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RESEARCH ARTICLE

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Optimal design and development of PV-wind-battery based nano-grid system: a field-on-laboratory demonstration

Abstract The present paper has disseminated the design approach, project implementation, and economics of a nano-grid system. The deployment of the system is envisioned to acculturate the renewable technology into Indian society by field-on-laboratory demonstration (FOLD) and "bridge the gaps between research, development, and implementation." The system consists of a solar photovoltaic (PV) (2.4 kWp), a wind turbine (3.2 kWp), and a battery bank (400 Ah). Initially, a prefeasibility study is conducted using the well-established HOMER (hybrid optimization model for electric renewable) software developed by the National Renewable Energy Laboratory (NREL), USA. The feasibility study indicates that the optimal capacity for the nano-grid system consists of a 2.16 kWp solar PV, a 3 kWp wind turbine, a 1.44 kW inverter, and a 24 kWh battery bank. The total net present cost (TNPC) and cost of energy (COE) of the system are US$20789.85 and US$0.673/kWh, respectively. However, the hybrid system consisting of a 2.4 kWp of solar PV, a 3.2 kWp of wind turbine, a 3 kVA of inverter, and a 400 Ah of battery bank has been installed due to unavailability of system components of desired values and to enhance the reliability of the system. The TNPC and COE of the system installed are found to be US$20073.63 and US$0.635/kWh, respectively and both costs are largely influenced by battery cost. Besides, this paper has illustrated the installation details of each component as well as of the system. Moreover, it has discussed the detailed cost breakup of the system. Furthermore, the performance of the system has been investigated and validated with the simulation results. It is observed that the power generated from the PV system is quite significant and is almost uniform over the year. Contrary to this, a trivial wind velocity prevails over the year apart from the month of April, May, and June, so does the power yield. This research demonstration provides a pathway for future planning of scaled-up hybrid energy systems or microgrid in this region of India or regions of similar topography.

Keywords photovoltaic (PV), wind, battery, nano-grid, hybrid optimization model for electric renewable (HOMER), field-on-lab demonstration (FOLD)

1 Introduction

The present civilization is facing an immense energy crisis due to fossils fuel depletion, industrialization, and urbanization. This crisis of energy is coming forth as a great threat to energy security of any nation. There is continuous price hike of imported fuel, which greatly affects the economy of importing countries. For sustainable, inclusive development, and environmental concerns, people all over the world are in quest of an alternative solution to this energy crisis. This apprehension results in investment of resources toward research and effective utilization of renewable energy sources.

Renewable energy resources are never ending and are freely available in nature. But the main disadvantage of these resources is that they heavily depend on the topographical condition of the specific site and subsequently on various meteorological data [1]. The output from renewable sources are sporadic in nature and thus, a single source may not be viable for the whole duration of certain energy demand [2]. Therefore, two or more than two renewable energy sources are integrated into a single unit with back-up storage option to provide continuous energy [3,4]. These renewable sources considered in the hybrid system are generally complimentary in nature [5]. At present, the photovoltaic (PV) system and wind turbine system are dominant among various renewable sources across the globe [6].

Various aspects of hybrid renewable energy system (HRES) or microgrid systems (MG) have been deliberated

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in recent years by different researchers. Optimal sizing and feasibility studies [7–11] of hybrid renewable systems considering different performance indices like loss of power supply probability (LPSP), relative excess power generated (REPG), total net present cost (TNPC), total annualized cost (TAC), levelized cost of energy (LCE), life cycle assessment (LCA), etc. [1,12–14] have been discussed for certain sites [9,15,16]. The studies have been conducted either by various optimization software like HOMER, i-HOGA, etc. [17–20] or by implementing different single [21,22] or multi-objective [23,24] meta-heuristic techniques. The hybrid systems have also been appraised based on different field of applications [25–27]. The literatures recommend that hybrid renewable energy systems comprising several renewable sources like PV, wind along with storage options are a quite feasible option for energy supply (heat or electricity) depending on the topography of the site under consideration. These types of systems can also reduce the burden of hefty fuel cost as well as emission generated otherwise from conventional systems.

The performance assessment of various deployed hybrid renewable systems has been presented by different research groups in sparse form [27–31]. Yamegueu et al. [28] and Giraud and Salameh [29] have presented a field-on-laboratory demonstration (FOLD) of two hybrid systems. The solar PV/diesel, inverter hybrid system without battery storage for off-grid area of Kamboinse, Burkina Faso has been demonstrated by Yamegueu et al. [28]. The power generated and fuel consumption of the system at varying load have been reported. Giraud and Salameh [29] have studied the performance of a 1.5 kW wind turbine, a 2.5 kW of PV, and a 44 kWh of battery storage installed in College of Engineering New-England (TNE) during two years of operation. Diaz et al. [30] have evaluated the field performance of a hybrid system installed in a rural area of the province of Jujuy, north-west of Argentina. The energy demand, system sizing, energy output, and fuel consumption of diesel, hydro-diesel, and photovoltaic-diesel hybrid systems have been studied for 16 locations. The on field PV-wind hybrid system deployed in a remote island along south-east coast of China has been looked upon by Yang et al. [31] in their study. More recently, Cordiner et al. [27] have presented a fuel cell based hybrid renewable system for telecom stations, and the characteristics of the current output of the system components during three representative days have been discussed.

The electrical performances of the above mentioned systems have been laid down quite clearly; however, the economic aspects of the systems are not reported very persuasively. Besides, the literatures on field study of hybrid systems from an Indian perspective are not available to the research community.

The novelty of the present paper lies in bridging the knowledge gaps of research, development, and implementation by disseminating the research experience of working on a PV, wind, inverter, and battery based hybrid system installed on rooftop of an Institute of Kolkata, India. The techno-economic performance of the system is clearly described and compared with the simulation results. The detailed costs of the system components as well as of the system are discussed along with the electrical performance. The present paper propagates the project experience by emphasizing on the presentation of each and every components used in the system, their layout, detailed specification, and detailed cost components of the system. A decisive observation has also been made regarding the use of the solar PV and wind system for the site under consideration or similar sites. The analysis of the simulated and practical results of the hybrid system may also be foreseen to propose future up-scale hybrid/microgrid systems.

2 Site consideration

The rooftop of a campus building of Jadavpur University, India is selected for installation of the hybrid system. The university is located in Kolkata of West Bengal, a state of eastern region of India. It has three campuses; main campus and National Instruments Limited (NIL) campus at Jadavpur, Kolkata 700032, India, and second campus in Salt Lake City, Kolkata 700098, India. The Department of Power Engineering (22°33.7′N, 88°24.8′E) of Jadavpur University is located at Salt Lake Campus of Salt Lake City, Kolkata and is considered for prototype installation. The department has a main 6 storied building apart from other buildings. It is surrounded by various small office buildings and domestic habitants. The renewable resources, especially solar, are affluent in this region and the place is free from any nearby obstacle for wind flow.

3 Assessment of site load and renewable potential

3.1 Assessment of load

The system is intended to cater mainly the light and fan load of the laboratory, a model class room and corridors, apart from the load of computers and test benches housed in the laboratory. The total load consists of 40 numbers of fluorescent lamps and 15 ceiling fans. There are 3 desktop computers and 4 test benches. The detailed load distribution is given in Table 1.

