Cost Analysis of an Off-Grid Solar/Wind/Battery Based Renewable Energy System for Variable Load

Sujeet Singh, Krishna Murari Pandey, and K. K. Sharma

Abstract Off-grid renewable energy systems have been fascinating to provide energy to different sectors in all the directions like sustainability, viability and environmental safe-conduct, particularly for the societies living in remote areas where expansion of grid is not relevant. Renewable energy system shows numerous combinations built on the basis of renewable sources that can be practiced together to provide power in the form of a dedicated off-grid system supported by battery-bank storage and diesel generator as backup systems. In this article, wind turbine-PV-battery storage-inverter was used as system components and these were simulated and optimized for the entire NIT Silchar campus in the state of Assam, India. The primary load demand of the entire campus is 11,378.94 kWh/day and peak load of 671.62 kW. A popular freeware HOMER modelling software has been used to analyze the stand-alone RES system. Solar energy and wind are used as prime sources to generate power and supply it straight to the load. If excess electricity is produced, it is used to charge the battery bank. The campus's load consists of power required for lighting, pumping of water, hotel electricity load, different department electricity load and various quarters load which are situated inside the campus. While analyzing this energy system, the simulation is done and results are optimized on the basis of power load, meteorological data sources. The economics of energy components and other parameters in which the net present cost (NPC) is to be minimized to select an economically viable energy system. However, other criteria, such as additional power generation, capacity shortage, COE, were also acknowledged to investigate the technological ability to choose an excellent system in techno-economic perspectives. The two approaches are used as a comparative criterion to select an energy system from the chosen options that give sufficient merit to one of the measuring tools (Net present cost and low cost of energy).

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1 Introduction

Energy demand is growing at an increasing rate and can not be fully met by conventional energy systems because of inadequate supply. As we all know that fossil fuels are depleting, and energy needs are growing day by day, the production of renewable energy is attracting worldwide attention. Specially, for stand-alone applications, the hybrid solar photovoltaic system and the wind power generation system become a desirable solution. Combining solar and wind power sources together can deliver much better reliability, and their renewable energy system becomes more cost-effective because one system's deficiency can be complemented by another's power. The combination of solar and wind generation systems into a grid should further enhance the overall economy as well as reliability of renewable energy sources in delivering their energy. Similarly, integrating solar and wind power into an off-grid system can decrease the amount of power storage required for continuous power supply. There are several storage components and power generators for hybrid power systems. It is designed to meet the remote area's energy needs. Wind generators, PV generators and other electricity sources are added to meet local geographical conditions and other specifications. It is important to know the specific energy demand and available resources for that location in order to develop a hybrid system for a specific location. Energy planners, therefore, need to explore the potentially available resources for solar, wind and hydropower for a specific site location.

2 Literature Review

A detailed study was needed to gather intelligible information on the country's renewable energy potential, hybrid power systems, and rural electrification techniques using combined resources. Renewable energy opportunities for access to renewable energy potential and stand-alone hybrid systems have been implemented in various research efforts. The following different authors were conducted at different times, locations and countries for a number of hybrid systems; the simulation methodologies used are Genetic algorithm and HOMER.

Nfah et al. [1] describe the solar photovoltaic system project information and the wind generator hybrid electricity generation system to supply power to societies of 110 households, a public health centre and a primary school. Research has started by exploring the potential of interesting solar and wind sources in our area. In optimized simulation, the result revealed that the system was configured by PV/wind turbine/diesel generator/battery and converter. The total value of NPCs and COEs for this configuration is $113,814 and $0.312/kWh, respectively, an 84% renewable share, and 1,945 L of diesel consumed per year, corresponding to 635 h per year.

