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Study of grid integrated biomass-based hybrid renewable energy systems for Himalayan territory

Prashant Malik[a*], Mamta Awasthi[a], Sunanda Sinha[b]

[a] *Centre for Energy & Environmental Engineering, National Institute of Technology, Hamirpur, Himachal Pradesh, India, Pin - 177005*
[b] *Centre for Energy & Environment, Malaviya National Institute of Technology, Jaipur, Rajasthan, India, Pin - 302017*

ABSTRACT:

Unutilized pine needles are not only a significant issue of environmental hazards like recurrent forest fires and greenhouse gas emission but also a wastage of resources. The pine needles can be used efficiently for electricity generation. In the present study, simulation research on a grid-connected biomass-based hybrid energy system was conceived to examine the feasibility in the western Himalayan territory. The locally available abundant pine needle was used as a biomass gasifier fuel with solar and wind resources. The Hybrid Optimization of Multiple Energy Resources software was used to model three distinct configurations of hybrid systems, Photovoltaic/Biomass gasifier/Grid (Case1), Photovoltaic/Biomass gasifier/Wind/Grid (Case 2), and only Grid (Case 3) for feeding electricity to selected educational building loads currently run by state grid. Lowest energy costs, total net present cost, and CO_2 emission were considered as parameters for electing feasible system configuration. The Photovoltaic/Biomass gasifier/Grid was found to be optimal hybrid energy system with the lowest cost of energy 0.102 $/kWh (29% and 7% lower than Case 2 and Case 3 respectively) and total net present cost $42081 at 83% renewable fraction without any power shortage. The biomass gasifier contributes most (61%) of the overall power output, led by PV (22%) and grid (17%) in the optimal configuration of the hybrid power system. The CO_2 emission analysis shows that the proposed system will save 27.8 Mt CO_2/year (equated to the diesel-only system). The outcomes are found to be very pertinent to policymakers, hybrid system designers, and investors in the field of biomass-based hybrid renewable energy systems.

Keywords:

PV system;
Biomass energy;
HOMER;
Wind energy;
Hybrid energy system;

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1. Introduction

Renewable energy generation is established globally as the foremost source of electricity generation to cater to the load demands in diverse sectors. The renewable energy annual growth has been around 2.3 % since 2006, which is higher than growth (1.4%) in fossil fuel and nuclear energy. However, the overall gain in total final energy consumption is low because the global energy demand is also increasing due to industrialization, technology advancement, etc. [1]. Globally the renewables contribution in power, transport, and heating/cooling sectors is 10%, 3%, and 26%, respectively [1]. The electricity generation cost from renewables is decreasing day by day due to technical advancements in energy systems and new policies implemented by the government in renewable energy fields.

The economy of India is also proliferating in the world. Therefore It is expected that energy demand will accelerate. Renewable energy resources can play an imperative role to compensate for the increased energy demand [2]. Energy sector emissions can be reduced to 11 percent (375 MT CO_2) if the share of RESs is

*Corresponding author - e-mail: prashantmaik04@yahoo.in

Abbreviations

HOMER	Hybrid Optimization of Multiple Energy Resources
PV	Photovoltaic
TNPC	Total Net Present Cost
HRES	Hybrid Renewable Energy System
i-HOGA	Improved Hybrid Optimization by Genetic Algorithm
TRNSYS	Transient Energy System Simulation Program
BG	Biomass Gasifier System
RF	Renewable Fraction
PCU	Power Controlling Unit
MHP	Micro Hydropower system
LCOE	Levelized Cost of Energy
NREL	National Renewable Energy Laboratory
MATLAB	Matrix Laboratory
RETScreen	Renewable Energy Project Analysis Software
WT	Wind Turbine system
DG	Diesel Generator
O&M	Operation and Maintenance cost
STC	Standard Test Condition

increased to 45 percent by 2030 [3]. The renewable resources power generation system can perform an indispensable role in supplying uninterruptible power supply in isolated areas in which the grid is not present or otherwise available in an erratic nature at a higher cost. Further, it also supports the attainment of the CO_2 emission reduction target. Renewable energy generation also contributes to local job opportunities, infrastructure development, energy security enhancement, emission control, and health conditions improvements in provincial areas [4,5,6].

The sporadic existence of renewable resources is still a significant obstacle to their sustainable implementation. Therefore, the hybridization of two or more renewable resources could be the most appropriate solution in terms of intermittency of renewable resources, energy production costs, overall system performance, and power reliability [7,8,9]. Hybrid renewable energy system (HRES) is a combination of renewable energy systems based on available renewable resources, such as solar, wind, hydro, biomass, etc. within the local area. It provides an additional benefits over a single resource-based generation system in which other renewable generation systems will serve if one energy system fails due to the absence of renewable resources.

In the typical hybrid system, N no. of power generation sources are connected to a single point (DC/AC) using an appropriate power controlling unit (PCU). The power can be transmitted from this point to loads (DC/AC) or can be sent to the storage devices (Battery, Ultracapacitor, Fuel cell) for later use. Remote villages, usually abundant in renewable resources like solar, wind, hydro, biomass, etc., therefore a hybrid renewable energy system can be a viable solution because of the high cost associated with grid connectivity in hilly areas [10].

Nevertheless, rural electrification using HRES still is not ramping up due to various social, political, economic, and technical hurdles. Funding framework for rural electrification growth is a crucial requirement, and restricted organizational ability, small-scale project encouragement with an adverse environmental policy are the obstacles that restrict funding capability [11]. Other challenges include cost-effectiveness in installing and sustaining HRES, changes in the region's demographics, lack of awareness and expertise among local communities, lack of willingness on the part of power generation, distribution and transmission agencies to link such locations due to lack of investment returns, which limit rural electrification possibilities [12,13].

In recent years, numerous studies based on renewable integrated hybrid energy systems have been investigated using different simulation tools (MATLAB, HOMER, HYBRID2, RETScreen, TRNSYS, iHOGA, etc.) to check the feasibility for different worldwide locations [14,15,16]. A critical review of various software tools for optimization for hybrid renewable energy systems has been carried out by Sinha and Chandel [17] and found that HOMER is the most efficient and user-friendly tool for an on-grid and off-grid renewable hybrid energy system design. Many researchers have explored feasibility analysis and evaluation of renewable energy systems for the electrification of rural areas around the globe.