Here, the autonomy of 2 h is considered purposefully and may be justified since all the loads will not be present throughout the day. For example, the fan and light load of model class room, corridor, and the load of test benches are present for specific time period only whereas the load of laboratory is present almost for 8–10 h. Since the site under

Table 1 Electric load considered for the system

Sl. No.	Load type	Rating/kW	Units	Total/kW
1	Fan	0.074	15	1.11
2	Light	0.030	40	1.2
3	Computer	0.150	3	0.45
4	Test benches	0.050	4	0.2
Total load				2.96
Total energy required (2 h per day)/(kWh·d^{-1})				5.92

consideration is affluent in solar irradiance throughout the year almost uniformly[1], the autonomy of 8–10 h for only the load of laboratory is feasible without compromising the system reliability. Keeping this energy requirement in mind, a typical daily load data of 24 h are obtained and the data are synthesized to produce the hourly load data of one year. The 15% time step variation and the 20% day to day variation are considered to produce the yearly load data.

The synthesized load data of 8760 h for one year are used for the system evaluation. The load has a peak load of 1.46 kW and an average scaled data of 5.92 kWh/d. The annual total load of the system is 2161 kW. The synthesized load profile of the system is given in Fig. 1.

3.2 Assessment of renewable potential

The hybrid system is designed to install on rooftop of the six storied building where there is no obstacle nearby at that specific height of around 22 m. The wind speed data are obtained from the meteorological site of NASA[2] and synthesized in the HOMER software[3] for a specific year. The average data of 8760 h of a year are used for simulation. The monthly average wind speed and hourly wind speed data for the site are listed in Figs. 2 and 3, respectively. Since the flat plate PV array is used in the project, the monthly average solar global horizontal irradiance (GHI) data are obtained from the database of the National Renewable Energy Laboratory and synthesized for one year and depicted in Fig. 4.

The maximum monthly average wind speed of 3.87 m/s in the month of June and the annual average wind speed of 2.28 m/s are observed. A high wind speed at hub height (28.1 m) is observed despite the low speed at the reference

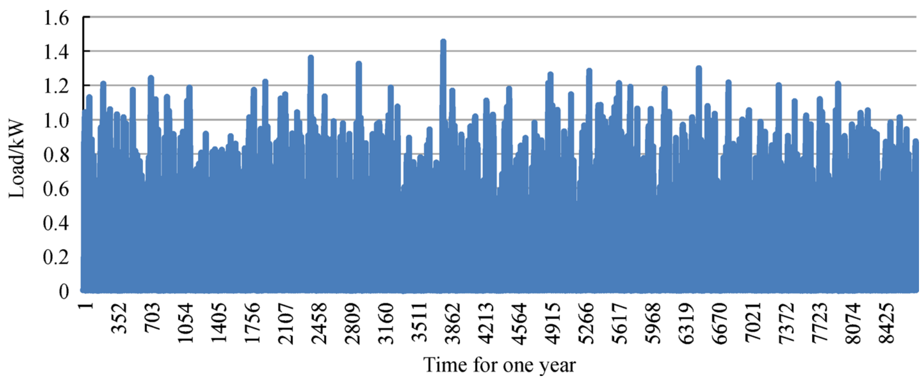

Fig. 1 Synthesized load profile of the site for one year

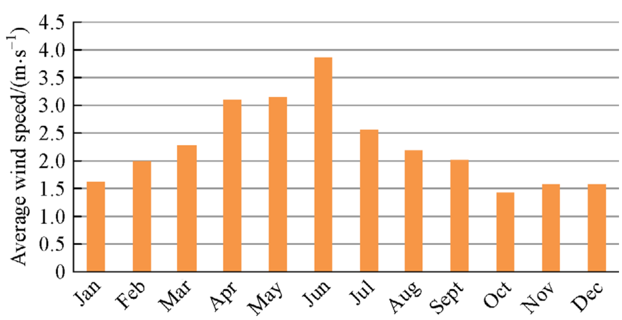

Fig. 2 Monthly average wind speed (22°33.7′N, 88°24.8′E)

1) Solar Radiation Hand Book. A joint Project of Solar Energy Centre, MNRE Indian Metrological Department. 2017–05–18, available at indiaenvironmentportal.org website
2) Surface Meteorology and Solar Energy. 2017–05–18, availabe at nasa.gov website
3) Energy HOMER. 2017–05–18, available at homerenergy website

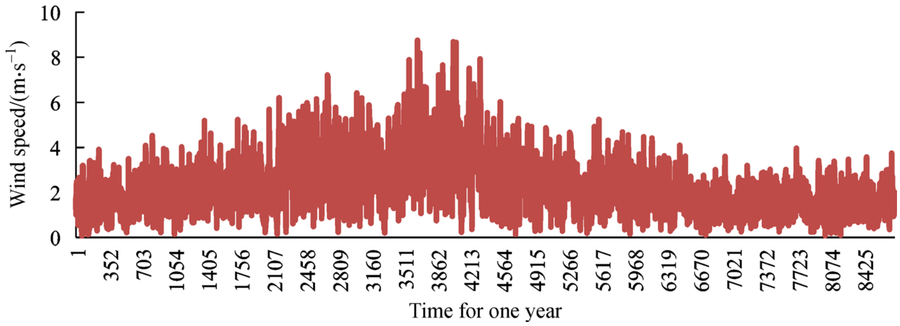

Fig. 3 Hourly wind speed for one year (22°33.7′N, 88°24.8′E)

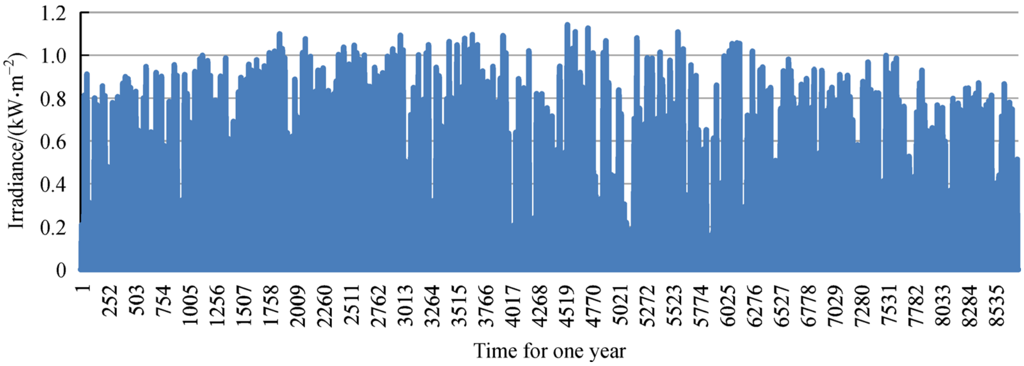

Fig. 4 Hourly solar global horizontal irradiation for one year (22°33.7′N, 88°24.8′E)

height (10 m). The hourly peak wind speed of 8.75 m/s is available when the monthly average data are synthesized for one year as shown in Fig. 3. The trivial wind speed is observed for most of the time of the year. Similarly, a peak daily average solar irradiation of 5.92 $kWh \cdot (m^2 \cdot d)^{-1}$ is observed in the month of April. The annual average value of solar irradiation is 4.70 $kWh \cdot (m^2 \cdot d)^{-1}$ which is a quite considerable irradiation for power production from the PV system. The peak hourly irradiance of 1.14 kW/m^2 is observed in the specific year as displayed in Fig. 4.

