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Optimum-cost-based renewable energy chart considering micro-hydro, solar-PV, and hybrid systems using HOMER suitable for eastern Himalayan regions of India

Adikanda Parida, Bikuk Lomdak
Department of Electrical Engineering, North Eastern Regional Institute of Science and Technology, Nirjuli, India

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ABSTRACT

The climatic change issues can only be addressed by adding more and more renewable energy into the energy chart for any region. However, the criteria for the composition of the chart shall be based on availability, cost-effectiveness, complementary nature, and optimally fit with the load curve. Based on the geographical diversity and availability of renewable energy in India, the energy chart is different for different regions. In this paper, an attempt has been made to prepare a renewable energy chart based on the equality constraint optimization technique for economical load sharing between the locally available renewable energy sources. The HOMER-based software platform has been utilized for cost analysis purposes. Based on locally available renewable energy sources, micro-hydro, and solar-PV are considered for analysis. In this paper, the electrical load of an educational institution situated in the eastern Himalayan region is considered for the case study. The data received from the case study has been utilized for the preparation of an appropriate and economically viable renewable energy chart for the mentioned region. Even though the analysis model applies to a particular region, it can be suitably modified for other regions also.

Corresponding Author:

Adikanda Parida
Department of Electrical Engineering, North Eastern Regional Institute of Science and Technology
Nirjuli, Arunachal Pradesh, India
Email: adikanda_2003@yahoo.co.in

NOMENCLATURE

U_{ds}, U_{qs}	: 2-axis stator voltages of the DFIG	Ls	: DFIG stator self-inductance
U_{dr}, U_{qr}	: 2-axis rotor voltages of the DFIG	P_r	: Rotor active power of the DFIG
I_{ds}, I_{qs}	: 2-axis stator currents of the DFIG	P_{net}	: Rotor active power of the DFIG
I_{dr}, I_{qr}	: 2-axis rotor currents of the DFIG	Q_s	: Power at load bus
Lm	: DFIG magnetizing inductance	Q_s^*	: Stator reactive power of the DFIG
P_s	: Stator active power of the DFIG	ω_e	: Reference reactive power of the DFIG
R_s, R_r	: Stator and rotor resistances of the DFIG	ω_r	: Frequency of the DFIG stator flux

Supercripts: (s, r, e): Stator, rotor, synchronous reference frames

1. INTRODUCTION

Almost 70% of global energy needs have been fulfilled with the burning of fossil fuels which significantly contributes to greenhouse carbon emissions. Emissions from thermal and gas turbine power units are significant contributors to greenhouse carbon emissions. To address the global climatic change issues, the Kyoto Protocol to the United Nations Framework Convention was brought up with quantified and legal bindings to greenhouse gas emissions [1], [2]. The mentioned bindings were reflected in the form of carbon tax and high energy bills in many developing countries where energy demand increases exponentially [3]. To avoid the financial and legal bindings, expansion of renewable energy generation and its technology upgradation was the only feasible option for the energy planners.

Energy cost plays a vital role in the expansion, competition, and implementation of renewable energy generation projects. To address this issue, proper renewable energy planning is the need of the hour [4]. Therefore, nonconventional energy integration with the already existing energy supply as the distributed generation has become the need of the hour to minimize the energy demand deficit within the Kyoto Protocol framework [5]. Renewable energy capacity addition requires energy planning and energy management [6]–[9]. Therefore, energy planning and energy management must be operated concurrently to maximize renewable energy generation at a minimum cost. Considering the criteria for the renewable energy composition chart, the cost of renewable energy and its availability is the key factor that influences all other factors mentioned in the abstract section. Therefore, renewable energy planning and its technology development must be directed by mentioned two key factors.