For instance, Patil [18] developed an optimization model for MHP/BG/biogas/wind/solar hybrid system to encounter the load consumption of a cluster of villages in the hilly state of Uttrakhand, India. Neto [19] PV/Biogas hybrid energy system was proposed for rural electric applications and goat manure used as biomass. Aziz [20] carried out a feasibility analysis of different hybrid system configurations using HOMER and found PV/hydro/diesel/battery hybrid system as the optimal solution to satisfy the electricity demand of an Iraqi rural village. Rajbongshi [21] compared a grid-connected PV/BG/DG hybrid energy system with a stand-alone system and found that the grid integrated proposed system offered the lowest cost of energy generation. Parihar [22] et al. noticed that the biomass gasifier system with storage is more economical compared to a standalone system.

An optimization model of a grid-connected hybrid system using a biogeography-based optimization (BBO) algorithm was developed by Chauhan [23] to satisfy the load demand of an un-electrified village in Uttar Pradesh. Ramchandran [24] carried out a feasibility analysis of off-grid biomass and PV/BG hybrid energy systems in Uttar Pradesh, India, and found unfeasible due to higher fuel cost, which encourages researchers to evolve a new mechanism to fuel cost reduction. Sarkis [25] investigated the feasibility of PV/BG hybrid power generation systems, which shows that energy costs for hybrid systems have been reduced to $74.94/MWh, with CO_2 emissions reduction up to 0.62T/MWh. Lozano [26] proposed a diesel–solar hybrid system to supply the power in Gilutongan, an off-grid island of the Philippines, and it reduces the cost of energy up to 70%.

Islam [27] investigated PV/DG hybrid energy system feasibility to meet the energy demand in isolated areas of Algeria, and it has been found more competent for higher load and higher solar radiation with minor fuel storage capacity. Gebrehiwot [28] found the PV/WT/DG/Battery off-grid hybrid energy system a more efficient and reliable solution to fulfill the load requirement of rural areas in Ethiopia. Østergaard [29] used an innovative cross-sector approach to find the most effective and economical storage solution for renewable energy system integration. The results revealed that the smart energy system (electricity sector integration with other elements of the energy system) is more economical and efficient, except electricity storage integration.

Nazir [30] proposed a grid-connected solar power plant with battery storage to supply the electricity to high-speed railway tracks. Changizian [31] a three-phase topology based on the multi-stage converter for solar grid-tied inverters to use in medium or high power applications and proposed topology performed better as compared to traditional topologies. Ahmed [32] developed a power prediction model using a five parameter model for solar panel with efficiency improvement using a genetic algorithm, and the proposed model results are found very close to actual output with –0.33% error. A comprehensive study of India scenario in 2030 has been modeled by Laha [33] and found that the addition of an optimum percentage of biomass and nuclear can fulfill the power requirement in the absence of solar and wind resources.

Tariq [34] investigated two different scenarios (current system, a renewable-based system with hydrogen) using HOMER and found that a renewable-based energy system can reduce the diesel share from 65.78% to 0.53%. Malik [35] suggested an integration of the biomass gasifier system to enhance the generation capacity of the existing PV/WT hybrid system to fulfill the growing load demand of institute building. Chambon [36] simulated a biomass-based mini-grid renewable hybrid energy system in HOMER and found BG/PV hybrid energy system more reliable and economical. The study also suggested that a mini-grid energy system is not economically viable for stand-alone biomass gasifier system, hybrid of PV/BG is needed.

Kaur [37] simulated two different mini-grid renewable energy systems in HOMER and found that PV/BG-based microgrid systems are an efficient way of using biomass in the electrification of rural areas in Punjab at least LCOE 0.0735 $/kWh. Among many reports, several scholars have discussed viability review and assessment of clean energy projects for the electrification of rural areas around the world [38,39,40]. However, very few focused on grid integrated biomass-based hybrid systems for hilly regions.

In the present study, a feasibility analysis of an on-grid integrated hybrid energy system with biomass gasifier in the western Himalayan region has been conducted, and locally available unutilized pine needles are used as fuel. CO_2 analysis of the proposed system also has been performed to examine the impact and suitability of the proposed microgrid system in utilizing biomass to mitigate environmental pollution.

In this study, an institute building of Centre for Energy and Environmental Engineering (CEEE), National Institute of Technology (NITH)-Hamirpur (Himachal Pradesh), located in western Himalayan hilly region is elected as the location of interest. The novelty of this study is the use of realistic inputs for techno-economic analysis of grid-integrated biomass-based hybrid energy systems for the western Himalayan region, namely the latest equipment market prices, kind of biomass raw material (unutilized pine needles) and real-time hourly energy consumption and location-specific renewable resources data. That is hardly reported in the literature. This research would help to provide a framework for incorporating operational requirements in the design of a grid-connected biomass hybrid energy network in the west Himalayan region and other remote hilly forest areas around the world.

The paper is organized as follows: methodology with resource and load assessment is enlightened in section 2; Section 3 addresses results and discussion followed by Conclusions in Section 4.

2. Methodology

An ingenious and efficient way of integrating a grid-connected hybrid energy system is required to meet end-user energy needs at the lowest cost. The methodology is described in the flow chart (Figure 1).

2.1 Simulation software description

In the present study, Hybrid Optimization of Multiple Energy Resources (HOMER) developed by NREL [41] is used for optimization. It is a micro-system optimization tool that can be used for both off-grid and on-grid modes of energy systems for a wide range of applications. HOMER simulates the system for 8760 h in a year and scale the optimized results based upon total net present cost (TNPC). Additionally, sensitivity can also be performed to reveal how the outputs change according to the sensitivity inputs. Figure 2 presents a graphical depiction of HOMER with input and output parameters. The justification of selecting HOMER for this analysis over other available options is illustrated in table 1 below [17,36]. The modeling equations used by HOMER to calculate the system output power and economic output for optimization are described in Appendix1.

