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Article

Cost-Effective Hybrid Wind-Photovoltaic Generation System for Isolated Critical Loads: A Case Study

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Abstract: This study provides a technical and economic analysis of integrating a microgrid structure for power generation with wind energy and photovoltaic (PV) generation. The study mainly focuses on providing optimal generation from renewable energy sources for supplying isolated critical loads with optimized cost. Using HOMER software, a financial study of the proposed wind-PV-based microgrid is presented. A model is built with artificial neural network (ANN) to further tune the simulated economic optimization results obtained for further economic optimization and validation analysis. A reduction of about 22% in cost of energy is obtained from the ANN based optimization of system cost. This indicates that the proposed hybrid generation system is a profitable one serving localized loads in isolation with 100% renewable energy utilization. The proposed system can modelled and established in an onshore area in eastern India with optimized utilization of renewable sources for generation with minimal cost as observed.

Keywords: artificial neural network (ANN), microgrid, optimization, technical and economic analysis, wind power

1. Introduction

These days, the majority of the energy required to generate electricity is obtained from burning fossil fuels like coal, oil, and natural gas. These fossil fuels have a finite supply, and burning them releases a significant amount of harmful gases into the atmosphere. Moreover, their usage leads to a continuous increase in the concentration of air pollutants, which also causes global warming besides creation of photochemical smog and acid rain [1]. Use of renewables is a solution; however, most renewable sources are of stochastic nature and weather-dependent and thus requires proper management [2]. Thus, the need and management for clean, sustainable energy sources remains continual. Wind is clean, limitless renewable energy source [3]. There are several ways to transform wind energy into electrical energy, but using a wind turbine is by far the most common method. Any generator may theoretically be installed coupled to a wind turbine to produce electricity. Even if the generator only produces direct current or alternating current with variable amplitude and frequency, the requirement for grid-compatible electric current may still remain. Fortunately, this need may presently be met by connecting proper converters.

Due to its robustness, minimal maintenance requirements, and straightforward controls, the induction generator (IG) seems to be a good option for electricity generation [4]. IG is suggested for the generation of wind energy due to its ease of use, robustness, and compact size per generated kilowatt. Additionally, isolated IGs may require an excitation magnetic field even when no external power source is present and this is met

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utilizing capacitor banks. They can therefore be utilized in isolated regions [5], for utilizing wider range of wind speeds [6] and also using different converters in isolation for supplying critical loads [7]. The main limitations of IGs continue to be the need for reactive power consumption and poor voltage regulation at varying speeds and loads. This is despite the introduction of static power converters which makes it easier to control the output voltage of IGs [8] and also for fault ride through of IGs [9]. Although SEIGs are popular in microgrids, sustainable grid connection of isolated renewable sources following intelligent algorithms have been studied and found quite useful for optimized generation and production cost [10].

The self-excited induction generator (SEIG) is an excellent option for wind-driven electric production applications since it does not require an additional power source to create the magnetic field, especially in locations with variable wind speed and isolation. A large number of research articles have lately begun to concentrate more on the analysis and applications of single-phase SEIGs [11], SEIGs with current compensation control [12], for high power operation [13] and unbalanced SEIGs [14]. This is due to advances in voltage and frequency management methods over the past thirty years, as well as a greater worldwide emphasis on the development of isolated renewable energy sources.

The SEIG system's inability to regulate voltage and frequency under varying load situations is its primary operating issue. The machine excitation is immediately impacted by a change in the load impedance. This is because both the load impedance and the induction machine acting as the generator share the reactive power of the excitation capacitors. Therefore, when the load impedance increases, the generator's voltage falls, leading to poor voltage control. The induction generator's slip, on the other hand, rises with increasing load even when the prime mover's speed stays constant, resulting in a frequency that is load-dependent.

Renewable energy from hybrid generation such as wind and PV can often supply isolated loads without storage [15], and sometimes with the need for storage battery for critical loads [16]. Hybrid sources alike wind-PV [17] and hydro-PV [18] are also employed to provide remote and grid-inaccessible loads for standalone or isolated generating. PV along with wind is most popular as they complement each other well in different weather conditions. Moreover, solar energy is also easily available, safe for the environment, and easy to install and maintain and thus is the automatic choice for its use with wind [19]. However, they increase system initial and present cost of running. Thus, an economic analysis along with technical investigation is also essential. Maximum power point tracking (MPPT)-based control techniques are also often employed [20]. MPPT approaches can make it easier to control grid-connected generation [21]; however, grid-secluded generation is often handled without MPPT to reduce system complexity [22]. Different types of wind turbines for harnessing wind energy is also studied recently. The use of INVELOX turbine is shown to be a good option for increased performance in some places [23]. However, as independent generations are frequently employed to complete important tasks, and maintaining a stable generation also becomes crucial [24].

