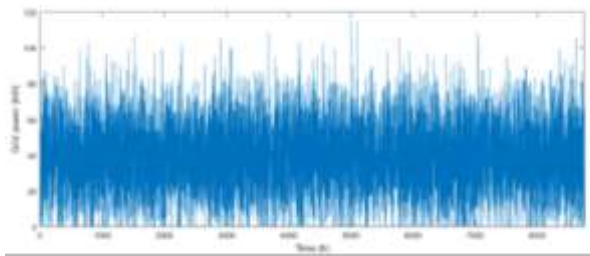

Fig. 6. Average annual available power from the main grid.

2.2. Specifications of the Hybrid Power System

In this paper, hybrid power generation system includes solar panels, wind turbines, wave generators and storage batteries. Figure 7 shows the hybrid power system. The technical and economical parameters used to solve the problem of optimal design of the hybrid power system are presented in appendix.

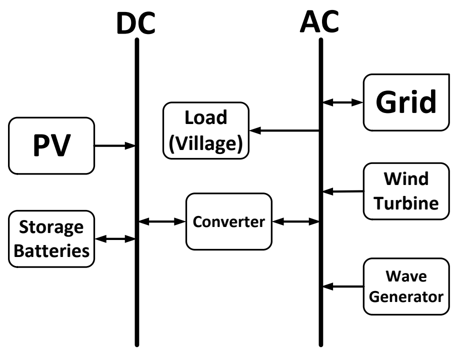

Fig. 7. The studied hybrid power system.

3. Simulation and Results

To better understand the impact of each component of the hybrid system on the results of studies, various scenarios are defined below. The results obtained from the simulations with the Homer software provided by NREL company for each of these scenarios are presented in each section.

3.1. Basic Scenario

In this scenario, the aim is to study the status of the village before installing the hybrid system. In fact, the total amount of energy needed for the homes in this scenario is only provided through the main power grid. Therefore, the number of wind turbines (A_w), solar panels (A_{pv}), wave generators (N_o), and batteries (N_b) are assumed zero. The simulation results are shown in Table 2.

Table 2. Simulation results of the basic scenario

C_T ($)	$LPSP$	C_a ($)	$E_b(kWh/year)$	N_o	N_b	A_w	A_{pv}
228120	0.0368	17456	45625	0	0	0	0

According to Table 2, the average annual consumption of 15 homes is 45625 kWh. Therefore, the average monthly consumption of each home will be equal to 253 kilowatt hours. The annual cost of purchasing electrical energy from the main grid is 17,456$ for 15 homes, which is 97$ per month. In addition, on average, 3.68% of the total load has not been provided, which is much higher than the expected (2%). Therefore, it is necessary to improve the reliability of the system by adding new production units. It should be noted that the total cost of electric power (C_T) is 228120$ for the entire study period of the project, which was 25 years old.

3.2. The First Scenario

In this scenario, the goal is to find the optimal number of wind turbines, solar panels, wave generators and batteries, if the village is not allowed to sell its extra energy to the main grid. In this case, if the power generated by the hybrid system in addition to the stored energy of the battery is less than the total power consumption of the village, the amount of power required is purchased from the main grid, but if the total power generated by the hybrid system and the power stored in the battery is greater than the total power consumption, the excess power is returned to the main grid free of charge. The simulation results of this scenario are presented in Tables 3 and 4.

Table 3. Simulation results of the first scenario

C_T ($)	$LPSP$	C_a ($)	$E_b(kWh/year)$	N_o	N_b	$A_w(m^2)$	$A_{pv}(m^2)$
157030	0.0087	2338	12409	12	6	16.97	37.55

Table 4. The number of optimized units for the second scenario

	Number of units	Total capacity (kw)
Solar Panel	24	5.64
Wind Turbine	6	6
Wave generator	12	4.2
Battery	6	4.8

By analysing Table 3 and comparing with the results obtained in the basic scenario, it is clear that the average annual electricity consumption of the village after the installation of the power generation hybrid system has decreased by 73%. Meanwhile, the monthly electricity consumption per household is 69 kilowatt hours and the monthly cost is about 13$. The total annual cost of the village is 2,338$, which is more than 86% lower than the basic scenario. The LPSP index in this scenario is 0.0087, which is much lower than the desired value (2%). An important point in this scenario is to reduce the total cost of the project over the project period (25 years) compared to the basic scenario. For the first scenario, economic analysis is based on the classification of costs in Fig. 8.