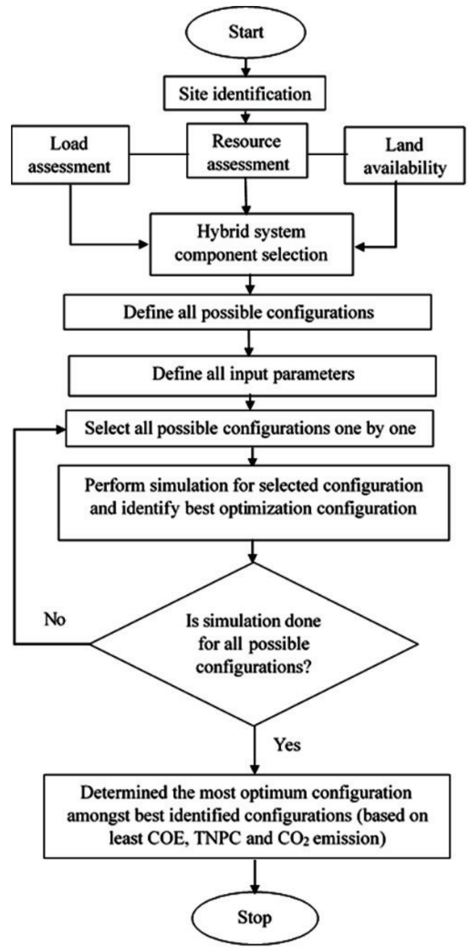

Figure 1: Flow chart of the methodology used in hybrid system designing

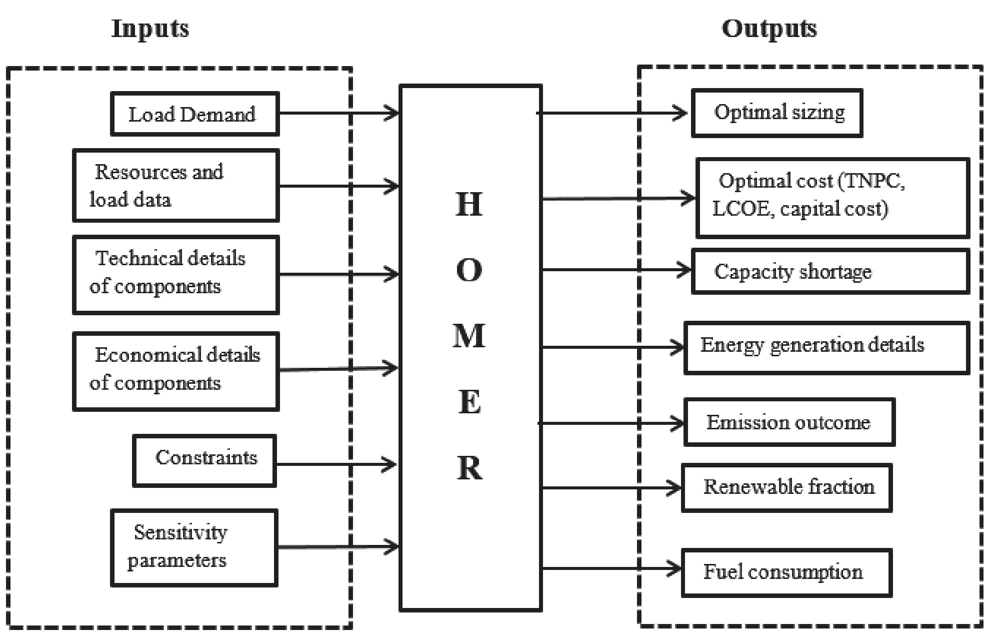

Figure 2: Schematic representation of HOMER software

Table 1: Overview of hybrid system software tools [17,36]

Tools	Design optimization	Data input in time series format	CO_2 analysis	BG model	Net metering	User friendly
HOMER	☑	☑	☑	☑	☑	High
TRNSYS	☑	☒	☒	☒	☒	Medium
HYBRID 2	☒	☒	☒	☒	☒	Medium
RETScreen	☑	☒	☑	☒	☒	Low
i HOGA	☑	☑	☒	☒	☑	Low

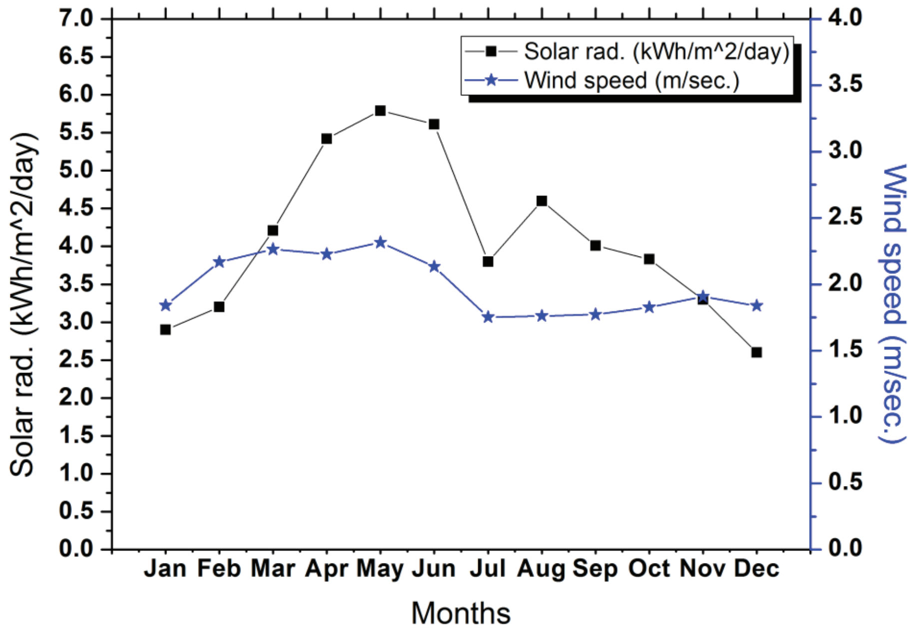

Figure 3: Monthly average global solar radiation and wind speed at CEEE, Hamirpur (H.P)

2.2 Details of resources

The accessibility of ground measured meteorological data at the site of interest is essential to get more accurate results. A solar radiation data monitoring station was installed in June 2011 at the roof-top of (CEEE) (Lat. 31.590N, Long. 76.520E; altitude 875 m) and one-minute average measured solar radiation data of the year 2018 from this station are used in this study for simulation.

The study site average monthly daily global solar radiation ranges from 2.53 kWh/m^2/day to 5.5 kWh/m^2/day, and the peak occurs in May, while the least is in January, which is shown in figure 1. The monthly average wind speed varies from 1.8 m/s to 2.32 m/s (measured at 10 m height) with maximum wind speed in May, and the lowest occurs in July, as shown in figure 3.