Since hybrid energy systems are quite flexible and efficient, they may enhance both technical and financial elements of infrastructures and recently, different case studies were taken up for such analysis. This is possible with the formation of energy internet with smart building establishment and interaction of demand side with the supply side [25]. These interactions are flexibility measures and recently reported in [26] with home crypto miners, adaptive parking lots, etc. A digital model of a smart microgrid including a battery swapping station, storage, and renewable energy sources is created to evaluate performance in [27]. Storage also has an impact on such grids. Different battery types perform differently in terms capital and operational expenses, capacity degradation, battery life, and state of charge limitations [28]. Impact of diverse penetration levels of thermal units is studied on energy management of a hybrid microgrid [29].

The primary goal of the proposed study is to offer a hybrid generating option for serving isolated and critical loads with stable generation in an onshore eastern Indian location. A hybrid wind-photovoltaic scheme is examined for its cost-effectiveness and technical analysis in order to supply isolated critical loads at the location chosen. The optimization system uses a software simulation study using HOMER (Hybrid Optimization Model for Multiple Energy Resources). The results obtained from the same are further tuned using Artificial Neural Network (ANN) based analysis, the results of which also indicate the viability of the setup when installed originally. The rest of the paper is structured as follows: in Section 2 of the paper, a description of the system, including software-based cost analysis and technical specifications is presented. The software-based evaluation and artificial neural network (ANN) based cost evaluation and tuning is explained in Section 3 and Section 4 respectively. Results and associated discussions are provided in Section 5. Finally, conclusion is drawn in Section 6 along with limitations of the study and discussion on future scope of research.

2. System Description

The three-phase induction machine is employed as induction generator which is operated using wind turbine. The IG is connected to an AC bus so that system loads can also be supplied by that bus. The stator windings of the induction motor are connected to a capacitor bank to provide the initial reactive power. From reactive power balancing, the initial excitation is computed [4]. The IG system is linked to a backup PV panel to supplement and support generation. In order to support the loads during times of low generation, a storage battery is additionally connected via a charge controller. Figure 1 depicts the block diagram of the connected system.

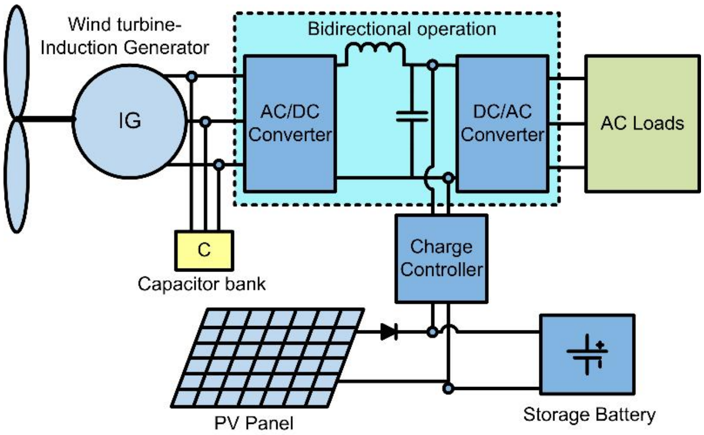

Figure 1. Proposed system block diagram.

The proposed system is meant to be utilized in an onshore eastern coastal remote area in West Bengal, India, that is isolated from the grid. Due to the lack of a grid connection, the proposed generation plan's utility is crucial in supplying electricity to the critical loads that are linked remotely. The daily primary AC load profile chosen is shown in Figure 2 and it primarily consist of a household with moderate load demand.