Discontinuity of energy supply from renewable sources is a major limitation. However, properly analyzing the power generation tendency, another renewable energy source that possesses the complementary nature of the parent source shall be selected for hybridization [10]–[14]. A storage battery augmented solar-PV based renewable energy supplied smart building energy management system has been proposed in [15]. However, the integration of a large storage battery is not cost effective and environmentally friendly [16]. Therefore, optimum sizing of integrated renewable energy systems is essential to target the load pattern of the load [17]–[19]. In a different technological dimension, some researchers also suggest the adoption of renewable energy not only addresses the climatic change issues but also will unburden the power sector economically as it reduces power theft [20], [21]. This is true to some extent. However, improper renewable energy capacity augmentation at individual load terminals as suggested in [20], [21] is not economically viable [22]. A similar type of renewable energy architecture using multiple energy inputs has been proposed [23]. Over the last few years, effectual research is going on to come up with appropriate integration of conventional energy input with its non-conventional counterparts. In this track, the presented research as reported in [24]–[28] is helpful to limit the overloading of the utility supply. However, the involvement of large storage batteries in these systems is not appreciable. A solar-PV and micro-hydro hybrid generation-based energy system is presented in [29]. In this case also, due to improper load matching, a large number of storage batteries are required. Therefore, the scheme proposed in [29] is not cost-effective. For all smart systems energy efficiency must be high and energy cost must be as low as possible [30]. While planning for the rural area energy needs, the configuration of a smart village energy load has been taken into account and properly analyzed in this paper. The presented paper considers the proper augmentation of locally available renewable energy sources for hybridization. The significant contribution of this paper can be summarized as follows: i) The availability of matching optimum cost renewable power at the load terminals with minimum battery backup; ii) Implementation of equality constraint criteria technique for load sharing among selected renewable sources for minimum energy cost; and iii) Moreover, the availability of low-cost renewable energy at the load center is an encouraging factor for rural electrification in terms of consumer friendliness.

2. LOCALLY AVAILABLE RENEWABLE ENERGY SOURCES

Energy charts are generally prepared through proper energy planning based on availability and cost-effectiveness. Through field survey, it has been found that micro-hydro and solar-PV energy is abundantly available in the location where case-study has to be carried out. Wind energy potential is almost nil over this location. In this paper, an educational institution is considered as the case study for the preparation of an energy chart. The organization is situated at a global positioning latitude: of 27.0844° N and a longitude: of 93.6053° E in the eastern Himalayan region. The per day average solar radiation between January 2021 to December 2021 in the open premise of the organization can be observed in Figure 1. The average solar radiation is almost 0.3 kW/m^2 throughout the year between 9 a.m.-4 p.m. This level of solar insolation is best-suitable for the generation of electrical power.

Similarly, the mentioned location is surrounded by many water bodies as shown in Figure 2 and all can be the source of micro-hydro power generation. However, the water stream having a 43 m gradient is considered for analysis. Practically, two parallel water lines were existing for drinking water purposes in the organization, out of which one is on standby for any emergency. The idle water line was used as the penstock for the proposed work. Therefore, one solar-PV unit and one micro-hydro unit of 3 kW capacity each are considered for the analysis as shown in Figure 3.