Because of the widespread availability of pine needles at study location, the biomass-based hybrid system is selected for electricity generation, which will not contribute to the electricity demand only but also reduce the chances of environmental hazards. The total pine forest covers 58 hectare land inside the campus, and 1-hectare pine forest typically gives 11.9-ton pine needles per year [42]. So, the total biomass availability in the study location is 690 tons/year at a very cheap rate of 14.57 $/ton (including collection and transportation cost). The pine needles properties are described in table 2.

Table 2: Properties of fuel (pine needles) used in biomass gasifier[42]

Parameters	Values
Carbon content	52.60%
Calorific value	20 MJ/kg
LHV	18.97 MJ/kg
Moisture content	9.76%
Ash	1.31%
H	7%
O	40.40%

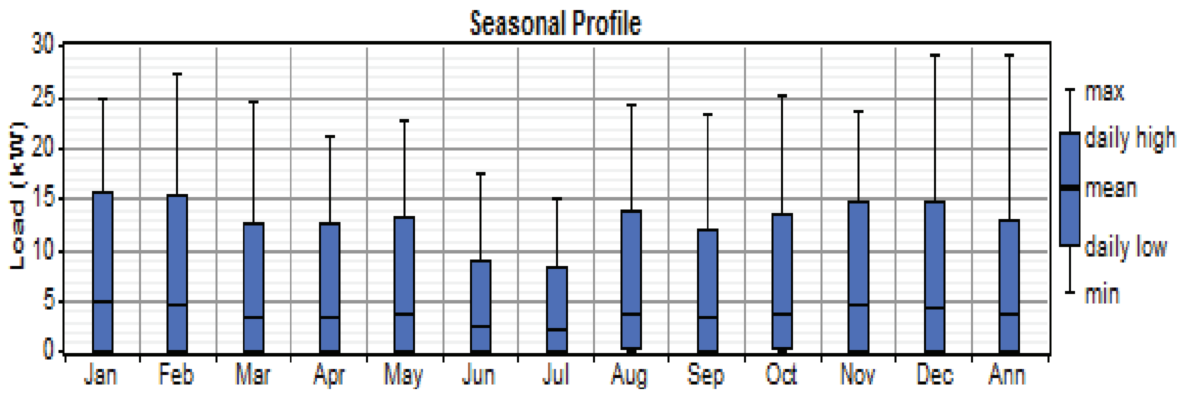

Figure 4: Month-wise electric load profile of CEEE building

2.3 Electrical load profile

System sizing strongly depends on the study area's power demand for electrical load. The load demand is thus one of the critical parameters for optimized system design. In this report, the hourly consumption details of the CEEE building was used for weekdays of a year, since the institute remains operating five days a week. The majority of the energy requirement for a typical weekday is between 9 am and 6 pm. The load demand is low in the month of June-July due to summer vacations. The average daily load demand, mean energy demand, peak load demand, and building load factor is 3.65 kW, 87.6 kWh/day, 29.2 kW, and 0.125, respectively. Figure 4 shows the monthly trend of load requirements.

2.4 Hybrid renewable energy system configuration

Three different combinations with biomass are considered in this study based on the following components: The proposed arrangement of renewable resources contains the solar photovoltaic system (PV), biomass generator (BG), wind turbine system (WT), and grid. The diagram of the proposed arrangement is shown in figure 5. The technical specifications and cost details of the significant parts of the proposed hybrid system are explained in table 3.

3. Result and Discussion

Different systems are studied through HOMER simulation for the same load profile, which provides a list of possible combinations in system designing relative to the energy generation cost and net present value. This section describes and discusses the technical and economical results of all three configurations.

3.1 Simulation cases:

Case1: PV/BG/grid:

The most optimized configuration of this case consists of 11 kWp PV array, 5 kW gasifier system, and 7 kW converter with 18 kW grid purchase capacity when maximum grid sale capacity is limited up to 5 kW. Figure 6 shows the schematic of Case 1. The total net present cost (TNPC) of this combination is $42081 at a Levelized cost of energy (LCOE) 0.102 $/kWh. The renewable fraction (RF), in this case, is 83% at 0% capacity shortage (CS) and unmeet load demand. The monthly average power production of the different electricity generation units (PV/BG/grid) is shown in Figure 7.

Solar has a relatively steady monthly and annual production, with a slight decline from May to September because of monsoon season with low radiation values and higher ambient temperature on sunny days. Generation of biomass gasifiers peaks in the months of November to February, because load demand in these months is higher than other months. This hybrid renewable power system generates 59.7 MWh/year annually, of which just 17% (9.9 MWh /year) is imported from the grid.

Case 2: PV/BG/WT/grid:

In this case, the simulation analysis shows that the hybrid system with 11 kW_p PV array, 5 kW gasifier system, 5 kW AC wind turbine, and 7 kW converter with 18 kW grid supply is the optimum configuration. Wind turbine contribution is less as compared to other renewable resources because of the low wind profile at the study location. Micro-wind turbines with a smaller cut in speeds can perform better at this location. Figure 8 shows the schematic of Case 2. The TNPC of this con-