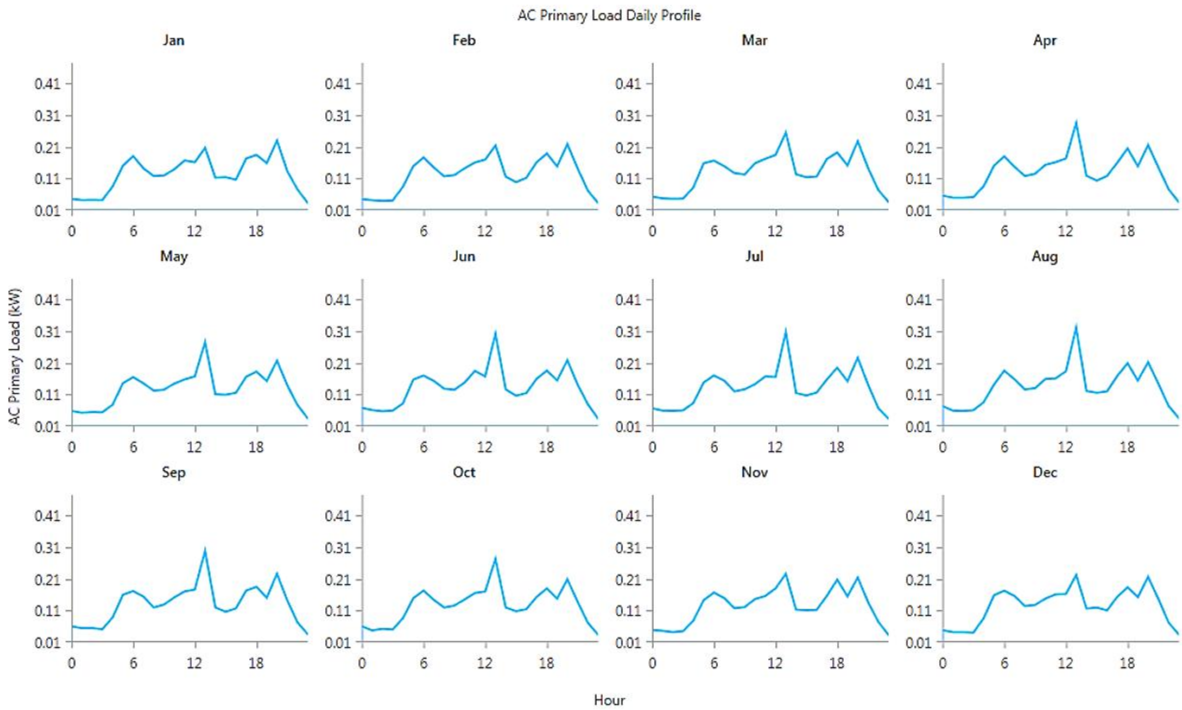

Figure 2. Daily load profile of a household under study.

The aim of the proposed generation scheme is to provide stable voltage with changing loads and wind speeds. Thus, the generator control is focused on providing stable voltage during all such disturbances. The control for the induction generator is done using an active voltage reference control. In this process, the IG generated voltage is compared with a proportional wind turbine speed reference. The reference voltage is variable in proportion to change in wind speed. The variable reference is compared with generated voltage from IG and the error signal is passed to a proportional integral (PI) controller. The output of which is the current reference. The IG current is sensed and fed to a hysteresis band controller for generation of pulses for the inverter. The frequency at load end is maintained constant by using fixed frequency switching of 50Hz for the DC/AC converter. The controller for AC/DC converter is shown in Figure 3.

The PV panel is always connected to the DC bus which will also maintain the stable voltage. It is controlled using the popular perturb and observe based maximum power point tracking controller.

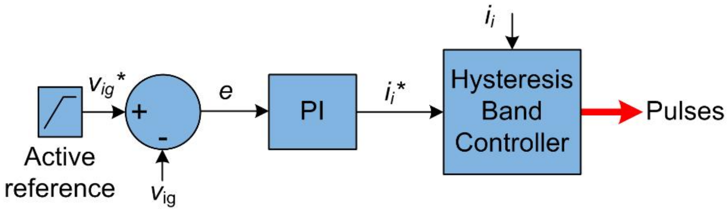

Figure 3. Controller for IG side converter.

2.1 *System Ratings*

Two numbers of 500W-peak polycrystalline Silicon PV panels are utilized with the IG for the arrangement. Each of the panels has 48V voltage rating. For linked systems with a peak load of 650W, deep cycle lead acid batteries with ratings of 12V and 100Ah of four numbers in series and overcharge/discharge prevention are utilized, providing a two-hour backup. The charge controller used has a rating of 22A. The bidirectional converter is built with MOSFETS having rating of 1200V and 20A rating with dedicated driver circuit. The circuit also has short-circuit and overcurrent protection.

2.2 *System Installation*

The proposed approach is intended for use in an off-grid onshore eastern coastline remote region of West Bengal, India in location of (21.7690°N, 87.8652°E). The wind profile of the place along with the wind frequency rose is shown in Figure 4. The data is obtained from the National Renewable Energy Laboratory (NREL) and it shows that the months of June and July provide peak power from the wind.