A study conducted by [2] to evaluate the potential for electrification in rural areas of villages in Bhutan. The research work was conducted across the country at four different locations. Furthermore, only for lighting and communication services was the load requirement taken. The article's main purpose was to optimize aggregates of hybrid energy. The PV/battery power system is Gasa and Lunana's cheapest technology, while the Getena area's cheapest hybrid diesel/battery system. It is better to implement the introduction of a wind and rechargeable battery system instead of Yangtse. According to the study [3] on the technical and economic aspects of rural community schemes in Algeria in the hybrid (wind and diesel generators). In order to reduce fuel consumption, a detailed research was conducted to include a wind generator to the current diesel power plants. The author concludes that the wind speed of 0.04–0.189 $/L is economically viable from the hybrid system below 6 m/s of existing diesel fuel. The hybrid system's feasibility is guaranteed at a wind velocity of 6.58 m/s, a maximum yearly capacity shortage of 0%, a minimum return of 0% and a fuel price of $0.151/L. Kasuakana et al. [4] explore the feasibility of a renewable energy system as a primary source of electricity for mobile phone stations in the DRC. The survey was carried out for three different non-network-connected areas: Fireplace, Mbuji-Mayi and Cabinda. Possible setting options are PV-WT-diesel generator, clean PV and clean wind energy systems; the techno-economic and environmental effects have also been studied. Bilal et al. [5] presented a multi-purpose PV-battery-wind hybrid system that fulfils two basic objectives to minimize LPSP and annual costs. The production of the produced hybrid system (kWh/year) is 63,035 and the annual cost system (EUR million) is 0,110 with 95 kW h/day load. Bilal et al. [6] approach MOGA which has been used to optimize and design a stand-alone hybrid PV- diesel hybrid system that reduces energy costs and CO_2 emissions in Senegal.

3 Cost Data and Size Specifications of Each Component

The basic measure of choosing the right energy system components in this current work is the cost of the components, as the primary objective of the paper is to find the optimal energy system configuration that will meet the demand with minimum COE and NPC. The cost of the components was estimated based on current market values.

3.1 Solar PV Size and Cost

The following panel was selected after surveying various products taking cost into consideration. The reason why the stated company chooses the product is because of its low cost delivered until and unless until efficiency becomes a major concern here. A 1 kW solar panel was used with four solar module numbers having 250 W capacity.

Table 1 Size and cost of PV panel

PV size (kW)	Capital cost (₹)	O&M cost (₹/year)	PV life (year)
1	80,000	800	25

Table 2 Size and cost of wind turbine

Capacity (kW)	Capital cost (₹)	Replacement cost (₹)	O&M cost (₹/year)
3	450,000	315,000	9000

Table 3 Size and cost of battery

Capacity (kW)	Capital cost (₹)	Replacement cost (₹)	O&M cost (₹/year)
1	8000	5600	800

In this analysis, the installation cost is considered to be 8% of the photovoltaic module cost, and the cost of operation and maintenance will be 1% per annum (Table 1).

3.2 Wind Turbine Size and Cost

The wind turbine taken for this paper has a power output of 3 kW. The wind turbine is manufactured by Vikktor & Co. KUG, Germany. The proposed wind turbine costs for operation and operation are about 2% of its initial capital expenditure (Table 2).

3.3 Cost and Size of Battery

Like other power system components, battery cost and number are input parameters that are introduced in the software. Pay attention to the definitions; the nominal capacity of the battery is the amount of power the battery emitted. The minimum battery charging status is the charging state under which the battery will never discharge to prevent any potential which can cause damage to the battery. The recommended minimum charge state is 30–50% (Table 3).

3.4 Power Converter Size and Cost

The flow of power between the DC and AC power system components must be maintained by a converter. The power rating of the inverter must be equal to or greater than the peak value of the load, but since both the renewable and non-renewable

Table 4 Size and cost of power converter

Capacity (kW)	Capital cost (₹)	Replacement cost (₹)	O&M cost (₹/year)	Life (year)
10	75,000	52,500	750	15

loads will supply, it will be installed below the peak. In this case, there is no need for estimating operating and maintenance costs. The capital cost of the converter is taken as 75,000, the cost of replacement is around 52,500, the efficiency of the converter is about 92%, and the lifetime of the converter will last for 15 years (Table 4).

4 Methodology

The methodology used in this present analysis is primarily two-fold. In case of the first one, four different models of RES are analyzed while taking their fundamental costs, technological specifications into account. Wind and solar data are used to simulate the RES model mentioned above. The load characteristics of the RES system are matched with the hourly energy demand so that the load profile can be matched. Subsequently, net present cost (NPC), lifetime installation cost and operation and maintenance costs and energy costs (COE) are calculated to estimate the economic feasibility of RES.