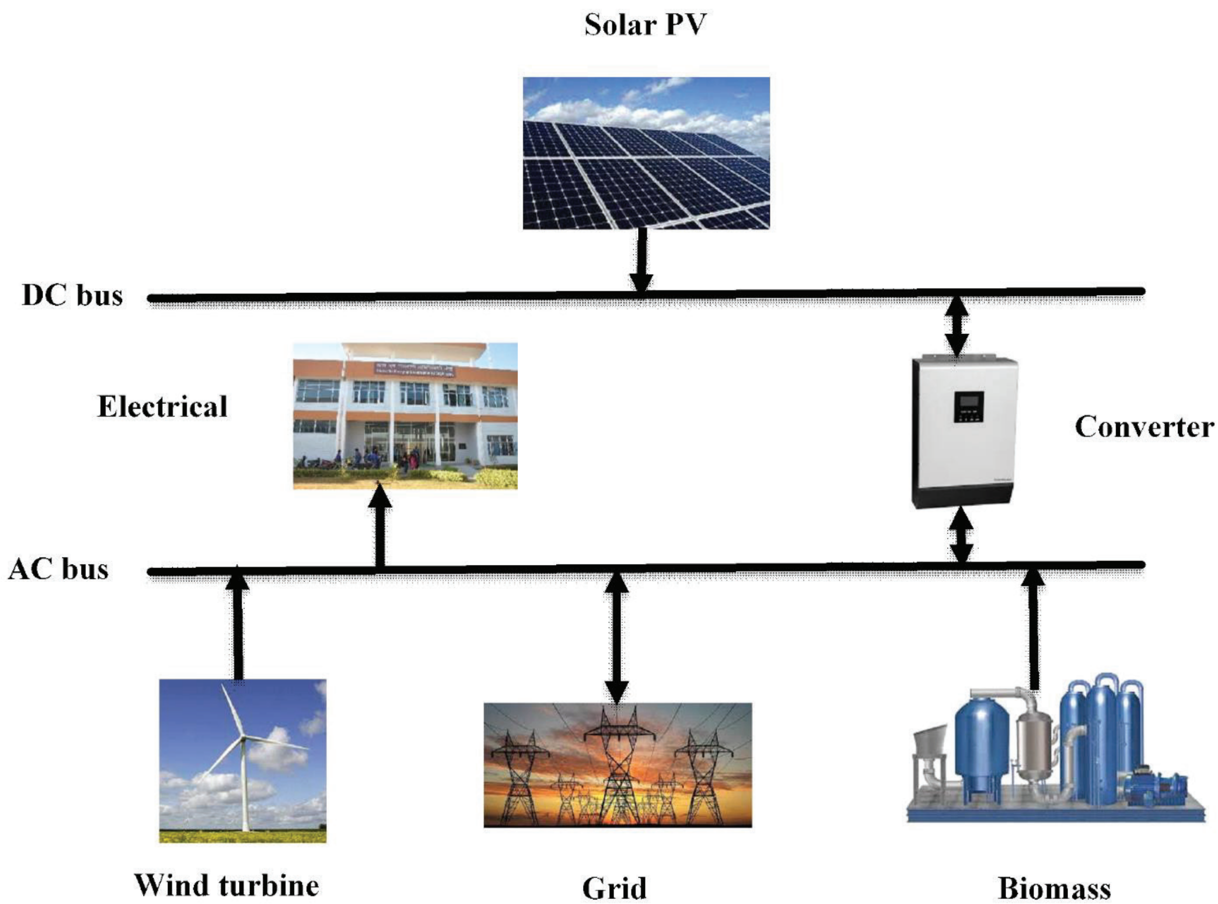

Figure 5: The schematic diagram of the proposed hybrid energy system

figuration is $54381, with LCOE 0.132 $/kWh at 84% RF and 0% capacity shortage. The annual, monthly power contribution of the different generating units (PV/BG/WT/grid) is shown in Figure 9.

Due to low wind speed at the study site, the average monthly contribution of electricity generation from the wind turbine system is observed to be very small. The obtained results indicate that in months from February to June, the wind turbine generation is high because maximum wind speed has recorded in these months. In contrast, the generation is minimal in other months. The biomass generation unit delivers maximum power mainly early in the morning and in the evening, when wind and solar are unable to satisfy the loads demand. In this case, the hybrid renewable power system generation is found to be 59.8 MWh/year annually, in which only 16% (9.6 MWh /year) is imported from the grid.

Case 3: Grid only
In the grid only Case 24kW grid supply is sufficient to meet the load demand at TNPC $44810 with LCOE 0.109 $/kWh at 0% capacity shortage. Figure 10 shows the schematic of Case 3. In this case, the average annual grid importation of electricity is found to be 31.9 MWh/year. At the same time, the highest units are imported in the winter seasons due to the high demand for electricity, as shown in figure 11.

3.2 Comparison of different cases simulation results
The comparison of the systems is achieved on the bases of the following factors: total net present cost (TNPC), cost of energy, capacity shortage (low), fuel consumption, unmet load, and maximum renewable energy fraction, with more prominence on the LCOE and TNPC.

Table 3: Techno-economic details of the proposed hybrid system

Parameters	Values	Parameters	Values
PV system[1*]		**Wind system[3*]**	
Rated capacity (kWp)	1	Rated capacity (kWp)	5
Efficiency at STC (%)	13	Rotor diameter (m)	4.26
Slope or tilt angle (degree)	31	Number of blades	3
Capital cost ($)	619	Cut in wind speed (m/s)	2.50
Replacement cost ($)	619	Cut out wind speed (m/s)	25
O&M cost ($/year)	25	Rated wind speed (m/s)	11
Lifetime (year)	25	Replacement cost ($)	8413
		O&M cost ($/year)	144
Biomass gasifier system[2*]		Capital cost ($)	8413
Rated capacity (kW)	1	Lifetime (year)	15
Minimum load ratio (%)	30		
Capital cost ($)	1162	**Converter[4*]**	
Efficiency (%)	20	Rated capacity (kW)	1
Replacement cost ($)	872	Efficiency (%)	95
O&M cost ($/year)	0.010	Capital cost ($)	116
Lifetime (Hrs.)	15000	Replacement cost ($)	116
		O&M cost ($/year)	3
Other economic inputs		Lifetime (year)	10
Annual interest rate (%)	5.95		
System fixed capital cost ($)	2331.2		
System fixed O&M cost ($/year)	116.56		
Project lifetime (year)	25		

1* PV Module Data (2019), Data collected from PV module manufacturers and utilities., 2* Biomass Gasifier Data (2019), Data collected from biomass gasifier manufacturer (Ankur Scientific Energy Technologies Pvt. Ltd)., 3* Wind turbine Data (2019), Data collected from wind turbine manufacturers (Supernova Tech. Pvt. Ltd.)., 4* Converter Data (2019), Data collected from converter manufacturers and utilities.