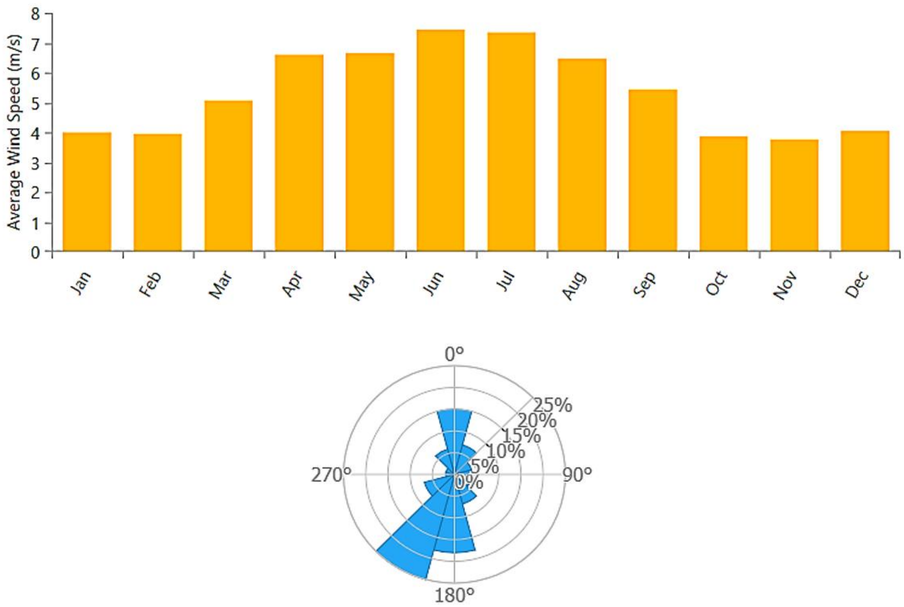

Figure 4. Wind resource profile of the place under consideration for installation along with the wind frequency rose.

Similarly, the solar resource data is depicted in Figure 5 and obtained similarly from the NREL database. Summer months of March, April and May provide better solar energy for generation. The clearness index is also shown which determines the clearness of the atmosphere for better generation.

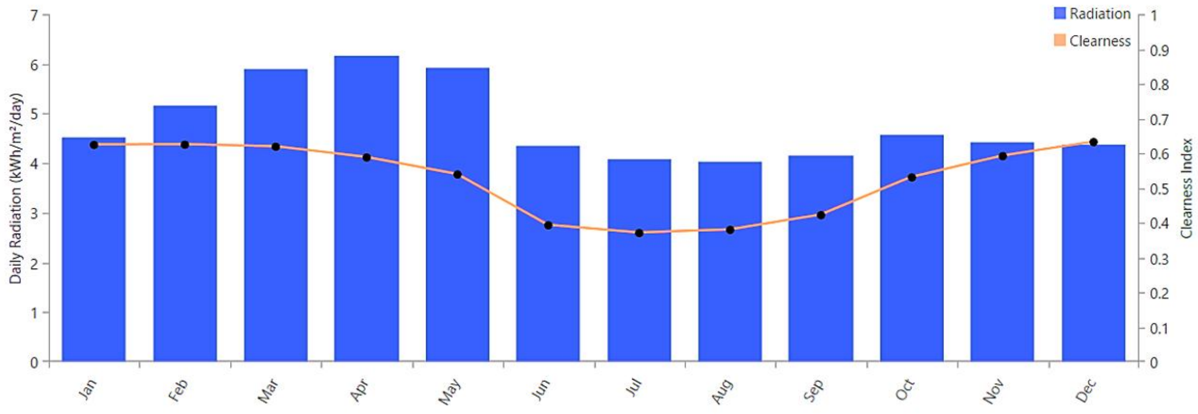

Figure 5. Solar resource data.

3. Cost Assessment and Optimization Using HOMER

It is necessary to assess the cost of connecting the IG and PV resources in a microgrid. Utilizing HOMER software, the cost estimation and optimization are carried out. HOMER, which was initially created at the National Renewable Energy Laboratory (NREL, USA) and improved and made available by HOMER Energy. It is a single software program to enable the coexistence of engineering and economics and is also now an industrial standard for carrying out economic analysis for distributed resources in a microgrid.

Some components are utilized in the creation of the online microgrid simulation of the proposed system. An IG-based wind generator, a primary load, a converter, a battery, and a PV cell are the components. The results of the connection can be calculated and optimized after a variety of iterations. A 1kW wind turbine and 1kW PV panel off-grid system with a 48V, 100Ah storage battery are employed for the simulation. The cost estimates for the individual components are established on market data garnered from a survey. Below are explanations of the simulation-related components that were taken into consideration for the present study.

3.1 *Wind-Powered Generator*

The system under consideration employs a 1kW AC-output wind turbine generator. The cost of the turbine-generator system is approximately $3500, while the cost of replacement is $3000. The cost of operation and maintenance is calculated as 2% of the initial cost every year. The wind turbine is considered installed at a hub height of 10 meters.

3.2 *PV Panel*

The PV panel utilized for the simulation has a capital cost of $1200 and is rated for 1kW-peak, 48V. The same has an O&M cost of 2% of initial capital cost, primarily for cleaning. Due to lower technological malfunctions, the lifespan is assumed to be 25 years.

3.3 *Bidirectional Converter*

The suggested generating method employs a rectifier to convert produced AC power from the generator to DC and an inverter to convert DC power from the PV panel and battery to AC. These two systems may be simulated as a bidirectional converter that can convert power in both directions from source to load and back to source using the HOMER program. The converter has rating of 1kW, initial capital cost of $300, and $200 as replacement cost. The O&M expense is taken as zero.

3.4 *Battery for Storage*

The storage battery under consideration is rated at 100Ah, 48V. The battery's efficiency is 80%. 50% is the bare minimal state of charge. The battery has capital cost of $100 upon purchase and a $50 as replacement cost. The battery's annual operation and maintenance fee of $5 mostly covers the cost of watering it. All the system component costs are provided in this research based on a market survey conducted by the authors.