4 System components, capacity, and design

The proper capacity selection of components is very crucial as it yields an optimized system configuration with the lowest project cost. The capacity of the system is determined based on a typical 24 h load profile, supposed to be catered by the system. The HOMER optimization tool is used for obtaining optimized system configuration. The system incorporates all real data of the system components. The optimal sizing analysis generates system configuration of the solar PV of 2.16 kWp, the wind turbine of 3 kWp, the battery of 24 kWh, and the converter of 1.44 kW. The optimized system configuration is summarized in Table 2.

Table 2 Optimized system configuration

Components	Capacity
Solar PV/kW	2.16
Wind turbine/kW	3
Battery/kWh	24
Converter/kW	1.44

The optimal sizing of the hybrid system is crucial in meeting the required load demand at optimal cost. Since solar irradiance is quite high for most time of the year in this region[1)], solar PV is a comfortable choice for the system component. A solar PV of a capacity of 2.4 kWp along with a 400 Ah capacity battery bank and a 3 kVA inverter is installed. The wind speed is quite considerable for the month of April, May, and June of the year, despite the frivolous monthly average wind speed as seen in Figs. 2 and 3. Since the system is designed for prototype installation, a wind turbine of a capacity of 3.2 kWp is installed for operability and feasibility check of future installation of wind turbine in this region. The wind turbine is installed on a 6.1 m guy rod supported tubular tower

1) Solar Radiation Hand Book. A joint Project of Solar Energy Centre, MNRE Indian Metrological Department. 2017–05–18, available at indiaenvironmentportal.org website

above the rooftop. Therefore, the effective hub height is 28.1 m from the ground level where the desired wind speed for power generation from the wind turbine is obtained. The deviation of installed capacity of the system from the simulated results is justified by the unavailability of proper capacity, system design bottleneck, and other constraints like cost. The practical system is presented in Fig. 5 and the structure and layout of the hybrid system is demonstrated in Fig. 6.

Other system components like the inverter, the master controller, and the data logging system are also installed for the optimal operation and monitoring of the system. The 3-phase terminals of the wind turbine are connected to a brake-switch fitted at the control room. The 3-phase voltage is measured with a voltmeter and the wind charge controller is used for optimal charging of the battery. The wind charging current is measured with an ammeter and the control logic of the wind charge controller prohibits the battery to be over charged and diverts the power to dump load in that case. Similarly, the DC solar power output is fed to the battery through the solar charge controller.

There is a provision to charge the battery from the conventional grid power when there is no power output from solar or wind turbine. The battery power is then inverted and is fed to the AC load supply terminals. The DC load also can be fed from the battery directly. The ammeter and voltmeter are provided to measure the solar terminal voltage and solar charging current. The battery voltage or DC bus voltage and battery charging/discharging current are also measured. Similarly, there are provisions to measure the AC voltage, the AC current, the AC energy supplied to the AC load, as well as the DC current fed to the DC load. All parameters such as voltages, currents, and energy are displayed on the computer screen in real time basis and logged for future analysis. A data logging and display system has been developed for this purpose. There are some indications like "battery low," "battery OK," and "battery fuse trip" on the control panel to monitor the battery health continuously. The detailed connection diagram of the system is exhibited in Fig. 7.

4.1 Solar PV systems

Eight solar PV modules produced by the WEBSOL Energy System Ltd., each having 300 Wp, a corresponding voltage of 36.2 V and a current of 8.3 A are installed. Two panels are connected in series to make a maximum voltage of 72.4 V and such 4 strings are connected in parallel to make a current of 33.2 A.

A panel of 300 Wp has an area of 1.94 m^2 and a total area of 21.5 m^2 is needed for placing the 8 panels. A gap of 1.52 m is provided between two rows of solar panels to avoid shading of one panel row onto other. The junction box is fitted at the basement of the solar panels which are placed 0.3048 m above the roof. The angle of placement of panels is 25° facing south. A cable length of about 7.6 m is provided to supply the power to the solar charge controller and the master controller placed in the control room. The layout of the PV system is given in Fig. 8 and the detailed specification of each panel is tabulated in Table 3.