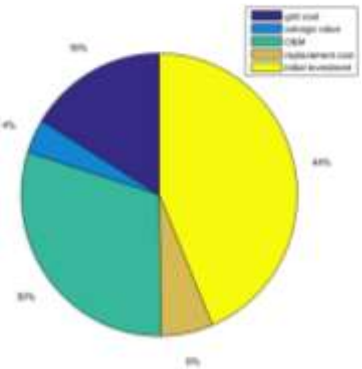

Fig. 8. The percentage of participation in the total cost.

As initially conceivable, most of the costs of this project are related to initial investment, which accounts for 44% of total costs. While the cost of purchasing electrical energy from the main grid is only 16% of the total cost. One of the reasons for this is a reduction in the purchase of electrical energy from the main grid, due to an increase in the domestic production of the village. The amount of stored power in batteries per hour of the year is shown in Fig. 9.

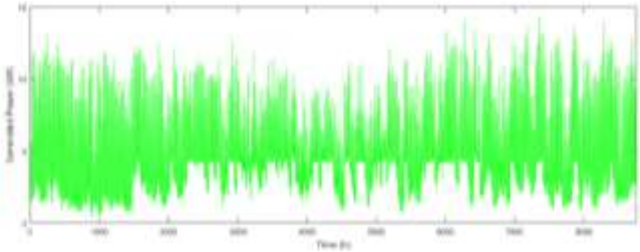

Fig. 9. stored power in batteries per hour of the year.

3.3. The Second Scenario

Unlike the first scenario, in this scenario, it is supposed to be paid to the village for additional transfer of the power to the main grid. In fact, in this method, the two-way meters are used and the total power consumption in the one-month period, which is equal to the consumed power minus the generated power is calculated at the end of each month. The simulation results of this scenario are presented in Table 5.

Table 5. Simulation results of the second scenario

C_T (\$)	$LPSP$	C_a (\$)	$E_b(kWh/year)$	N_o	N_b	N_w	N_{pv}
72216	0.0198	-2696	-22554	0	0	0	113

As can be seen from table 5, the annual cost of purchasing energy from the main grid by the village is negative. The mean of this sign is that over the year, the amount of power sold to the main grid is more than its power consumption in the village. In addition, the total annual cost is also negative, indicating the profitability of the project for the studied area. Figure 10 shows the average energy consumption and the cost of purchasing energy from the grid of each home during the year. The LPSP index is also fully respected in this scenario. In addition, the total cost of the project in the study period is much lower than the previous scenarios and is 72,216$ and is shown in Fig. 11.

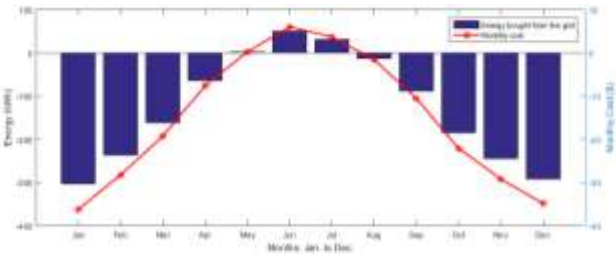

Fig. 10. the average energy consumption and the cost of purchasing energy from the grid of each home during the year.

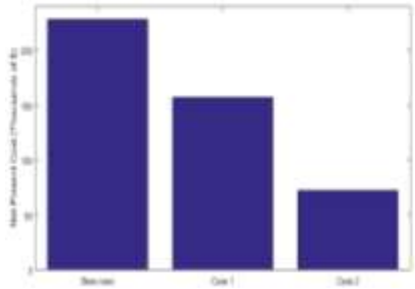

Fig. 11. Comparison of the total cost of the project in the study period in the basic, first and second scenarios.

3.4. The Third Scenario

This scenario is intended to analyse the state of the possibility of power injection into the main grid and the additional generated energy in the village to be sold at fixed prices to the main grid. In this case, the revenue from electrical energy sales is divided between the homes of the village. The simulation results of this scenario are presented in Table 6. It is clear that with the rise in the price of electrical energy sales to the grid, it is possible to reduce the total cost of the set during the study period of the project with adding the devices with lowest cost (which is here solar panels) to the hybrid system.