3.5 *Determination of System Cost*

The discounted costs are generally subtracted from the present values of the various power sources to determine the Net Present Cost (NPC) of the system. Thus,

$$NPC = C_{ic} + C_o + C_r - \left(C_e + C_s\right) \tag{1}$$

where, C_{ic} is the initial system cost and it is given as,

$$C_{ic} = C_{wtg}P_{wtg} + C_{pv}P_{pv} + C_{conv}P_{conv} + C_{batt}P_{batt} \tag{2}$$

where, the unit capital costs of the wind turbine generator, PV panel, converters and batteries are denoted as C_{wtg}, C_{pv}, C_{conv} and C_{batt} respectively. Also, P_{wtg}, P_{pv} and P_{batt} respectively are the nominal power obtainable from the wind turbine generator, the PV panel and the battery. P_{conv} is the combined nominal power of the converters. C_o is the system operation and maintenance cost and it is assumed as 2% of the C_{ic} annually, C_r is the system replacement cost while C_e and C_s are the net present cost of the sold surplus electricity and the equipment salvaged at the end of total lifetime. The value of C_e is calculated on hourly basis and it is dependent on the power produced from the system and the load demand.

The value of C_r can be calculated from [30] as,

$$C_r = \sum_{i=1}^{n} C_{rk} \frac{\left(1+g_k\right)^{in_k}}{\left(1+IR\right)^{in_k}} \tag{3}$$

where, C_{rk} is cost of the component replaced, expected inflation rate is denoted as g_k and IR is the interest rate. Also, n_k is total lifetime of k^{th} component. The C_s is calculated as,

$$C_s = C_{rk} \frac{R_c - \left(R_p - R_r\right)}{R_c} \tag{4}$$

where, R_c, R_p and R_r are the individual component lifetime, total project lifetime and replacement cost calculation duration. The operating cost per year is the annualized value of summation of running costs and expenses which excludes the initial system cost. As observed from the different equations, the NPC is a variable and can be optimized to minimize the system cost.

The parameter that determines the optimum net present cost is the levelized cost of energy (LCOE). This value is calculated as the ratio of annualized cost of producing electricity to the total electric load served. It is given as,

$$LCOE = \frac{C_{annual}}{E_{served}} \tag{5}$$

where, C_{annual} is total annualized system cost in $/year and E_{served} is total load served in kWh/year. Roughly, it can be taken as the ratio of NPC and the total load served. Figure 6 shows the simulated system.

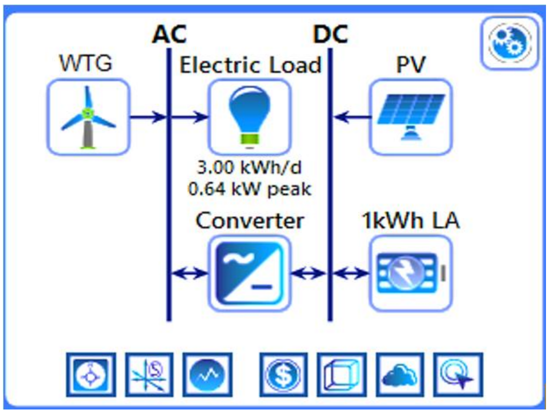

Figure 6. Simulated system.

4. Cost Assessment and Optimization Using ANN

ANN is a computational model that draws inspiration from the design and operation of the human brain [31]. It has also been previously applied to boost wind energy conversion systems' efficiency [32] and power tracking purposes [33]. ANN is a machine learning algorithm that can be taught to spot data patterns and generate predictions using those patterns. ANNs are made up of numerous layers of linked nodes, or "neurons", that analyze data before passing it on to the following layer. Each neuron in an ANN gets input from other neurons, processes that input using a mathematical function, and then outputs something that is then sent to other neurons in the network. In order to function better, the network can learn to modify the weights of the connections between neurons.

The ANN uses different inputs and has hidden layers for weightage adjustment and then finally the expected output is obtained. For the proposed work, a feedforward ANN model is employed to derive at the optimized NPC. A feedforward model is straightforward and can easily compute output through simple propagation. It uses six inputs as initial system cost, cost of operation and maintenance, cost of replacement, cost of sold surplus electricity and cost of salvage. The ANN structure is depicted in Figure 7. After finding the optimized results from the ANN, a software routine is enabled which will enable to adjust the weights in the hidden network of the ANN. The weight adjustment is done using back propagation method. It is a gradient descent-based technique for guided learning in ANNs. The approach determines the gradient of the error function with regard to the weights of the ANN given an error function and a neural network. The weights are adjusted for several iterations until minimum error is achieved with minimal simulation time.