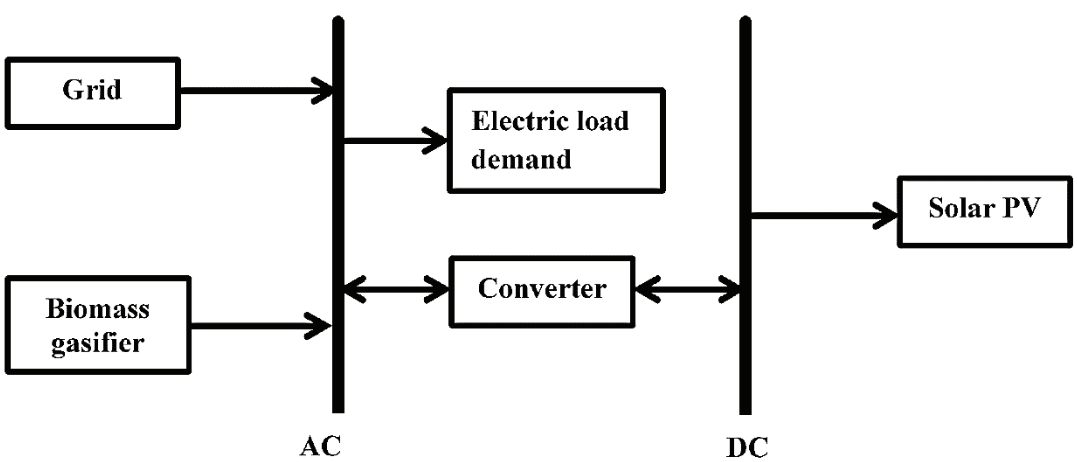

Figure 6: On-grid hybrid energy system for Case 1

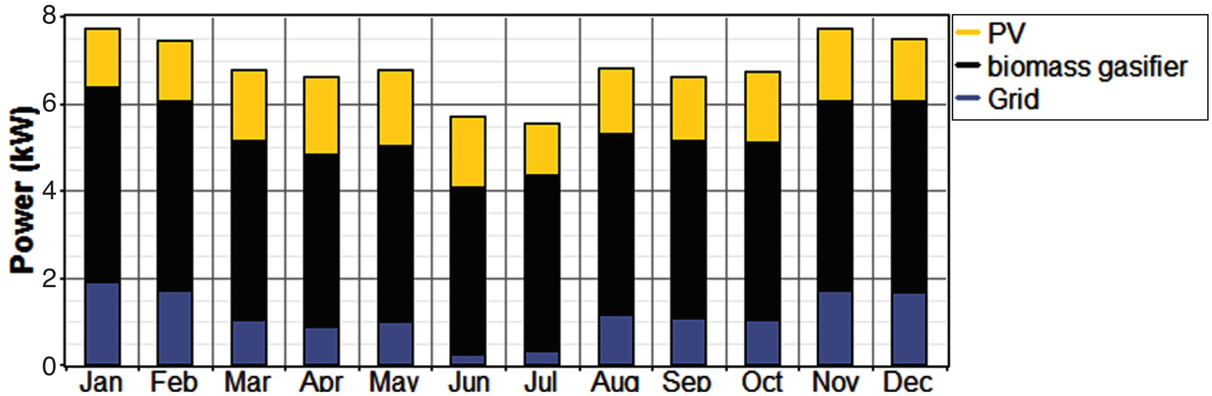

Figure 7: Monthly average electricity production of generation units in Case 1

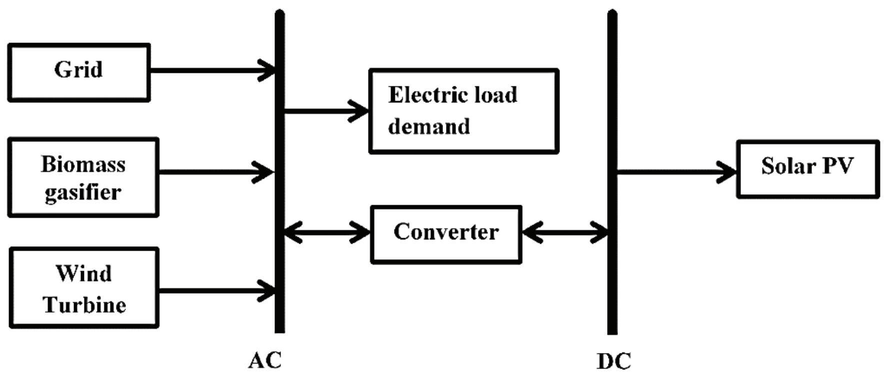

Figure 8: On-grid hybrid energy system for Case 2

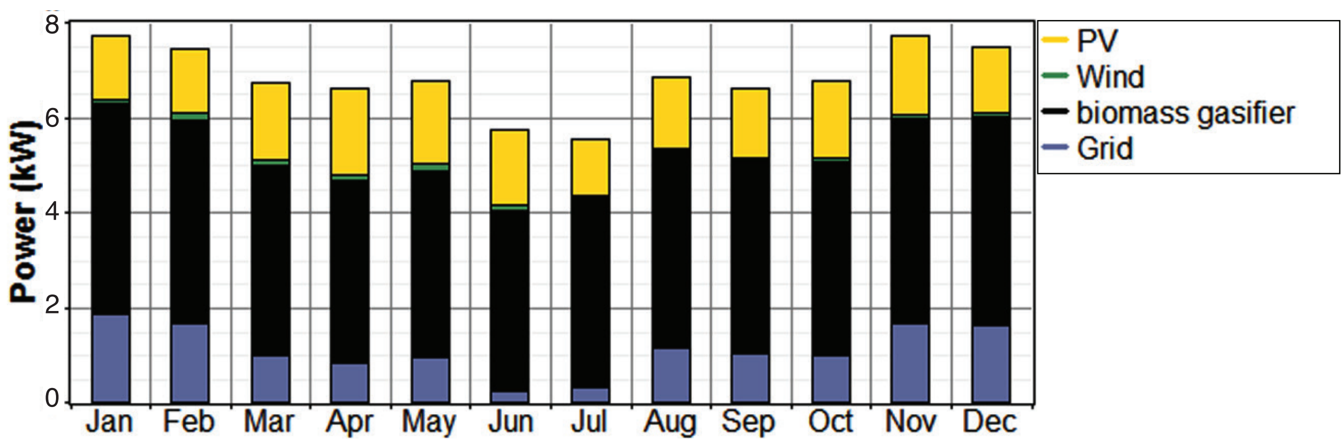

Figure 9: Monthly average electricity production of generation units in Case 2

The simulation results show that the most optimized hybrid renewable energy system (HRES) in all cases consists of 11 kW_p PV array, 5 kW gasifier system, 7 kW converter, and 18 kW grid purchase capacity with 5 kW grid sale capacity (Case 1).