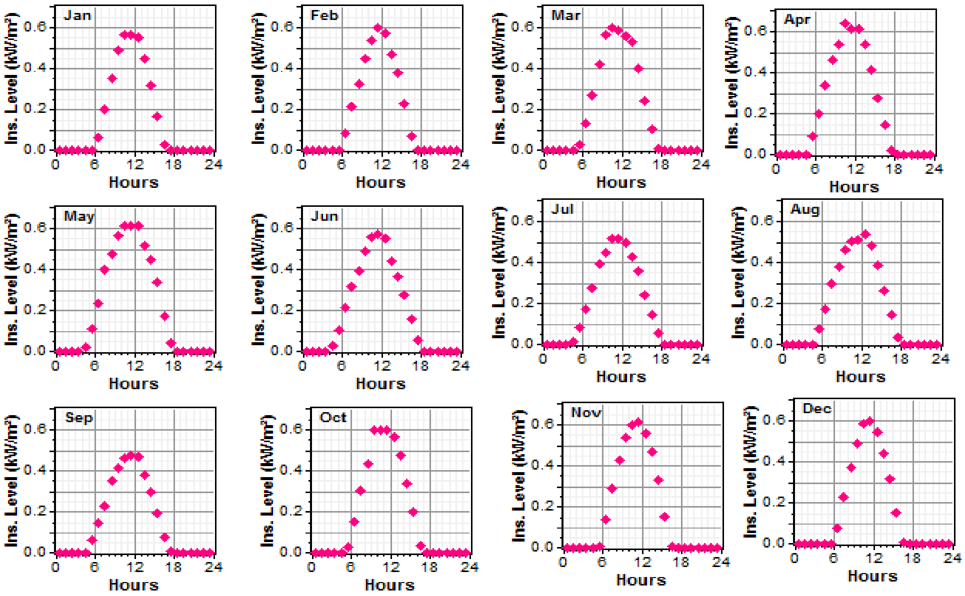


Figure 1. Average monthly insolation levels generated using HOMER pro-3.2

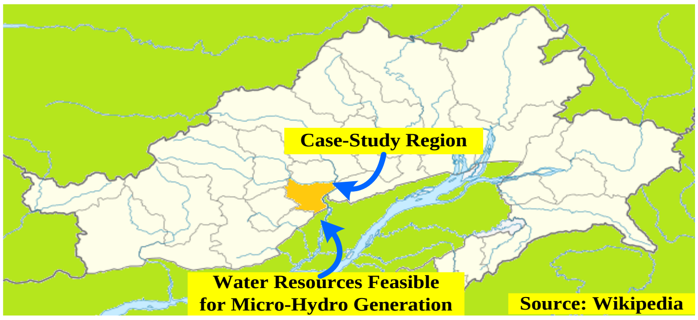


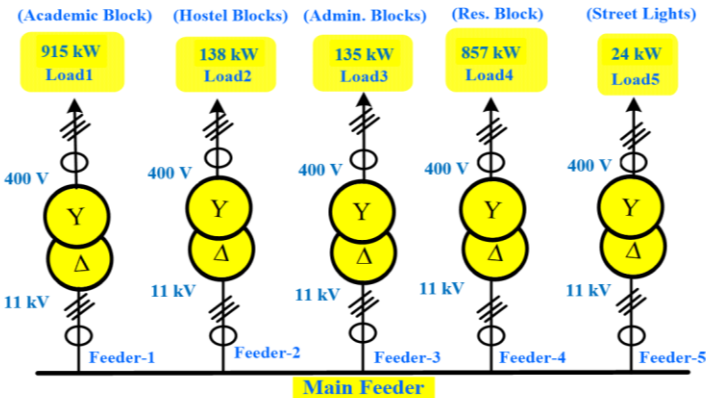
Figure 2. Potential for micro-hydro generation

Figure 3. Installed renewable generation system

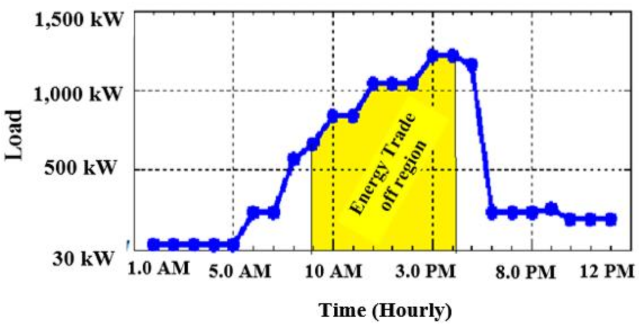
3. ENERGY DEMAND PATTERN

The existing structure of the electrical feeders in the load center that is considered for the case study is shown in Figure 4(a). In the specified location, as per the measurement, between 9am-4pm, the available solar radiation is suitable for usable electrical energy generation. The indicated average load at different feeders in Figure 4(a) has been recorded on an hourly basis for the year 2021 including seasonal loads.

The daily average load at the load center is shown in Figure 4(b). At present, the total power received at the load substation through the base feeder is distributed using Feeder-1 to Feeder-5. Table 1 shows the feeder's load, it's rating, and the average value of the energy consumption. The feeder's common loads consist of lighting, fan, AC, PC, and motors. Except for rest days, the class hours in the institute are for 8 hours between 8 a.m., and 5 p.m. As shown in Table 1, the load on the Feeder-2 is illumination, AC, and fans and the operational time on working days is 7 hours/day and 18 hours/day on nonworking days. The probability for computation of time of operation is 0.8. The load on Feeder-3 is almost similar to Feeder-2. Similarly, the working hours for administrative premises is almost 7 hours/day and 5 days/week. The load on Feeder-4 is almost similar to Feeder-2. For the presented study, the loading time for the residential area was considered to be 17 hours/day (6 a.m. to 11 a.m. of a day). During the analysis, the street light luminaries within the institute complex were found to be of 80 watts capacity and the has been assigned to Feeder-5.