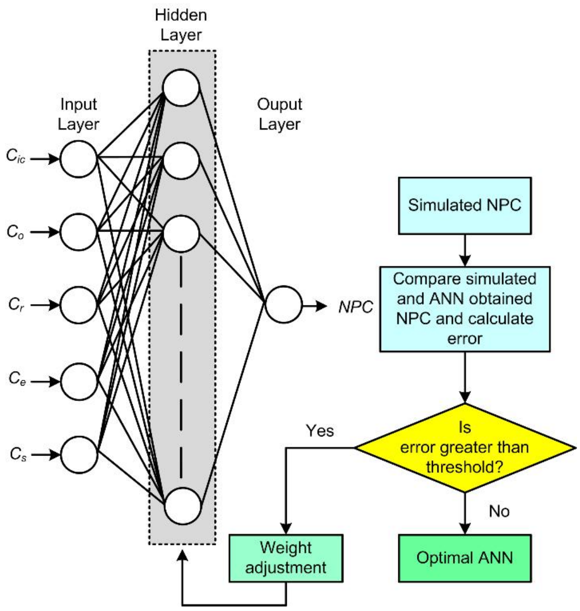

Figure 7. Proposed ANN structure.

5. Results and Discussions

The HOMER software (Ver. Pro x64 3.14) is run on an Intel(R) Core(TM) i5-8250U CPU @ 1.80 GHz personal computer with 8GB RAM and 64-bit operating system. Optimization results from the proposed simulation is shown in Figure 8. The hybrid system's higher initial cost is mostly caused due to the usage of PV panels and batteries, but their use makes the system more reliable than a traditional wind generator system in supplying a crucial isolated load across wide wind speed ranges. Additionally, it is anticipated that the majority of the system's original cost would be recovered over the course of the projected 25-year lifespan.

Architecture									Cost				System
				PV (kW)	WTG	1kWh LA	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)
				1.03	1	8	1.00	LF	$9,153	$0.677	$196.71	$6,638	100
				1.03	1	8	1.00	CC	$9,153	$0.677	$196.71	$6,638	100

Figure 8. Optimization results using HOMER.

As seen, the Net Present Cost (NPC) of the system is $9153 with cost of energy production of one unit from the system at $0.677 and annual operating cost of $196.71. The system is consisting of 1kW PV panel with 1kW generator and converter. The dispatch strategy may be load following (LF) which enables the generator to just supply the load without the surplus storage of energy or it may be cycle charging (CC) which causes generation of surplus power to charge batteries. The initial cost of the system is $6638 with 100% renewable energy utilization. The monthly electricity production from the wind turbine generator (WTG) and the PV panel during different months is shown in Figure 9. As observed, the PV generates most of the power and it is used largely to cater loads. Wind turbine generator on the other hand generates well mostly during the summer months and can easily serve the peak loads.

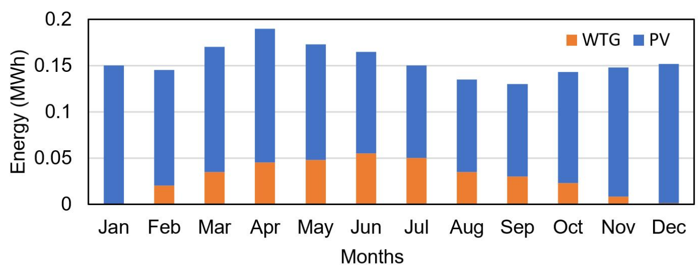

Figure 9. Simulated monthly electrical energy production from the system.

The battery average state-of-charge (SoC) percentage variation during different months is depicted in Figure 10. It is imperative that during the summer months, the battery SoC is reduced more than winter months indicating some load share is supported by the batteries. During the winter months, the generation from the system is sufficient enough to meet the loads and battery is in charging mode mostly.

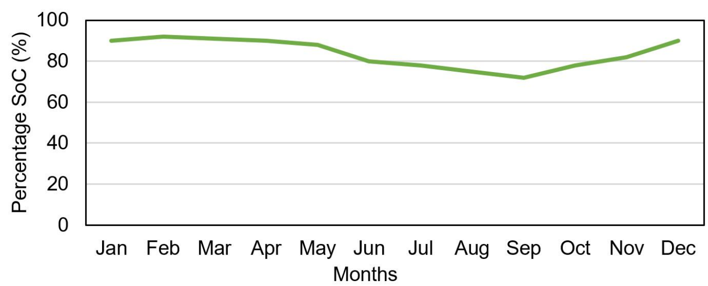

Figure 10. Variation of battery SoC (%) during different months of the year.

Next, a sensitivity analysis is carried out with wind speed as the variable. The net present cost variation with cost of production of energy is studied and the same is displayed in Figure 11. Two cases are considered, firstly during scaled average wind speed of 3m/s and secondly during a higher wind speed of 8 m/s. As observed, during higher wind speeds, the costs are reduced for production of similar amount of energy from the system. This also implies that the wind energy plays a significant role in production of electrical energy from the system.