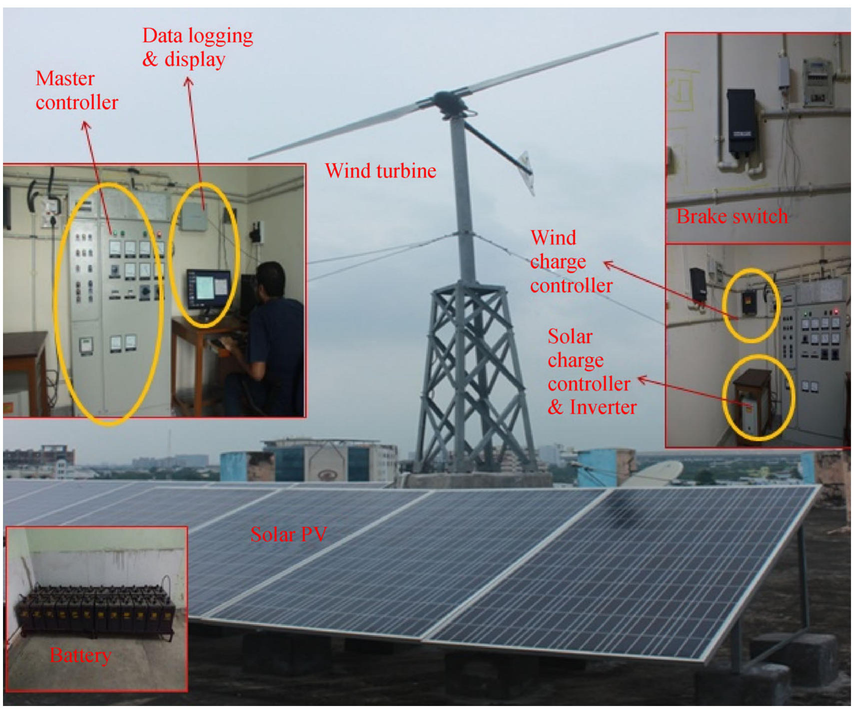

Fig. 5 Hybrid system installed on the rooftop

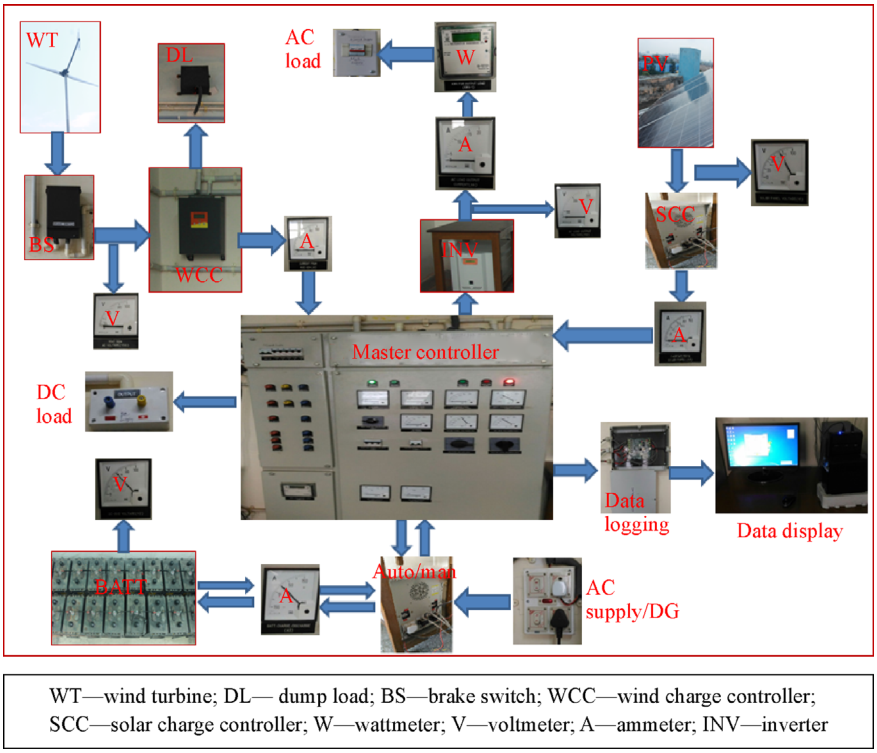

Fig. 6 Structure and layout of the hybrid system

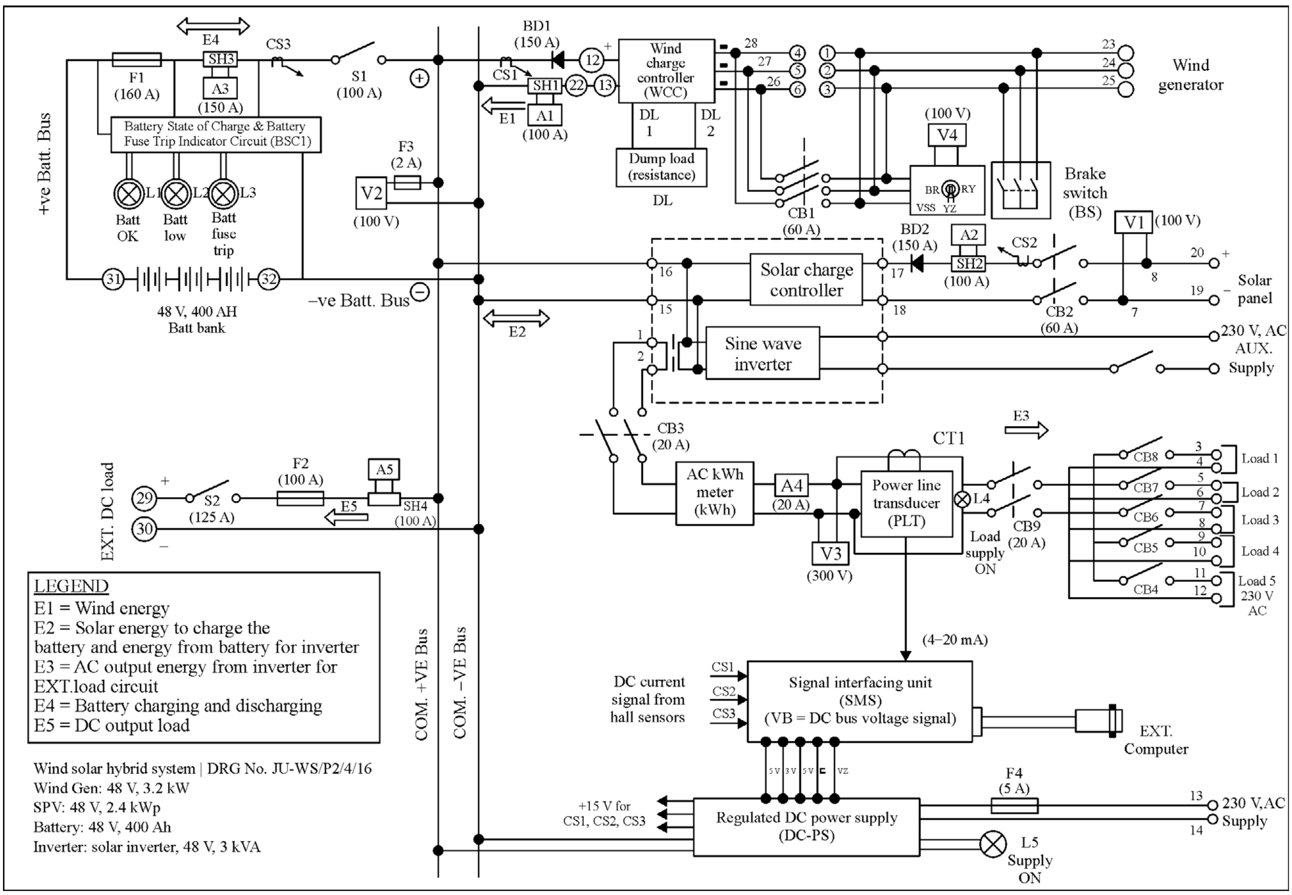

Fig. 7 Schematic diagram of the hybrid system

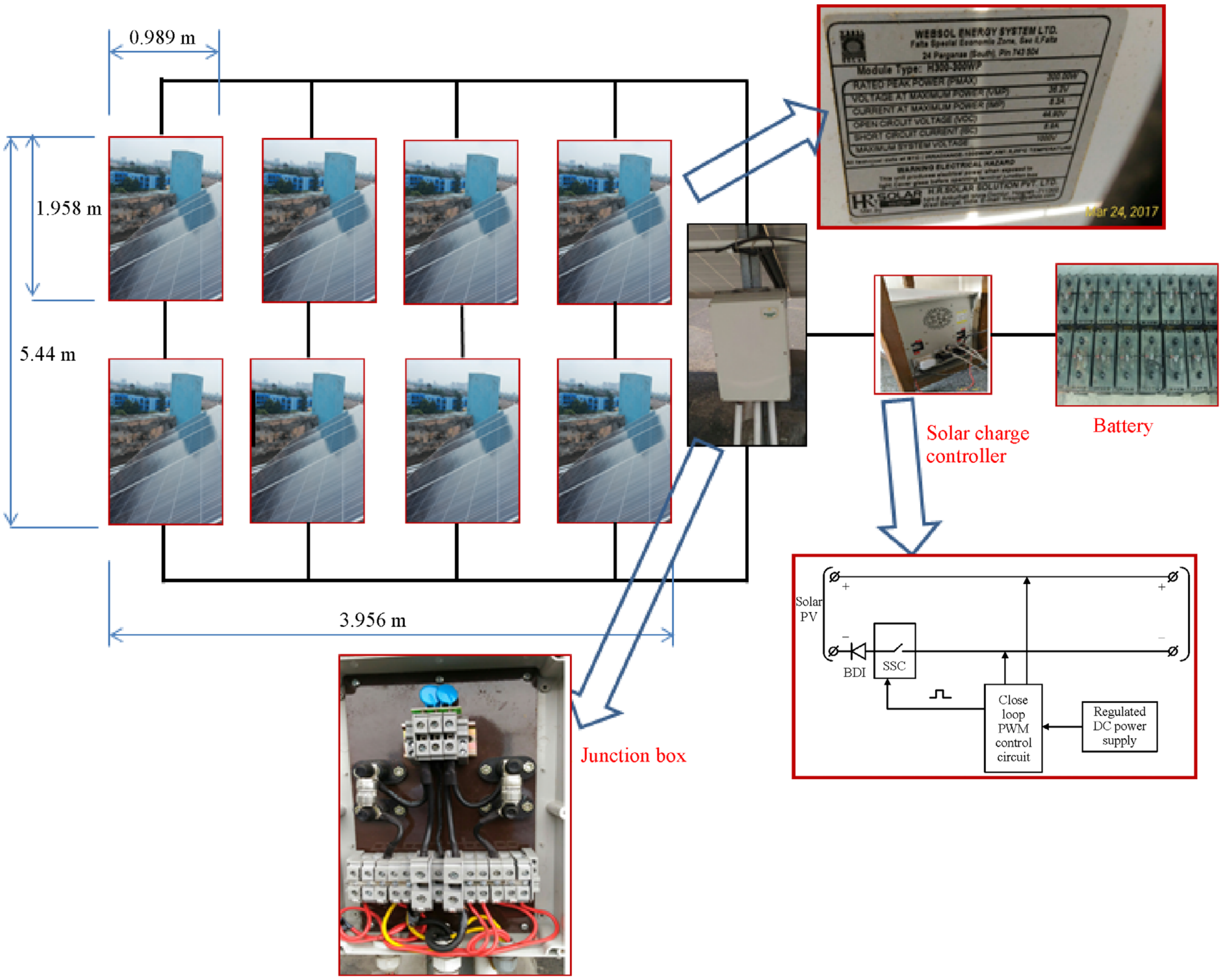

Fig. 8 Layout of the PV system

Table 3 Detailed specification of PV panels

Parameters	Values
Make	WEBSOL Energy System Ltd.
Module type	H300-300WP
Rated peak power (P_{MAX})/Wp	300
Voltage at maximum power (V_{MP})/V	36.2
Current at maximum power (I_{MP})/A	8.3
Open circuit voltage (V_{OC})/V	44.9
Short circuit current (I_{SC})/A	8.9
Temperature/°C	–40 – 90
Wind load/(km·h^{-1})	Up to 200
Humidity	0%–100%
Type of cell	Crystalline silicon
Efficiency of cell	13%–15%
Lamination type	Vacuum laminated glass to EVA and tedler

4.2 Wind energy system

The installed wind energy system of 3.2 kWp (Whisper 500) has a 3-phase, 16 pole permanent magnet alternator for power generation. It has two blades, a horizontal rotational axis, and a rotor diameter of 4.5 m. A tubular tower of about 6 m is used to uphold the wind turbine system supported by the guy rope. The whole system is fitted on the basement of 1.26 m^2, and 1.36 m above the roof. A 3 phase cable of about 6 m in length is used to connect the wind turbine system to the wind charge controller and master controller in the control room. The various parts and detailed layout of the wind system is presented in Fig. 9. The specification of the system is tabulated in Table 4.

4.3 Battery system

The SB400ST (T400P) tubular lead acid battery produced

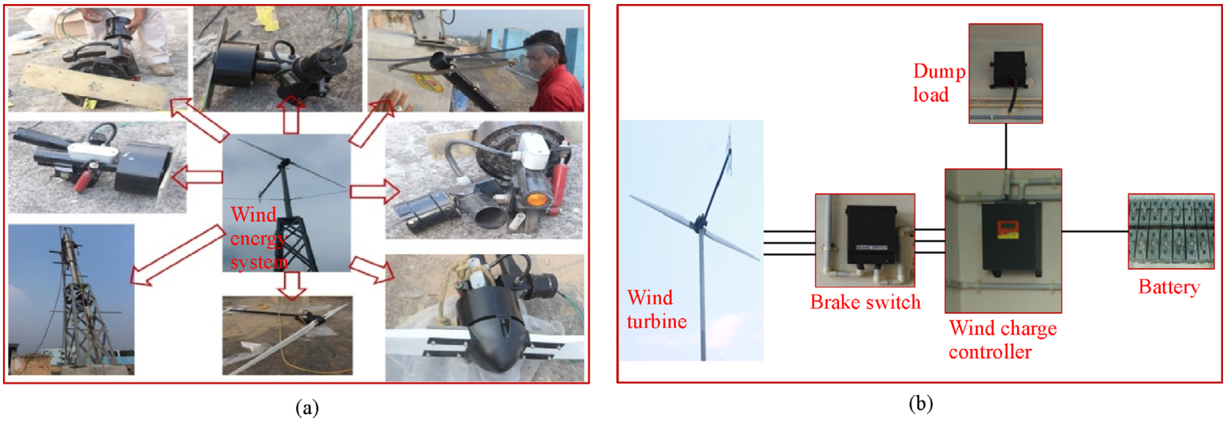

Fig. 9 Different components and layout of the wind system
(a) The various parts of the wind system; (b) detailed layout of the wind system

Table 4 Detailed specification of wind turbine (whisper 500) and accessories

	Parameters	Specification
General configuration	Rotation axis	Horizontal
	Orientation	Up wind
	Rotation direction	Clockwise facing upwind
	Number of blades	2
	Rotor diameter/m	4.50
	Weight/kg	Approx. 70±10%