The simulation results of optimum combinations from all cases are shown in table 4. The analysis of simulation results found that the configuration of Case 1 offers the lowest LCOE, TNPC, operating cost. Therefore, the configuration of Case 1 (PV/BG/Grid) is

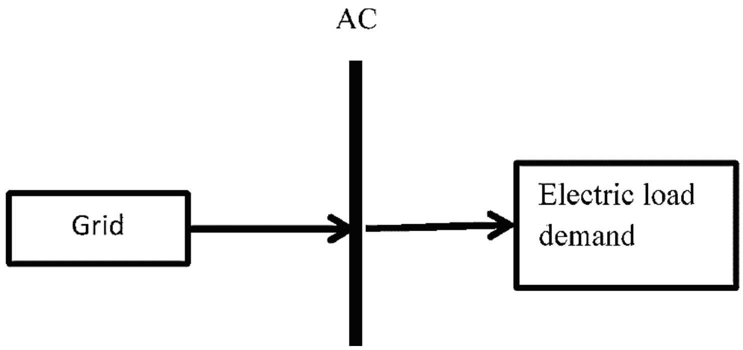

Figure 10: On-grid hybrid energy system for Case 3

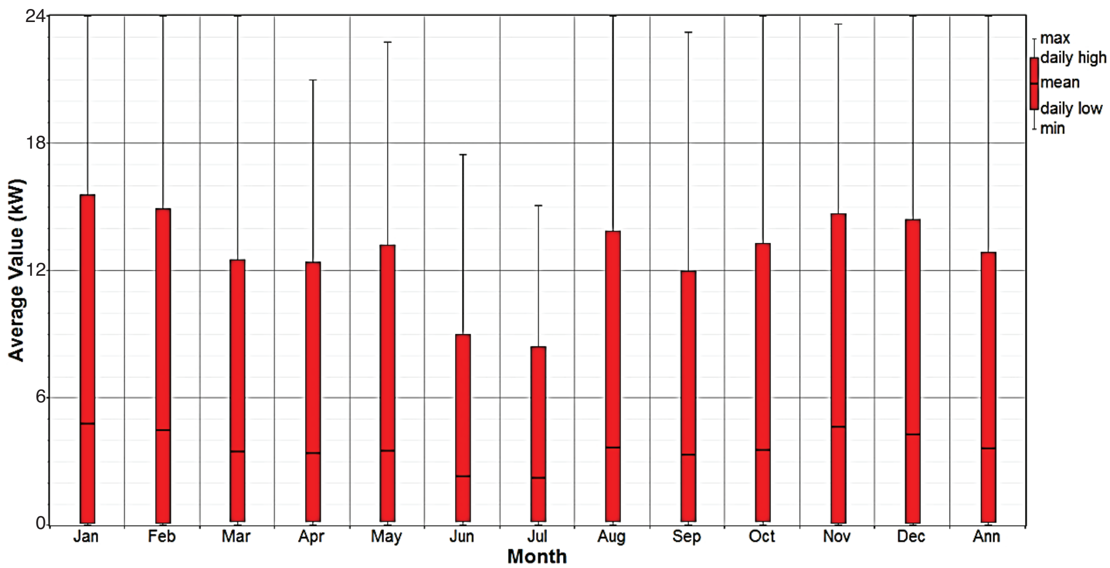

Figure 11: Monthly average power purchased from the grid in Case 3

Table 4: Relative simulation results of different configurations of HRES

Parameters	Case1	Case2	Case3	Parameters	Case1	Case2	Case3
PV(kW)	11	11	0	Total generation (MWh/year)	59.7	59.7	31.9
WT (kW)	0	5	0	PV generation (MWh/year)	13.3	13.3	0
BG(kW)	5	5	0	WT generation(MWh/year)	0	0.883	0
Converter(kW)	7	7	0	BG generation(MWh/year)	36.4	35.8	0
Grid sale (MWh/year)	26.5	26.4	0	Grid purchase(MWh/year)	9.9	9.6	31.9
Initial capital cost ($)	15762	24175	2331	Renewable fraction (%)	83	84	0
Operating cost ($/year)	2049	2352	3307	Biomass(ton/year)	19	18	0
TNPC ($)	42081	54381	44810	Gassifier running hours per year	7311	7193	0
LCOE($/kWh)	0.102	0.132	0.109				

recommended as the most optimized solution for the study location. The cost of energy generation from the optimum solution was compared to such a combination in the literature, and it has been found that the most optimized hybrid energy system showed better results in terms of COE [43,44,45].

The nominal cash flow of the most optimized hybrid energy system for 25 years is shown in figure 12. The cash flow study shows that the biomass gasifier has the highest capital cost of $15106, and there is a need for replacement of the gasifier system when a lifetime (15000 hours) is over. However, the PV array has the