(a)



(b)

Figure 4. Energy demand pattern (a) single line representation of the load considered for case-study and (b) load profile (daily average) of the organization considered for case-study

Table 1. The details of the load assigned to Feeder-1

S. N.	Load types	The capacity of devices (kW)	Load distribution (considering load factor of 0.7) (kW)				
			Load_1	Load_2	Load_3	Load_4	Load_5
1.	Luminary	0.055	181.5	58.0	44.0	110.0	24.0
2.	Fan	0.08	128.0	80.0	16.0	72.0	-
3.	Air conditioning	2.5	125.0	-	75.0	125.0	-
4.	Personal computer	0.3	300.0	-	-	-	-
5.	Motor	3.0	180.0	-	-	-	-
6.	Geyser	2.0	-	-	-	400.0	-
7.	Other Appliances	0.3	-	-	-	0.3	-

4. PROPOSED HYBRID RENEWABLE ENERGY SUPPLY

The prototype proposed micro-hydro and solar-PV-based hybrid generation system augmented with the utility is shown in Figure 5. The micro-hydro generator is realized by using a doubly fed induction generator (DFIG). The AC load is connected to the stator of the DFIG directly and the rotor is connected to the stator through a back-to-back converter system through the DC link. The solar-PV generation system is directly coupled to the DC link through a buck-boost regulator. The marginal storage battery backup has also been coupled to the DC-link but is not shown in the figure.

During reduced water flows into the reaction turbine, to maintain 1 p.u stator power and rated stator voltage level, the rotor side converter (RSC) will inject the additional power through the DFIG rotor drawn from the DC-link with the help of the presented controller. Moreover, the surplus power available in the DC-link will be delivered to the AC-link using a grid side converter (GSC) as shown in Figure 5. In the complete model of the proposed generation system, an appropriate amount of dummy load arrangement is essential if the system needs to be operated in standalone mode. However, for the testing purpose, the proto-type hybrid generation system is operated in grid-connected mode and hence there is no need for a dummy load. In the presented system, for lab experiment purposes, an arrangement for a small battery charging unit has been made which may be utilized in the future for electric vehicle charging.

Both active and reactive power control of the DFIG which is considered to be the reference energy source for energy planning through the energy trade-off process is accomplished through two control loops (10). The instantaneous active power is compared with the reference active power which is the active power rating of the DFIG set d-axis rotor current. Similarly, in the second loop, the instantaneous active power is compared with the reference reactive power which is set equal to 0 kVAR. This is because the system is supposed to operate at the unit power factor. For the proposed scheme, the availability of power at the load bus is ensured through either one of the following generation schedules in a day:

i) Both micro-hydro generators and solar-PV systems feed the power.
ii) Micro-hydro generator is only feeding the power.
iii) Solar-PV system is only feeding the power.
iv) Neither the micro-hydro generator nor the solar-PV system feeds the power.

The schedule mentioned in (iv) is the rarest of rare cases. Where the backup option is either infeasible or not economically viable. Rather, power is supplemented by the utility for the presented scheme. Similarly, the generation schedule mentioned in (i) is a natural and definite phenomenon and occurs for 7 hours. (9.0am-4.0pm) every day in a clear sky situation. Where excess power will be delivered to the utility if it is grid connected system or allowed to dissipate in a dummy load for a standalone system. However, the power schedule mentioned in (ii) and (iii) needs a very small storage battery backup. Where the capacity of the storage battery is much less than the existing schemes.