Table 6. Simulation results of the third scenario with various electric energy sales prices

P_s (\$)	N_{pv}	N_w	N_b	N_o	$E_b(kWh/year)$	C_a (\$)	$LPSP$	C_T (\$)
0	24	6	6	12	12409	2438	0.0087	157030
0.04	30	2	7	13	5474	2474	0.0088	156170
0.06	31	1	5	13	5113	2441	0.0087	154440
0.08	34	2	3	12	1840	2379	0.0085	151710
0.1	52	0	7	11	-4511	2105	0.0091	148260
0.12	143	0	12	9	-53621	1989	0.0091	139500

4. Sensitivity Analysis

In this section, the sensitivity of the number of components used in each technology is evaluated based on the wind speed, the price of wave devices, and the price of electrical energy sales according second scenario. The sensitivity of the number of solar panels and wind turbines to the increase in wind speed in Fig. 12, the sensitivity of the number of solar panels and wave generators to the decrease in the price of wave generators in Fig. 13, and the sensitivity of the number of solar panels, wind turbines and wave generators relative to the sales price of electric energy is shown in Fig. 14.

According to Fig. 12, if the wind speed in the village increases by about 13%, the cost of wind turbine from a solar panel will be cheaper during the study period of the project. Therefore, with increasing wind speed, it is better to use wind turbines. Figure 13, on the other hand, suggests that with decreasing the cost of wave generators about 50%, using of wave generator will be much cost-effective than solar panels. Of course, this will only be possible with the advent of the technology of exploiting the energy of the waves. That is why the current use of wave generators is not economically feasible. According to the analysis shown in Fig. 14, if solar energy prices rise, solar panels will be more cost effective.

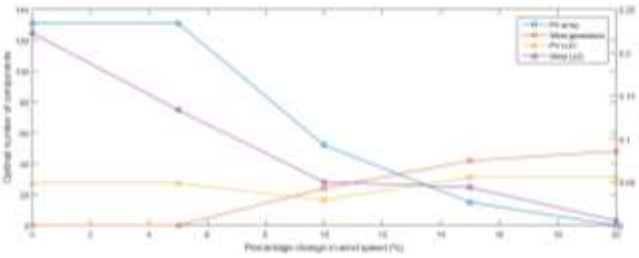

Fig. 12. Sensitivity analysis of the number of solar panels and wind turbines relative to wind speed.

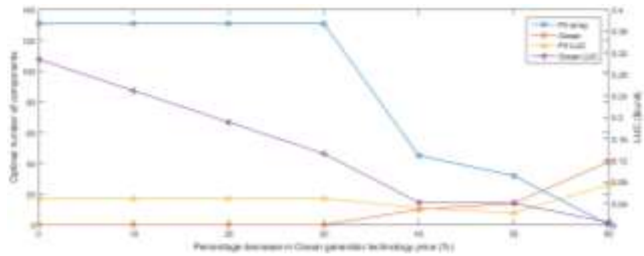

Fig. 13. Sensitivity analysis of the number of solar panels and wave generators relative to the wavelength generator.

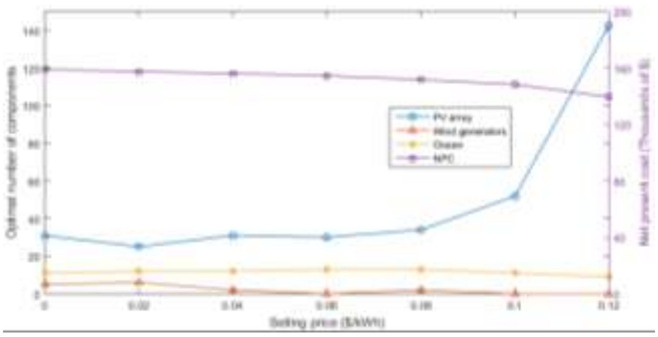

Fig. 14. Sensitivity analysis of the number of solar panels, wind turbines, and wave generators relative to the price of energy sales.