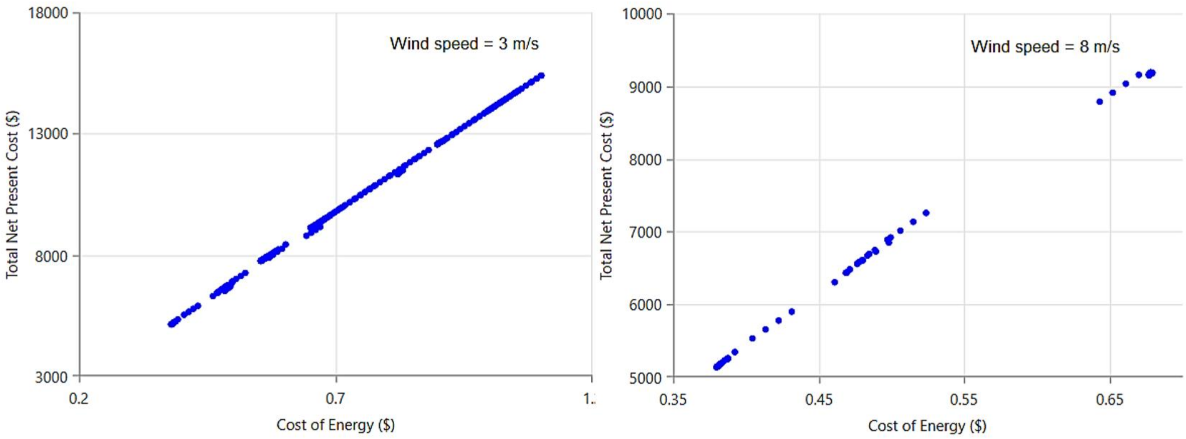

Figure 11. Variation of NPC with cost of energy at different wind speeds.

The proposed ANN based cost assessment and optimization study is also carried out. The ANN calculations were performed via MATLAB (R2016b) software. Tuning the parameters of an Artificial Neural Network (ANN) is a crucial step in achieving optimal performance. The process involves adjusting various hyperparameters to find the best combination for your specific problem. Initially, a moderate learning rate (0.01) is used and adjusted based on the model performance. The network performance is tested for the numbers of neurons in hidden layers and it was found that 8 hidden neurons provided the optimum result with a lowest mean square error (MSE) at best validation and the highest coefficient of determination (R^2). Complexity and computational cost of the network simulation is also increased further along with computational time (more fitted functions). The training may also be compromised by local minima or over-fitting. Rectified linear unit (ReLU) activation function is used and found suitable for the present problem. The gradient of performance for validation is expressed in terms of the MSE between the predicted and target outputs. Different algorithms of ANN are tested viz. scaled conjugate gradient (SCG), gradient decent (GD), and Levenberg-Marquardt (LM). The performance comparison is shown in Table 1.

Table 1. Comparison of different algorithms for optimizing NPC

Parameters	Algorithm		
	SCG	GD	LM
R^2	0.972	0.927	0.986
MSE	0.058	0.122	0.014

The LM algorithm is observed to have performed better as it has better R^2 and low MSE values. It is thus suitable for moderate feed-forward network like the present problem. Similar performance was also achieved for a similar network in water treatment problem [34].

Figure 12 shows the comparison of the obtained NPC using the software and using the ANN for the proposed system. The value of LCOE is also shown as a measure for judging the optimized NPC output. As observed, the ANN optimized output generates a lower value of NPC and consequently a lower levelized cost of energy. This also indicates that the system is marginally profitable than the simulated result obtained from HOMER. The system is thus sustainable to be set up in a remote and grid-isolated area as observed from the results obtained. Figure 13 shows the validation performance of the ANN structure used. The plot shows the MSE versus the epoch number. When the lowest MSE is reached or the maximum number of training epochs is reached, the ANN simulation stops.

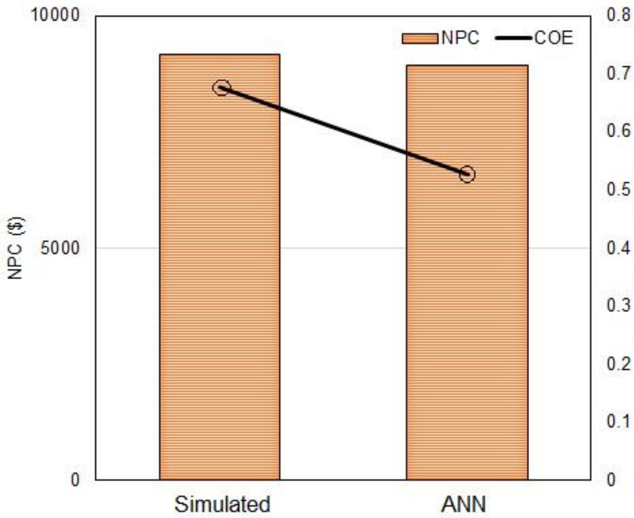

Figure 12. Comparison of NPC and COE from the simulated and optimized system data.