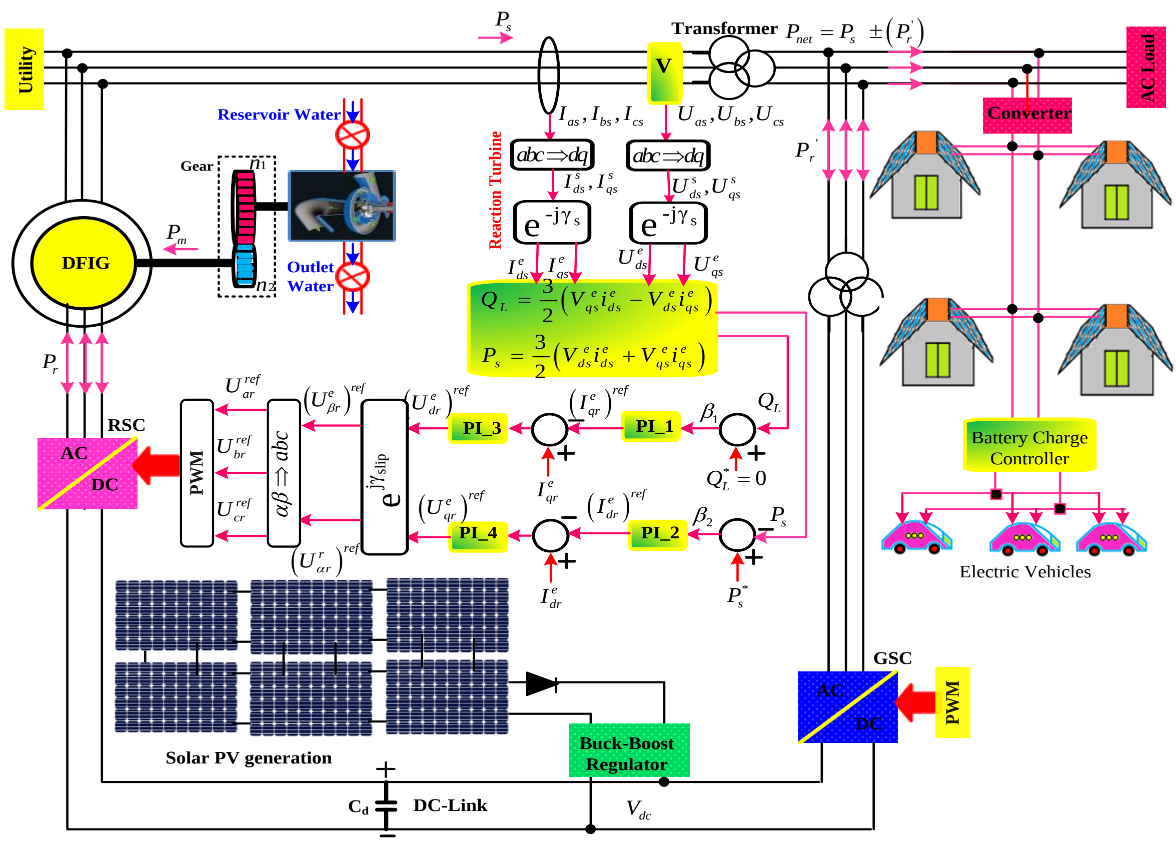


Figure 5. Proposed renewable hybrid energy supply system

5. HYBRID RENEWABLE ENERGY PLANNING BASED ON COST ANALYSIS

5.1. If the total load assigned to the micro-hydro generation system

Assuming continuous power supply, from Figure 4(b), the average power demand was computed to be 526 kW. Considering, the fixed and variable costs involved in the installed 3 kW micro-hydro generator proto-type system, the cost of energy (COE) as calculated using HOMER with a multiplying factor of 175, is found to be @$0.14/kWh. However, large micro-hydro power plants are always associated with social and environmental issues along with the duration of rainfall. Therefore, micro-hydro may not be the only option for any standalone load.

5.2. If the total load assigned to the solar-PV generation system

Similar to the micro-hydro generation system, in this case, also 3 kW solar-PV system has been installed for experiment purposes. An appropriate multiplying factor has been used for fixed and variable generation costs and used as the input for the HOMER. In this scheme, a rooftop solar-PV generation capacity of 1,260 kW has been selected to cater to both the average power demand and the charging of the marginal battery backup.

Based on the average energy demand and the selected capacity of generation, the charging cycle of the battery backup can be seen in Figure 6 by referring to Figure 4. Therefore, considering 220 V per phase of the terminal voltage, a battery backup capacity of 1,293 Ah is required for continuous power supply to the organization. As per the market survey on 29th March 2021, the cost of battery backup will be $1,939.5 (@ $1.5/Ah). Moreover, the life period of the storage battery is considered to be 5 years. Similarly, the cost of the solar-PV module will be $1,26,0,000 (@$1/W) and the life of the solar-PV will be 20 years. As per the designed capacity of PV modules and storage batteries, the HOMER Pro-3.2 software tool has been used to forecast the cost of energy and the same has been provided below in Table 2.

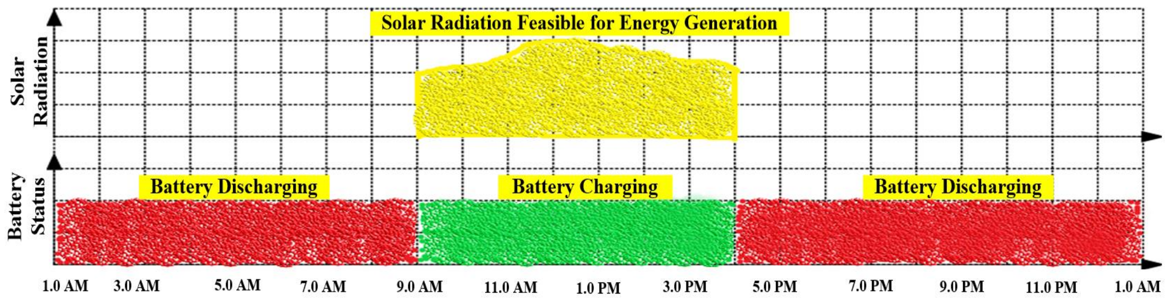


Figure 6. Availability of solar radiation and status of the storage battery backup