4.1 Cost Function

A key objective of this paper is to minimize several fixed and operating costs for chosen RES systems and to examine their cost performance. An optimal RES system is selected based on the minimum cost of energy production. An objective function is defined, which is to be minimized using HOMER software.

An objective function [7] has been generated, which is expressed as

$$\min\{C_{\text{NPC}}(x)\} - \min\{C_{\text{pv}} + C_{\text{wt}} + C_{\text{aux}}\} \tag{1}$$

where x is a particular RES configuration vector. C_{pv} denotes the photovoltaic module total cost along with the accessories, C_{wt} represents the wind generator total cost along with its other accessories, and C_{aux} represents all the other required components cost that is not either sized by the HOMER or not enlisted in the component list.

$$C_{\text{pv}}(x) = N_{\text{pv,total}}(C_{\text{pv}} + nM_{\text{pv}} + I_{\text{pv}}) + N_{\text{inv}}(C_{\text{inv}} + I_{\text{inv}}) \tag{2}$$

where N_{pv} represents the amount of the photovoltaic module in x vector; N_{inv} represents amount of the inverter module; C_{inv} represents an inverter/converter cost. M_{pv} is the cost of maintenance per year of the PV module, I_{pv} and I_{inv} are the respective component cost of installation and n is lifespan of component, taken as 25 years. C_{wt} represents the wind generator system cost, and is expressed as

$$C_{wt} N_{inv,total}(C_{inv} + I_{inv}) + N_{wt,total}(C_{wt} + nM_{wt} + I_{wt}) \tag{3}$$

where N_{inv} is the number of inverter model; N_{wt} represents the number of the wind generator system; C_{inv} denotes the cost of a single inverter; C_{wt} is WT model cost; M_{wt} is the maintenance cost of the wind generator; I_{inv} and I_{wt} are cost of installation of inverter and WT respectively and n is lifetime, which is taken as 25 yr. The final term, i.e., C_{aux}, represents all additional system-specific components costs

$$C_{aux} = N_{bat} C_{bat} \tag{4}$$

where N_{bat} represents the number of battery and C_{bat} represents capacity of battery.

4.2 Modelling Strategies and HOMER Simulation

By examining the meteorological inputs and load profiles of the selected location, unit sizes of system components are selected on the basis of the accessibility of standard renewable systems in the market with due attention to their economics. Subsequent to choosing the components required in the RES, input data are inserted for every single component, which essentially depicts the cost of components, technical features, and resource data. HOMER analyzes demand to the power that system delivers and estimates the flow of power to and from every single component of the system (Fig. 1).

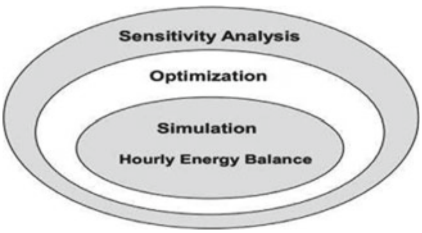

Fig. 1 Interaction between simulation, optimization and sensitivity analysis

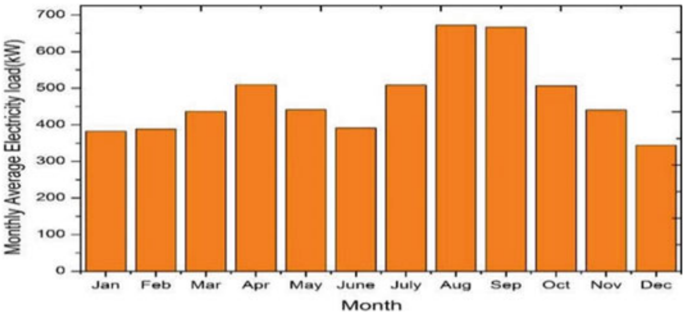

Fig. 2 Monthly average electricity load

4.3 Electricity Load Input

The electrical load is first entered into the modeling tool when selecting the component technology from the HOMER software library. The primary load input was entered daily (data for 24 h) and the software subsequently modelled the peak load (Fig. 2).

5 Results and Discussions

Though HOMER has simulated many configurations of power system components, however, it only shows the scenario of energy systems possible for detailed study. Complexity and computation time relate to the amount of parameters and the total number of implicit values included in the design. Two different scenarios have been suggested for further study and to develop the possibility of finding the most optimized system. Power schemes (scenarios) with low NPC, low COE, low capacity constraints, small standby power would be suggested as an optimal system.