Performance	Peak electrical power/W	3200
	1 min max average power output/W	3200(As per IEC 61400 Test Certificate)
	Rated wind speed/($m \cdot s^{-1}$)	12
	Startup/cut in wind speed/($m \cdot s^{-1}$)	3.1
	Cut out wind speed/($m \cdot s^{-1}$)	14–16
	Survival wind speed/($m \cdot s^{-1}$)	55
Rotor	Swept area/m^2	15.9
	Rotational speed/($r \cdot min^{-1}$)	700–800
	Blade pitch	Fixed
	Direction of rotation	Clockwise
	Over speed control	Side furling and dump load Manual stopping by brake switch installed on the base of the turbine tower
Yaw system	Wind direction sensor	By tail fin and tail boom
	Yaw control	Free/passive yaw
	Type	Mild steel tubular-5” diameter – 20 feet height on roof top with guy support
	Guy material	Steel wire rope of 6 mm (for Tubular Tower)
	Accessories	Suitable turnbuckle, DC lamp, wire clamp, etc.

by Southern Batteries Pvt. Ltd. is used. Each battery is rated 2 V, 400 Ah. A total of 24 batteries are connected in series to give a terminal voltage of 48 V. Each battery can be charged up to 2.75 V; therefore a total voltage of 66 V can be realized at the end terminals of the battery bank. The PV and wind energy system can charge the battery bank through the solar charge controller and wind charge controller, respectively. The battery arrangement is shown in Fig. 10. The detailed specification of the battery is given in Table 5.

Fig. 10 Battery arrangement of the system

Table 5 Battery specification

Parameters	Values
Voltage configuration/V	48
Power factor/%	80
Battery efficiency/%	85
Battery capacity	48 V 400 Ah
Voltage of each cell (nominal)/V	2
Combination of batteries	24 nos. of 400 Ah
Type of battery	Tubular lead acid flooded electrolyte
Positive plate	Tubular
Negative plate	Pasted flat
Electrolyte	Sulphuric acid

4.4 Inverter

The system incorporates an inverter of 3 kVA which is designed to operate in off-grid mode. The inverter is used to convert the DC power of the battery to an AC power of 230 V, 50 Hz. The inverter can also charge the battery at a desired rate by inverting grid supply. The detailed specification of the inverter is given in Table 6.