Table-2. COE for solar-PV generation with battery back-up

Factors	Solar-PV generation with battery back-up
Initial capital required ($)	41,69,325.00
Cost of energy ($/kWh)	0.175
Net present cost ($)	1,12,14,818.00
Operating cost ($/year)	5,51,146.00

5.3. If the total load assigned to micro-hydro and solar-PV hybrid generation system

Considering, p_{gi}^{e} as the total power fed from both the renewable sources selected and p_{d}^{e} as the average demand in the trade-off region. Therefore, the energy cost function can be defined as (1).

$$C = \sum_{i=1}^{2} C_i\,(p_{gi}^{e}) \tag{1}$$

For meeting the load demand under the equality constraints:

$$\sum_{i=1}^{2} p_{gi}^{e} - p_{d}^{e} = 0 \tag{2}$$

therefore, expressing (1) using the Lagrange multiplier function (λ) can be defined as (3).

$$C = \sum_{i=1}^{2} C_i\,(p_{gi}^{e}) - \lambda\left[\sum_{i=1}^{2} p_{gi}^{e} - p_{d}^{e}\right] \tag{3}$$

For energy cost minimization, $\frac{\partial C}{\partial p_{gi}^{e}} = 0$. Therefore, $\frac{dC_1}{dp_{g1}^{e}} = \frac{dC_2}{dp_{g2}^{e}} = \lambda$. Where p_{g1}^{e} is the active power generation from the solar-PV unit, p_{g2}^{e} is the active power generation from the micro-hydro generation unit, and λ

($/kWh) is the incremental cost of energy. The generation capacity from both sources must match with the average demand between 9 a.m.-4 p.m. which is 1,260 kW. Therefore, the constraints for optimization are:

$$p_d^e = 1{,}260\ kW;\ p_{g1}^e \leq 1{,}260\ kW;\ p_{g2}^e \leq 1{,}260\ kW \quad (4)$$

The cost of energy (COE) in-case of only micro-hydro generation is 0.14$/kWh and that for solar-PV is 0.175$/kWh. Therefore, the incremental COE can be (5).

$$IC_1 = 0.175 p_{g1}^e, IC_2 = 0.14 p_{g2}^e \quad (5)$$

From (5), the maximum value of λ is 220.5. As per the constraints in (4), the optimum allocation of load between the mentioned renewable sources of energy for minimum total energy can be seen in Table 3.

It has been observed in the Himalayan region that the water flow in the case of a micro-hydro type of plant as proposed in this paper is highly dependent on rainfall. Therefore, micro-hydro and solar-PV generation are complementary to each other. Therefore, for the proposed analysis, solar-PV is proposed to be integrated with the micro-hydro generation system to supply the average power required by the load during the availability of solar-PV power. Otherwise, the supply will be from the micro-hydro generation system. The benefit of the proposed scheme is that it can be realized with no or minimum battery backup.

For this case study, to generate an average power of 560 kW from solar-PV, 600 kW of solar-PV generation plant has been recommended with 100 Ah of the storage battery. The cost of energy from the solar-PV with a marginal storage battery to supplement power between 9 a.m.-4 p.m. has been computed using the HOMER Pro-3.2 software tool. The same has been presented in Table 4. The COE, in this case, is $0.145 which is comparable with the COE of the micro-hydro generation system. Therefore, considering the average load profile of the load center as shown in Figure 4(b), 14 units of micro-hydro generators 50 kW each and 600 kW of solar-PV generation system are proposed for the mentioned designated load

Table 3. Load sharing among renewable option

λ	$(p_{g1}^e) kW$	$(p_{g2}^e); kW$	$(p_{g1}^e + p_{g2}^e); kW$
220.5	1,260	1,575	2,835
100	571	714	1,285
98	560	700	1,260
95	543	679	1,222