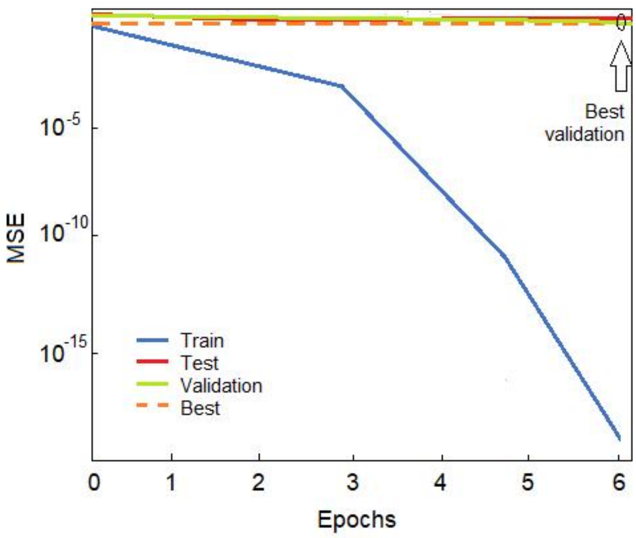

Figure 13. Validation performance of the ANN structure.

At epoch 3, the MSE dropped and a considerable decline is shown afterwards. The capacity of the ANN model to predict the output by modifying the weights and biases may be linked to the decrease in the training mean square error. Epoch 6 (MSE = 0.014) yielded the best validation results, after which the ANN model began to overfit the data and make the results ambiguous.

The system control is also simulated in MATLAB/Simulink (R2016b) with a system designed using same components and parameters as the HOMER simulation. The load voltage with change in wind speed and with step change in load is shown in Figure 14. As observed, the voltage could be maintained at a constant level with load and speed transients.

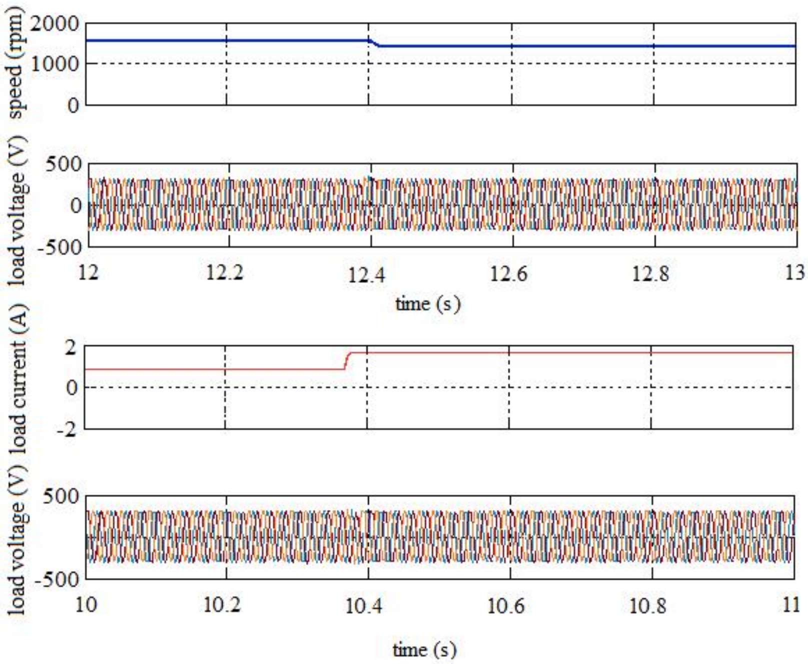

Figure 14. Variation of load voltage with change in speed and load current.

6. Conclusions

This paper presents a technical and financial study of a hybrid microgrid structure for power generation. Using HOMER software, a financial study of the proposed wind-based microgrid system is presented with optimized cost. The simulated system net present cost (NPC) is calculated along with the levelized cost of energy (COE). A model built on an artificial neural network (ANN) is also used to find and compare and tune the obtained results. Both the NPC and the COE are lesser than simulated model as found from the further optimized ANN model. It was found that a reduction of about 22% is obtained in COE indicating that the system is a profitable one for serving localized loads in isolation with 100% renewable energy utilization. A further lowering of COE indicates that the system is cheaper for production of electricity and is also efficient for future installations.

The proposed strategy shows the system can be modelled and established in an onshore area in India with optimized utilization of renewable sources and generation using minimal cost. There are some limitations in the proposed study. It requires detailed input data. HOMER does not guess key values or sizes and thus optimal sizing of resources is important. In the presented study, a further optimized sizing of the equipment can be carried out in future for better results. In future, the IG voltage regulation and load and speed transients can be carried out for optimized system output.

Conflict of Interest

There is no conflict of interest for this study.

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