Table 6 Inverter specification

Parameters	Values
Inverter capacity/kVA	3
Efficiency/%	90
Duty	Continuous
Wave form	Sine wave
Ambient/°C	60
Protection	I/P under voltage, I/P over Voltage, O/P Overload, O/P Short – Circuit
Relative humidity/%	98
Power device	MOSFET/IGBT
Control	Pulse width modulation
Power factor	0.8

4.5 Master controller and data logging system

The master controller houses the control circuits and all measuring and monitoring instruments. The various parameters like solar voltage (DC), solar charging current (DC), wind line voltage (AC), wind charging current (DC), battery voltage (DC), battery charging or discharging current (DC), DC load current, AC load current, AC load voltage, and AC energy supplied to load are measured and displayed on the front cover of the control panel. It also has a manually selectable 230 V grid or DG supply switch to charge the battery in event of no power from wind/solar modules and if the battery bank is fully discharged. It can also monitor the battery status of charge and battery fuse trip status. The system has a data logging and display system. All relevant data of one year with an interval of one minute are logged for analysis, and the data are displayed on a real time basis. The logging and display system is presented in Fig. 11.

5 Technical and economic performance of hybrid system

5.1 Electrical performance

The feasibility analysis of the hybrid system for the site under consideration has been conducted with the HOMER software. The optimal capacity obtained in HOMER is presented in Table 2. While designing the hybrid system in HOMER, the project lifetime of 25 years has been considered. A discount rate of 0.08 and an inflation rate of 0.03 are considered to calculate the real rate of interest. The costs and other parameters considered for HOMER optimization are presented in Table 7.

The optimization considers a total PV capacity of 2.16 kW and a wind capacity of 3 kW. The yearly total electrical output from the PV system and the wind system are 3321.65 kWh/a and 1037 kWh/a, respectively. The rated capacity of the solar PV is less than the wind capacity;

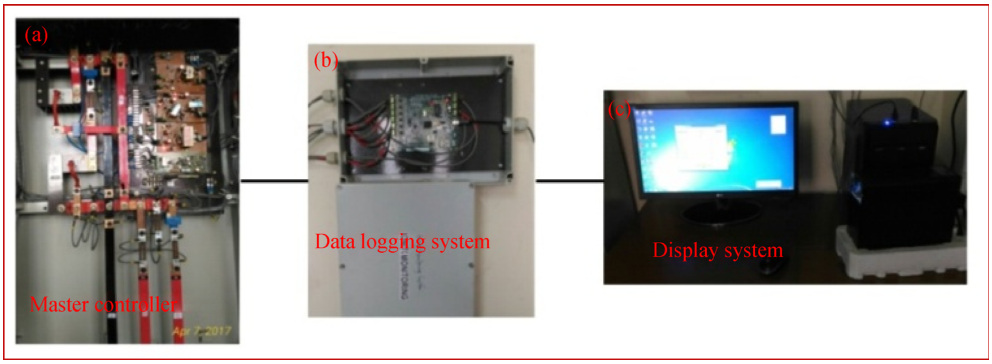

Fig. 11 Logging and display system
(a) Master controller; (b) data logging; (c) display system

Table 7 Cost and other parameters considered for optimization

Component	Size	Capital cost/US$	Replacement cost/US$	O & M cost/(US$·a^{-1})	Other parameters
PV	0.3 kW	537.00	306.00	0.00 [32]	Derating factor: 0.9 [32]; Lifetime: 25 years
Wind	3 kW	4350.00	3000.00	114.00	Reference height: 10 m; Hub height: 28.10 m; Lifetime: 20 years
Battery	1 kWh	150.00	140.00	15.00	Throughput (kWh): 3000.00; Roundtrip efficiency: 90%; Lifetime: 15 years
Inverter	1 kW	180.00	150.00	3.00	Efficiency: 96%; Lifetime: 15 years

nevertheless the yearly power output from the PV is more than three times that of the yearly power output from the wind system due to affluent availability of the solar irradiance. This aspect will play a vital role in future deployment of hybrid systems in the vicinity. The average electrical outputs are 9.1 kWh/d for the PV system and 2.84 kWh/d for the wind system. The peak power outputs are 2.16 kW and 2.60 kW in any hour from the PV and the wind system, respectively. The levelized cost for the PV system is US$0.082/kWh and US$0.435 /kWh for the wind system. The average hour of operation of the PV system is 12 h/d which indicates that most of the daytime, it generates power substantially. For the wind system, though it is operating throughout the year, yet the trivial output is observed. The significant output from the wind system is only realized in the month of April, May, and June. A maximum power output of 2.60 kW is obtained only in the month of June. In the rest times of the year, wind is not feasible at all in terms of its power production. The power output from the solar PV and the wind system for 8760 h obtained in simulation is given in Fig. 12.

The total power output from the renewable system is 4359 kWh/a and the maximum power output at any hour is 3.41 kW. The total electrical load per year is 2161kWh and the maximum load at any hour is 1.45 kW. Hence, the system not only meets all the load demand but also produces an excess energy of approximately 2003 kWh/a. Due to this excess energy, the cost of energy is US$0.673/kWh but the generation cost is as low as US$0.33/kWh. This excess generation may be utilized to cater the load of other academic buildings of the Institute. With this amount of power production, an energy cost of US$475 per year (taking the cost of US$0.11 per unit) can be avoided.

The performance of the installed hybrid system, especially the electrical output from the solar PV and the wind system, has been monitored. The measurement is conducted for a couple of days but Fig. 13 which is given for power production from the solar PV and the wind system is representing a day of maximum power output. The power output from the installed PV and the wind system in the month of April, 2017 for 24 h are compared with the power output of the simulation. It is observed that the solar power production is almost uniform for most of the days except for a few cloudy days. The minimum radiation during night time is zero and so is the power. A peak power output of 1.8 kW from the PV panels is obtained at 1.00 pm and the total output for the day is 10.97 kWh. The simulation results indicate that a maximum total power output of 12.7 kWh/d from the PV occurs on 18th in the month of April and a peak output of 1.7 kW in an hour is available on that specific day. Here, the peak output measured is greater but the total power measured for the day is less than the peak output and the total power obtained in the simulation, respectively. The simulation results also suggest that the day of maximum power output for the solar PV is on the 3rd of November and the peak