5. Conclusion

The conclusion section should emphasize the main contribution of the article to literature. Authors may also explain why the work is important, what are the novelties or possible applications and extensions. Do not replicate the abstract or sentences given in main text as the conclusion.

In this paper, the optimal number of renewable energy sources of wind, solar, wave and energy storage batteries in a grid-connected hybrid power system based on different scenarios was determined. To design technical and economic parameters including the life time of the equipment, the time of the study period, the inflation and interest rates, fixed costs, operation, maintenance and replacement, and the parameters of the technologies used, including solar panels, wind turbines, wave generators, and batteries have been taken. One of the important indexes for designing hybrid power generation systems is the LPSP Reliability Index, which in addition to technical and economic optimization, this index was also considered and improved.

The Chabahar Bay in Iran is selected for optimal design. The purpose of this region is to investigate renewable energy potential in Chabahar Bay and economic feasibility of different renewable energy resources in a hybrid system.

Another objective of this paper is to examine the economic feasibility of using wave generators in hybrid power generation systems and their impact on the system. For this purpose, a village in the Chabahar Bay in south-eastern Iran was chosen and its climate information was used for design.

Based on the sensitivity analysis, if wind speeds in the region were about 13% higher, using wind turbines would be more cost-effective than using solar panels. In addition, if the initial cost of wave generators is reduced by about 50%, then this technology can be used in conjunction with solar panels in coastal areas with high wave energy.

Appendix

Technical and economic parameters for optimal design

System Parameters				Wind Turbine Parameter			
Parameter	Symbol	Unit	Qty.	Parameter	Symbol	Unit	Qty.
Inflation	r	-	0.1	Initial Cost	α_w	$\$/m^2$	544.2
Project period	N	year	25	Annual O&M Cost	α_{OMw}	$\$/m^2$	2% of α_w
Expected Reliability index	$\overline{LPSP}$	-	0.02	Sales Price	S_w	$\$/m^2$	30% of α_w
Converter efficiency	$\eta_{converter}$	-	0.9	Life time	L_w	year	20
Solar Panel Parameter				Efficiency	η_w	-	0.85
Parameter	Symbol	Unit	Qty.	Power Coefficient	C_p	-	0.59
Initial Cost	α_{PV}	$\$/m^2$	519.7	Air Density	ρ_a	kg/m^3	1.225

Annual O&M Cost	α_{OMPV}	$\$/m^2$	1% of α_{PV}	Area	A_w^{each}	m^2	3.14
Sales Price	S_{PV}	$\$/m^2$	25% of α_{PV}	Cut-in speed	V_{ci}	m/s	1.5
Life time	L_{PV}	year	25	Nominal speed	V_r	m/s	10
Efficiency	η_{PV}	-	0.14	Cut-off speed	V_{co}	m/s	25
Area	A_{pv}^{each}	m^2	1.63	Battery Parameter			
Wave Generator Parameter				Parameter	Symbol	Unit	Qty.
Parameter	Symbol	Unit	Qty.	Initial Cost	α_B	$\$/m^2$	724.5
Initial Cost	α_T	$\$/m^2$	2127.6	Annual O&M Cost	α_{OMB}	$\$/m^2$	2% of α_B
Annual O&M Cost	α_{OMT}	$\$/m^2$	10% of α_T	Sales Price	S_B	$\$/m^2$	25% of α_B
Sales Price	S_T	$\$/m^2$	15% of α_T	Life time	L_B	year	10
Life time	L_T	year	10	Max. Generation Capacity	Cap_B	kWh	0.8
Max. Generation Capacity	Cap_T	kW	0.35	Depth of Discharge	DOD	-	0.9

References

[1] Q. Zhou, Y. Bai, Y. Li, X. Wang, H. Wang, M. Du, et al., "Reviews of development and utilization of tidal energy over Chinese offshore", in OCEANS 2016-Shanghai, IEEE, Shanghai, pp. 1-5, 2016.

[2] World Energy Outlook 2014, IEA, International Energy Agency, Paris, 2014.

[3] L. Freris and D. Infield, Renewable energy in power systems, John Wiley & Sons, 2008.

[4] A. Kanase-Patil, R. Saini, and M. Sharma, "Integrated renewable energy systems for off grid rural electrification of remote area", Renewable Energy, vol. 35, pp. 1342-1349, 2010.