Table 4. COE for Solar-PV generation without battery back-up

Factors	Solar-PV generation without battery back-up
Initial capital required ($)	5,84,500.00
Cost of energy ($/kWh)	0.145
Net present cost ($)	1,44,4,245.00
Operating cost ($/year)	67,255.00

6. SIMULATION AND EXPERIMENT

The proposed scheme as shown in Figure 5 has been simulated using the MATLAB/Simulink platform. To simulate the micro-hydro turbine operated DFIG, a separately excited DC motor with decoupled torque control mechanism was considered which emulates the hydro-turbine. In this paper, while capturing the results, the emphasis was given to the active power flow in the system as per the literature objective. The simulated outcomes of the presented scheme are depicted in Figure 7. Initially, the performance of the RSC of the DFIG was tested by varying hydro-turbine input. It can be observed from Figure 7(a) that the RSC is accurately either injecting or evacuating power to or from the DFIG rotor terminal. In the second step in absentia of the solar-PV input, it has been observed that the utility is supplementing and extracting power under the hydro-turbine power variation circumstances. The same can be observed in Figure 7(b). In the third step, the micro-hydro turbine was stopped and the solar-PV power output was varied through a partial shedding mechanism. It has been observed that the utility is responding appropriately to maintain the power at the load terminals fixed for a fixed load. The utility response can be observed in Figure 7(c). It can also be observed from Figure 7(d) that the DC-link voltage remains constant during the entire period of operation while testing the performance of the system under the third step.

A precise experiment was conducted on the solar-PV and micro-hydro generation system shown in Figure 3. Since the proposed system was installed near the load center and far away from the laboratory, there was very limited scope for the extended experiment on the practical systems. However, some of the vital test results were captured and presented in Figure 8. As shown in Figure 8, it has been observed that by varying the water flow, the speed of the DFIG rotor varies continuously. However, the active power at the stator of the DFIG remains constant as the power fluctuation in the DFIG is adjusted through a power exchange between the DC-link and the rotor of the DFIG. However, the net power fluctuates at the load bus. This can be minimized through the augmentation of appropriate dummy loads at the load bus.

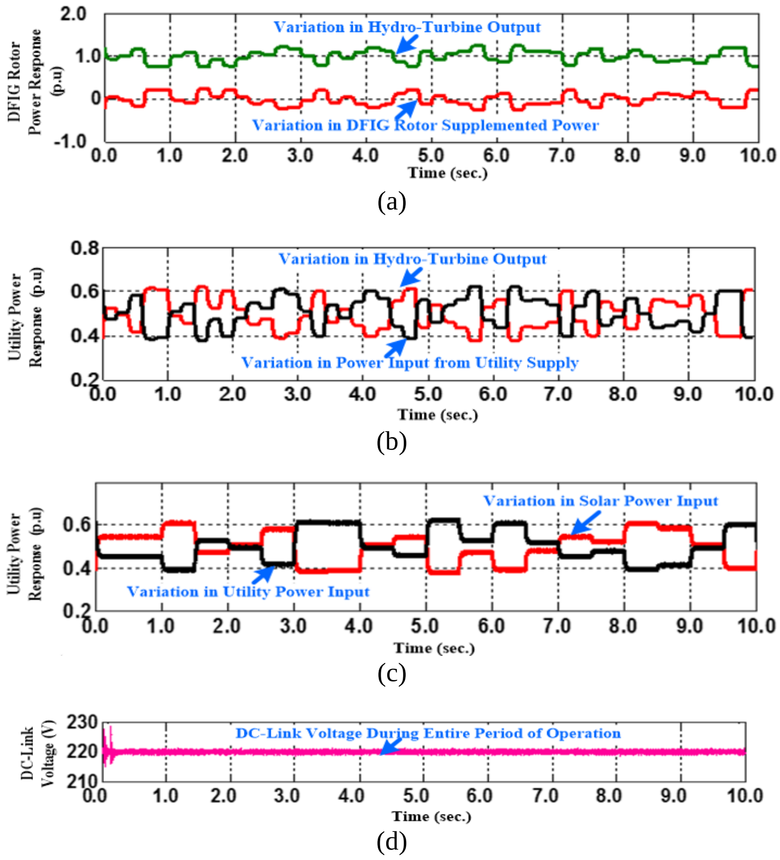


Figure 7. Active power sharing (a) DFIG rotor power response to turbine power output; (b) Utility power input variation in response to the wind turbine output variations; (c) Utility power input variation in response to the solar-PV power output variations; and (d) DC-link voltage profile of the proposed hybrid generation scheme