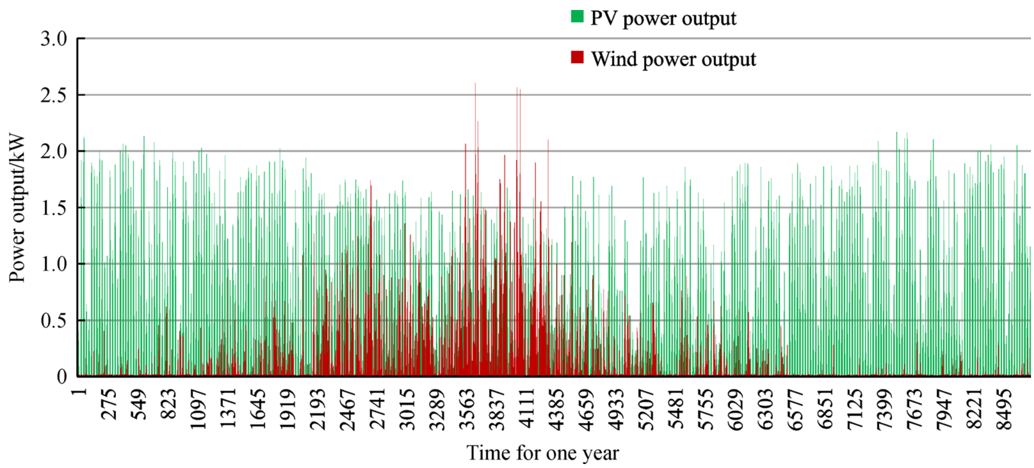

Fig. 12 Power output from PV and wind system in a typical year

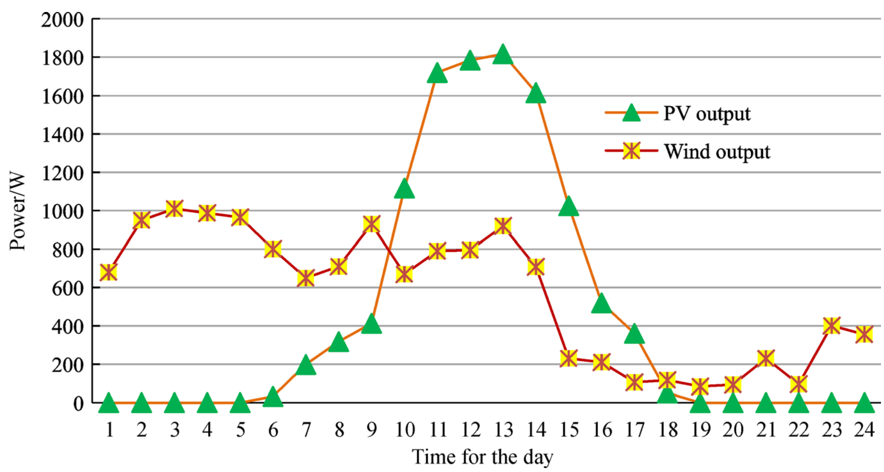

Fig. 13 Power generated by solar PV and wind system for 24 h in a typical day

power of 2.09 kW and a total power of 15.42 kW for the day are observed. These simulated power outputs are understandably higher than the measured power output on a specific day of April, but the power generated by the PV system is quite considerable and can be utilized effectively.

A wind turbine of 3.2 kWp generally produces 3.2 kW at the rated speed but in Jadavpur University, the rated speed is very low. Therefore, the power output from the system is low. The wind power measured in a particular day is quite fluctuating in nature and most of the time, it is zero or negligible. As it is observed in the simulation results, the wind power is only substantial in magnitude in the month of April, May, and June. The wind power measured for 24 h in the month of April, 2017 gives a total power of 13.49 kW and a peak power of 1.01 kW at a speed of 6.31 m/s as opposed to the simulated results of a total power of 20.23 kW and a peak power of 1.74 kW. This measured power from the wind system is in the high wind speed regime, which is not available for other days of measurement unlike the solar power measurement. The simulation results give a maximum total power of 26.8 kW and a peak power of 2.55 kW on 19th of June. However, HOMER gives a maximum power output of 2.60 kW at a speed of 8.75 m/s and the average power is 2.84 kWh/d when simulated for 365 days. The total energy produced for one year is 1037 kWh. The wind output power is not steady and is almost one third of the power produced from a smaller capacity of PV in a year, indicating the infeasibility of the wind system as compared to the PV system in terms of power output. Since this wind installation is for prototype and research purpose, the consideration of economic viability may be ignored in this case. The complementary nature of power production from the solar PV and the wind system will augment the possibility of deployment of Campus microgrid in the future.

5.2 Economic performance

The optimal capacity out of various configurations of the hybrid system is chosen based on the lowest total net present cost (TNPC) to meet all the constraints considered when designing the system. This TNPC of the system is the present value of all the costs and revenues that the system incurs or earns throughout its lifetime[1)]. Another cost associated with the system is the total annualized cost (TAC) which is the annualized value of the TNPC[1)]. Depending on TAC and yearly electrical load served by the hybrid system, the levelized cost of energy (LCOE) is obtained[1)]. Similarly, based on the TAC and yearly electrical power generated, the generation cost of energy (GCOE) is calculated. The net present cost and annualized cost of each component as well as of the hybrid system are obtained in the HOMER optimization tool. HOMER offers the total net present cost of the optimal system as US $20789.85. The cost of energy and generation cost of the system obtained are US$0.673/kWh and US$0.33/kWh, respectively. The detailed system net present cost and annualized cost breakup are given in Tables 8 and 9, respectively.

The summation of net present cost of each component gives the TNPC of the hybrid system. The net present cost of the PV system is US$3871.98. The replacement cost, operation and maintenance cost, and fuel cost of the PV system are zero. The salvage value of the PV is also zero since the lifetime of the PV is considered to be equal to the lifetime of the project. The net present cost of the wind system, the battery, and the converter are US$6455.03, US $10056.51, and US$406.33, respectively. The salvage value of the wind system is US$ 687.89 whereas the salvage values of the battery and the converter are US $342.42 and US$22.08, respectively. The TNPC of the system and salvage value are US$20789.85 and US $1052.39, respectively. It may be observed that the net present cost of the battery is predominant. Besides, although the battery capital cost is US$ 3600, its operation and maintenance cost is as high as US$5148.71. Therefore, the effective use of storage and cost of the same will play a pivotal role in decision making of installation of the system in particular application. It is observed that the annualized costs of the PV system of a capacity of 2.16 kW, a wind of 3 kW, a battery of 24 kWh, and a converter of 1.44 kW are US$270.73, US$451.34, US$703.16, and US$28.41, respectively. The annualized cost of the hybrid system is US$1453.63, as shown in Table 9. Here, also the battery cost, especially the operation and maintenance cost determines the magnitude of the annualized cost of the hybrid system.

The hybrid system installed has a controller, a control panel unit, a data monitoring and logging system, apart from the PV system, the wind system, the inverter, and the battery. These extra features are added to the system for better derivation of the system and system performance. The detailed per unit cost of each and every components of the installed system are given in Table 10.