[5] P. Ray, S. Mohanty, and N. Kishor, "Small-signal analysis of autonomous hybrid distributed generation systems in presence of ultracapacitor and tie-line operation", Journal of Electrical engineering, vol. 61, pp. 205-214, 2010.

[6] J. Brouwer, Hybrid gas turbine fuel cell systems, 2006.

[7] N. Barsoum and W. Goh, "Modeling the Feasibility of an Integrated Hydrogen Hybrid Energy System for Stand Alone Power System", in Proceeding, 2006.

[8] V. A. Ani, "Simulation of photovoltaic/diesel hybrid power generation system with energy storage and supervisory control", International Journal of Renewable Energy Research, vol. 3, pp. 605-614, 2013.

[9] M. B. Anwar, M. S. El Moursi, and W. Xiao, "Novel Power Smoothing and Generation Scheduling Strategies for a Hybrid Wind and Marine Current Turbine System", IEEE Transactions on Power Systems, vol. 32, pp. 1315-1326, 2017.

[10] N. S. Jayalakshmi, D. N. Gaonkar and P. B. Nempu, "Power Control of PV/Fuel Cell/Supercapacitor Hybrid System for Stand-alone Applications", International Journal of Renewable Energy Research, vol. 6, no. 2, pp. 672-679, 2016.

[11] K. Murugesan and V. Senniappan, "Dynamic Modelling and Analysis of Power Sharing Control Strategy Based Fuel Cell/Battery Assisted Hybrid Electric Vehicle System", International Journal of Renewable Energy Research, vol. 3, no. 1, pp. 139-150, 2015.

[12] M. Uzunoglu, O. Onar, and M. Alam, "Modeling, control and simulation of a PV/FC/UC based hybrid power generation system for stand-alone applications", Renewable energy, vol. 34, pp. 509-520, 2009.

[13] D. Rastler, Electricity energy storage technology options: a white paper primer on applications, costs and benefits, Electric Power Research Institute, 2010.

[14] P. F. Ribeiro, B. K. Johnson, M. L. Crow, A. Arsoy, and Y. Liu, "Energy storage systems for advanced power applications", Proceedings of the IEEE, vol. 89, pp. 1744-1756, 2001.

[15] O. Krishan, "Optimum sizing and economical assessment of grid integrated hybrid system for a rural village: A case study", in Power Electronics, Intelligent Control and Energy Systems (ICPEICES), IEEE International Conference on, pp. 1-5, 2016.

[16] A. Amevi, "Performance Analysis of Particle Swarm Optimization Approach for Optimizing Electricity Cost from a Hybrid Solar, Wind and Hydropower Plant", International Journal of Renewable Energy Research, vol. 6, no. 1, pp. 323-334, 2016.

[17] B. S. Borowy and Z. M. Salameh, "Optimum photovoltaic array size for a hybrid wind/PV system",

IEEE Transactions on energy conversion, vol. 9, pp. 482-488, 1994.

[18] S. Karaki, R. Chedid, and R. Ramadan, “Probabilistic performance assessment of wind energy conversion systems”, IEEE Transactions on Energy Conversion, vol. 14, pp. 217-224, 1999.

[19] H. Shahinzadeh, M. Moazzami, M. Abbasi, H. Masoudi, and V. Sheigani, “Smart design and management of hybrid energy structures for isolated systems using biogeography-based optimization algorithm”, in Smart Grids Conference (SGC), pp. 1-7, 2016.

[20] H. Yang, W. Zhou, L. Lu, and Z. Fang, “Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm”, Solar energy, vol. 82, pp. 354-367, 2008.

[21] S. B. Silva, M. M. Severino, and M. A. G. de Oliveira, “Sizing and optimization of hybrid photovoltaic, fuel cell and battery system”, IEEE Latin America Transactions, vol. 9, no. 1, pp. 817-822, 2011.

[22] J. G. Castellanos, M. Walker, D. Poggio, M. Pourkashanian, and W. Nimmo, “Modelling an off-grid integrated renewable energy system for rural electrification in India using photovoltaics and anaerobic digestion”, Renewable Energy, vol. 74, pp. 390-398, 2015.