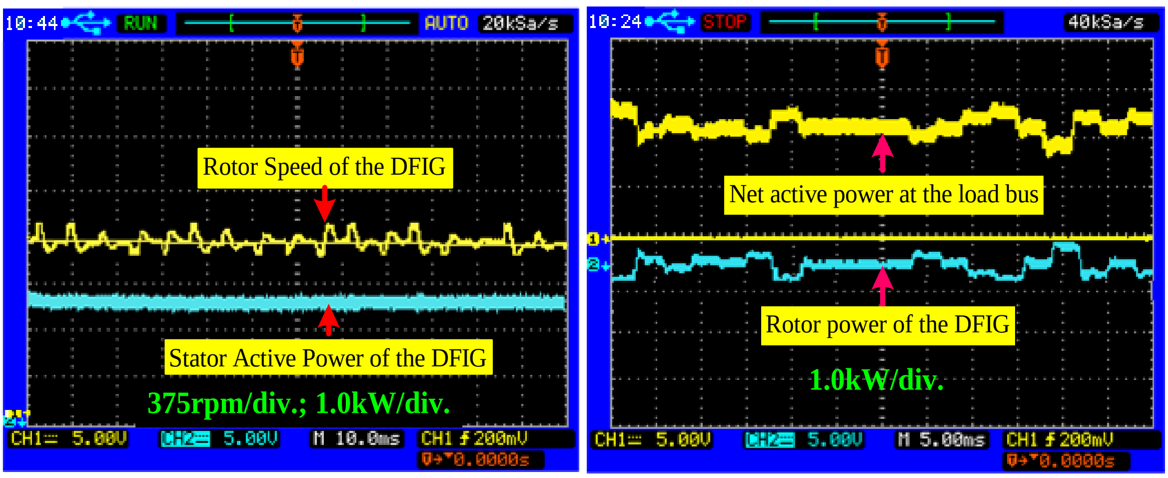


Figure 8. DFIG stator and net active power variation in response to rotor speed variation

7. CONCLUSION

The renewable energy chart for minimum COE has been successfully mathematically formulated and implemented using HOMER Pro-3.2. The equality constraint criteria technique was adopted for the mathematical formulation of the problem. The proposed renewable energy-based hybrid energy system suitable for rural electrification was initially simulated using the MATLAB Simulink platform. During the simulation, it has been observed that the proposed control model was appropriately participating in the energy exchange process. The simulated model has been implemented using a proto-type 3 kW micro-hydro and 3 kW solar-PV systems using suitable controllers. It has been observed that the COE when the load is independently supplied with the micro-hydro system is the lowest @$0.14/kWh. However, power generation from such units is highly dependent on rainwater as these systems are realized through small reservoirs. As the solar-PV generation is almost commentary to micro-hydro generation in the mentioned locality as experienced, it is considered for augmentation to overcome the above-mentioned limitations of the micro-hydro generation unit. When it is attempted to calculate the COE for solar-PV with battery back-up to supplement the total load, it is found to be @$0.145/kWh and without battery back-up @$0.142/kWh. Therefore, to overcome the limitations like the continuity of power supply from both generation options, energy cost limitations of solar-PV, and demography of the load center, micro-hydro, and solar-PV-based hybrid generation arrangement is recommended. In the recommended hybrid generation case, the COE is found to be @$0.142/kWh. Though, the COE of the hybrid generation system is marginally higher than the standalone micro-hydro generation system, considering the continuity of power supply, this marginally higher energy cost is within the accepted range. However, some more accurate economic analyses shall be considered using more advanced software platforms for more accurate COE.

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BIOGRAPHIES OF AUTHORS

Adikanda Parida received the M.Tech. degree in industrial systems and drives from RGPV, Bhopal, India, 2005, and a Ph.D. degree in electrical engineering department from Jadavpur University, Kolkata, India. His research interests include hybrid renewable power generation, rural electrification, energy conservation, and management. He is a member of IEEE. He can be contacted at email: ap@nerist.ac.in.

Bikuk Lomdak received the M.Tech. degree in power systems from North Eastern Regional Institute of Science and Technology, Nirjuli, India, 2021, and pursuing a Ph.D. degree in North Eastern Regional Institute of Science and Technology, Nirjuli, India, His research interests include hybrid renewable power generation. He can be contacted at email: bikukupsc@gmail.com.