(a) Solar Photovoltaic- Battery (scenario A)
(b) Solar Photovoltaic-wind generator-Battery (scenario B).

5.1 Optimization Analysis of the Selected Scenario

On the basis of inputs provided, 42,670 simulation runs were executed using a 64-bit OS, 3.8 GHz processor and 16 GB RAM desktop computer. While considering operating reserve as a safety margin, the energy system was created in order to allow the energy system to feed reliable power and make it easier for further load expansion in the upcoming future. Optimization result of all the possible configurations of viable energy scheme established on total net present cost (NPC) of the system are shown is Table 5.

Table 5 Overall optimization results using HOMER software

PV size (kW)	Wind turbine quantity	Battery quantity	Converter size (kW)	Initial capital cost (crores)	Q& M cost (crores/year)	Total NPC (crore)	Cost of energy (₹/kWh)	Capacity shortage (%)
3469	20	4458	684	40.14	0.54	50.04	8.56	9
3582	22	4512	632	40.84	0.56	50.13	8.61	7
3671	19	4496	652	41.14	0.57	50.34	8.72	9
3645	28	4317	721	42.31	0.58	51.32	8.86	8
3678	26	4389	726	42.98	0.61	53.32	8.91	6
3572	31	4485	690	42.16	0.55	52.61	8.89	9
3601	31	4369	668	42.21	0.56	52.85	8.94	5
3254	0	4256	676	37.90	0.52	45.21	7.56	0
3262	21	4360	712	38.23	0.53	46.32	7.72	0

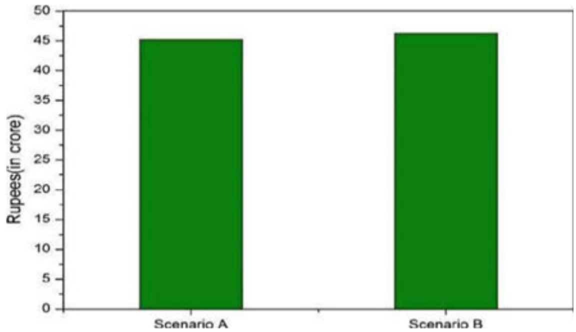

Fig. 3 Comparison of scenarios based on NPC

5.2 *Comparison of Scenarios*

5.2.1 Based on Total Net Present Cost

The principal load of 11,378.94kWh/day for which the parameters are specified, highest power shortage of 10% is considered for which comparison of parameters are addressed for the selection of the techno-economic feasible power system. Referring to Table 5, the NPC in case of scenario B is slightly greater than the scenario A, which is 45.21 crores (Fig. 3).

5.2.2 Based on Cost of Energy

For detailed information of the COE for every energy system arrangements (scenarios) refer to Fig. 4 and Table 5, two scenarios (scenario A and scenario B)

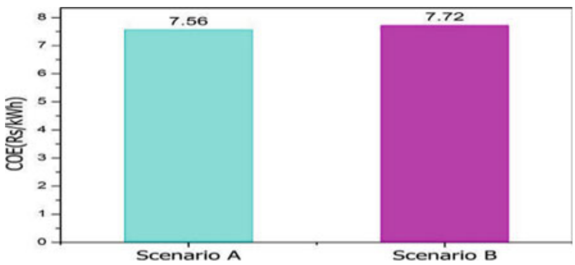

Fig. 4 Comparison of scenarios based on COE

there is a slight difference in cost of electricity. Scenario A showed the lowest value of COE. For case A the COE is ₹7.56/kWh and for case B, it is ₹7.72/kWh.

6 Conclusion

An optimization process was performed during the analysis of the stand-alone RES system set-up based on the power demand, climate data inputs, and economy of the energy components in which the net present cost must be minimized in order to select an economically feasible energy system. The result of HOMER simulation showed the most cost-effective system sorted by NPC from top to bottom. Two optimized results are found, one having configuration solar/battery while others having solar/wind/battery. The cost of energy in the first configuration is ₹7.56/kWh and ₹7.72/kWh in the second configuration respectively.

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