In most literatures, while feasibility analysis of the hybrid system are performed, detailed cost of each component and their accessories required for satisfactory

Table 8 System net present cost and component wise cost breakup (all in US$)

Cost summary (Net present cost)	PV system	Wind system	Battery	Converter	Hybrid system
Capital cost	3871.98	4350.00	3600.00	260.01	12082.00
Replacement cost	0.00	1162.49	1650.22	106.42	2919.13
Operation and maintenance cost	0.00	1630.43	5148.71	61.98	6841.12
Fuel cost	0.00	0.00	0.00	0.00	0.00
Salvage value	0.00	–687.89	–342.42	–22.08	–1052.39
TNPC	3871.98	6455.03	10056.51	406.33	20789.85

Table 9 System annualized cost and component wise cost breakup (all in US$)

Cost summary (Annualized cost)	PV system	Wind system	Battery	Converter	Hybrid system
Capital cost	270.73	304.15	251.71	18.18	844.78
Replacement cost	0.00	81.28	115.38	7.44	204.11
Operation and maintenance cost	0.00	114.00	360.00	4.33	478.33
Fuel cost	0.00	0.00	0.00	0.00	0.00
Salvage value	0.00	–48.10	–23.94	–1.54	–73.58
TAC	270.73	451.34	703.16	28.41	1453.63

1) NREL (National Renewable Energy Laboratory). HOMER Pro Microgrid Analysis Tool. version 3.8.6 (Pro Edition). 2017

Table 10 Detailed cost breakup of each component of the installed hybrid system

Components	Sub-components	Cost/W(Rs.)	Cost/W(US$)
PV systems	PV panels	70.00	1.08
	Panel fitment structure	10.00	0.15
	Cable and wire	5.00	0.08
	Charge controller	3.33	0.05
	Total	88.33	1.36
Wind system	Aero generator	73.44	1.13
	Brake switch, junction box	3.75	0.06
	Cable and wire	4.69	0.07
	Tower (6.5 m) and support system	12.5	0.19
	Total	94.38	1.45
Inverter	Per VA	11.67	0.18
Controller and Control panel unit		8.33	0.13
Data monitoring and logging		8.33	0.13
Battery	Per Wh	11.46	0.18
Other cost	Transport, loading and unloading	1.67	0.003
	Civil work, erection and commissioning	11.67	0.18
	Total	13.34	0.183
Total project cost		224.17	3.4348

operation of the system are absent. In this paper, all the cost of the system is presented both in Indian currency and in US currency (taking a conversion ratio of 65:1) for better comprehension. Apart from a cost of US$1.08/W for the PV panels, a cost of US$0.15/W for the panel fitment structure, a cost of US$0.08/W for the cable and wire, and a cost of US$0.05/W for the charge controller are shown. Similarly, the costs for the brake switch and junction box, the cable and wire, and the tower and supporting system are presented apart from the generator cost for the wind system. It may be observed that per watt cost of the wind system is higher than that of the PV system. The cost for the inverter is given in per VA while that for the battery is given in per Wh in Table 10. Other costs like a cost of US $0.003/W for transport, loading and unloading, and a cost of US$0.18/W for civil work, erection and commissioning also contribute significantly to the total cost of the system.

The TNPC as well as the annualized cost of the installed hybrid system is derived for better understanding of the economic performance and the representation of the system. Tables 11 and 12 represent the TNPC and the TAC of the system, respectively.

The capacities of the components of the installed hybrid system are different from the values obtained in the simulation results due to the unavailability of the same size of the component. Therefore, the TNPC of the installed hybrid system is US$20073.63 which is lower than the net present cost of US$20789.85 obtained in the simulation. The simulation results take the battery capacity of 24 kWh whereas the real system has a battery capacity of 19.2 kWh. This increased capacity is increasing the battery net present cost from US$8046.62 to US$10056.51. The PV system has a net present cost of US$4296.00 as opposed to the PV net present cost of US$3871.98 obtained in the simulation. Similarly, the wind and battery net present cost of US$6887.17 and US$843.83 are obtained in the installed system of a capacity of 3.2 kW and 3 kVA, respectively. Again the cost of the battery is predominant compared to the costs of other components.

The annualized cost of the installed system is US $1370.94 whereas the simulated results give an annualized cost of US$1453.63. Again the difference in cost is justified by the dissimilar component configuration from the system obtained in the simulation results. It may be noted that the cost of energy is US$0.635/kWh for the installed system. Therefore, looking into the detailed cost breakup in Tables 11 and 12, it may be concluded that the cost of the installed system is in line with the cost obtained in the simulation.

6 Conclusions

This paper demonstrates the techno-economic performance of a nano-grid hybrid system consisting of a 2.4 kWp solar PV, a 3.2 kWp wind turbine, a 400 Ah battery, and a 3 kVA inverter installed on the rooftop of an

Table 11 Net present cost breakup of installed system (all in US$)

Cost summary (Net present cost)	PV system	Wind system	Battery	Converter	Hybrid system
Capital cost	4296.00	4640.00	2880.00	540.00	12356.00
Replacement cost	0.00	1241.60	1319.81	220.95	2782.36
Operation and maintenance cost	0.00	1739.97	4120.99	128.78	5989.75
Fuel cost	0.00	0.00	0.00	0.00	0.00
Salvage value	0.00	–734.40	–274.18	–45.90	–1054.48
TNPC	4296.00	6887.17	8046.62	843.83	20073.63

Table 12 Annualized cost breakup of installed system (all in US$)

Cost summary (Annualized cost)	PV system	Wind system	Battery	Converter	Hybrid system
Capital cost	300.25	324.29	201.28	37.74	863.56
Replacement cost	0.00	86.73	72.32	12.20	171.25
Operation and maintenance cost	0.00	119.00	281.84	8.81	409.65
Fuel cost	0.00	0.00	0.00	0.00	0.00
Salvage value	0.00	–51.33	–18.97	–3.21	–73.51
TAC	300.25	478.69	536.47	55.54	1370.94

academic building in India. It is observed in the simulation results as well as in the real system that the power output from the solar PV is quite substantial due to the high solar irradiance throughout the year. A peak power output of 1.8 kW and a total power of 10.97 kWh/d from the solar PV are measured for 24 h in the month of April. The simulation results show that a peak output of 1.7 kW and a total power output of 12.7 kWh/d occur on 18th April. The annual simulation results give a peak output of 2.16 kW and a total annual power of 3321.65 kWh generated from the PV system. The wind speed in this region is very low and a considerable amount of wind speed is only realized in the month of April, May, and June. The wind power measured for 24 h in the month of April, 2017 gives a total power of 13.49 kW and a peak power of 1.01 kW at a speed of 6.31 m/s as opposed to the simulated results of a total power of 20.23 kW and a peak power of 1.74 kW. The simulated results show that a total of 1037 kWh/a is available from the wind system. The total power output from the renewable system is 4359 kWh/a and the maximum power output at any hour is 3.41 kW. This output power is quite significant which can be used to cater the electrical load of small community, hospitals, school, university, and others. This nano-grid system also possesses a great importance in electrification of rural sites where the conventional grid system is out of reach to the community in India.

A detailed cost analysis of the system has also been presented and compared with the simulation results. The TNPC of the installed hybrid system is US$20073.63 which is lower than the net present cost of US$20789.85 obtained in the simulation. The annualized cost of the installed system is US$1370.94 whereas the simulated results give an annualized cost of US$1453.63. The levelized cost for the PV system is US$0.082/kWh while for the wind system, the cost is US$0.435/kWh. The TNPC and annualized cost of the system are affected largely by the battery cost, especially operation and maintenance cost of the same. It is observed that a cost of energy of US $0.673/kWh is obtained in the simulation and for the installed system, and the cost of energy is US$0.635/kWh. The electrical performance analysis and economic consideration of the hybrid system shows that the system is quite feasible in terms of electrical power output but the system is not economically viable. The pragmatic techno-economic feasibility of the PV system is observed for the site under consideration or similar sites however, the wind system is not a commercially upright choice. This FOLD analysis lays a foundation for the future planning of microgrid or hybrid systems in the vicinity.

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