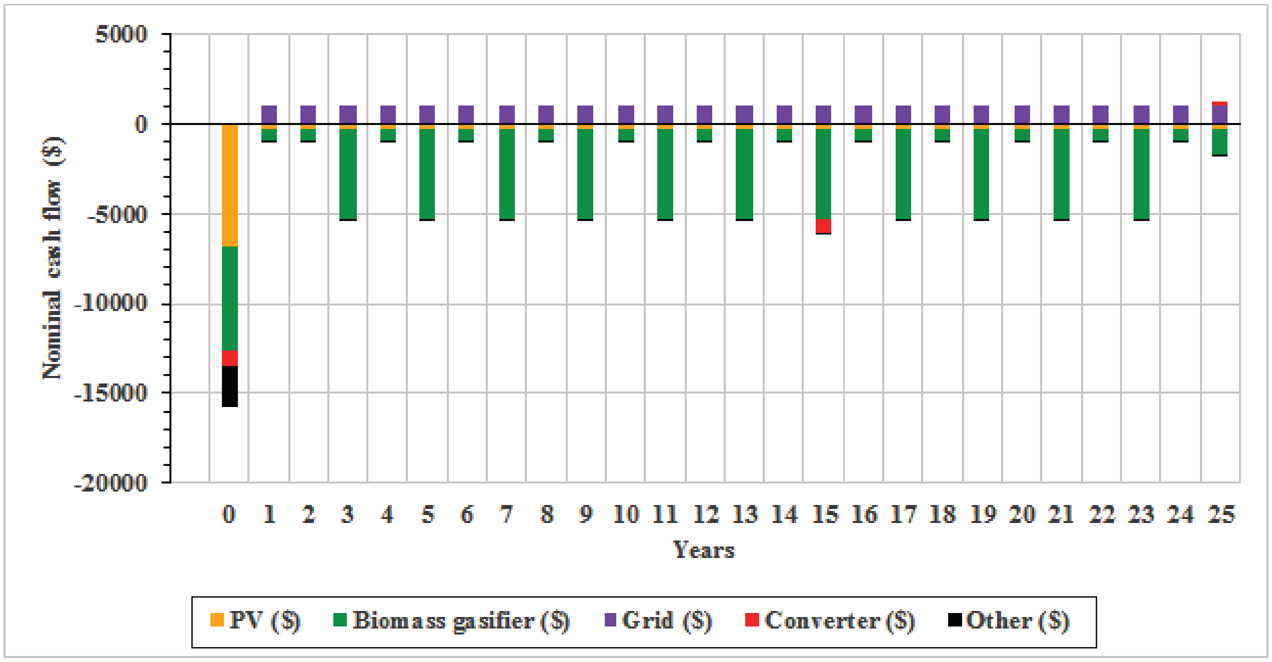

Figure 12: Cash flow details of the most optimized proposed hybrid system

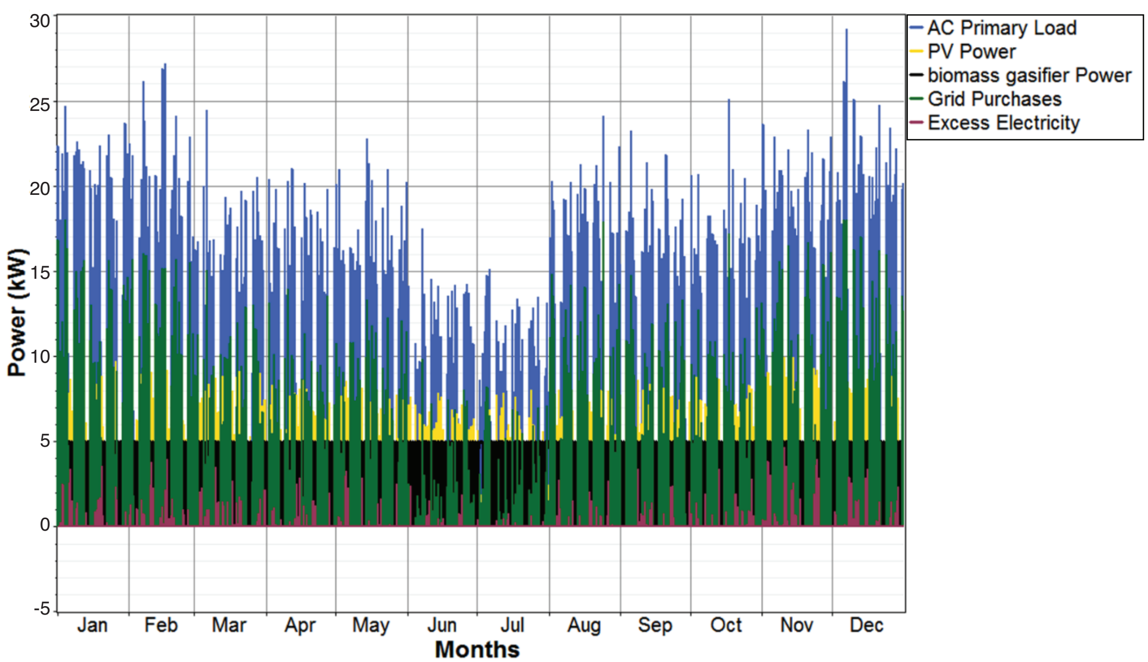

Figure 13: Hourly electricity generation from PV/Biomass/Grid hybrid system

highest operational and maintenance cost of about $ 4174 since cleaning is needed periodically after a few days.

The annual hourly production of electricity from the optimized hybrid system shows that the PV system primarily meets the demand for load, and the rest is filled with gasifier and grid. The proposed HRES also gives the option of selling back (up to 5 kW) the excess electricity generated during the off-peak period or in a no-load condition. The selling price of excess generation is considered to be equal to the purchased electricity rate (.083$/kWh). The gasifier has the highest percentage share in total electricity generation, followed by PV and grid. Figure 13 shows the annual hourly energy production of the most optimized hybrid system for the study area.

As shown from the figure, PV has a preference to serve the load demand when its output power is sufficient; thus, the electricity demand is served by the PV solely in the higher solar radiation hours, and the surplus energy is transmitted back into the grid. In another scenario, when the PV production capacity in the early morning, rainy seasons and evening hours can not meet the load requirement. At those periods, the gasifier and grid will fulfill the load. These considerations refer even to the night hours when the PV energy production drops to zero.

It is essential to consider that the hybrid device works in an off-grid condition during grid failures in which the PV/BM will provide the power. However, it is not possible to export surplus electricity into the grid. Preventing sale back to the grid during power failures is primarily for safety reasons to safeguard linesmen. In such cases, batteries can be used to store excess electricity.

Each month's hourly import and export of electricity from and to the grid are an emotive subject for discussion. Month wise hourly grid import and export along with load requirement and ambient temperature for one year is shown in Figure 14. The load demand is small in the summer season (March to October) compared to winter. The system analysis, therefore, reveals the lesser amount of grid import units in a winter context. In parallel, grid export units show a rise in this season. Importing units of electricity from the grid is raised for the winter period (November to February) due to a rise in load demand.

The overall analysis indicates that the grid import unit is minimal in the summer period, and therefore the grid export unit is maximum due to reduced load demand value. The lowest grid import value and the highest export value observed at weekends of each month and vacation time (June and July) since power demand is the lowest in these periods.

The average daily unit generation from power sources of the optimized hybrid energy system is shown in figure 15. In January, the gasifier generation unit is maximum because the solar output is small, and the demand for the load is highest. While in June it is lowest because of low energy demand. Solar PV produces maximum units in April because of the excellent solar radiation and moderate temperature. The biomass gasifier percentage is highest (61%) followed by PV (22%) and grid (17%) in total electricity generation.

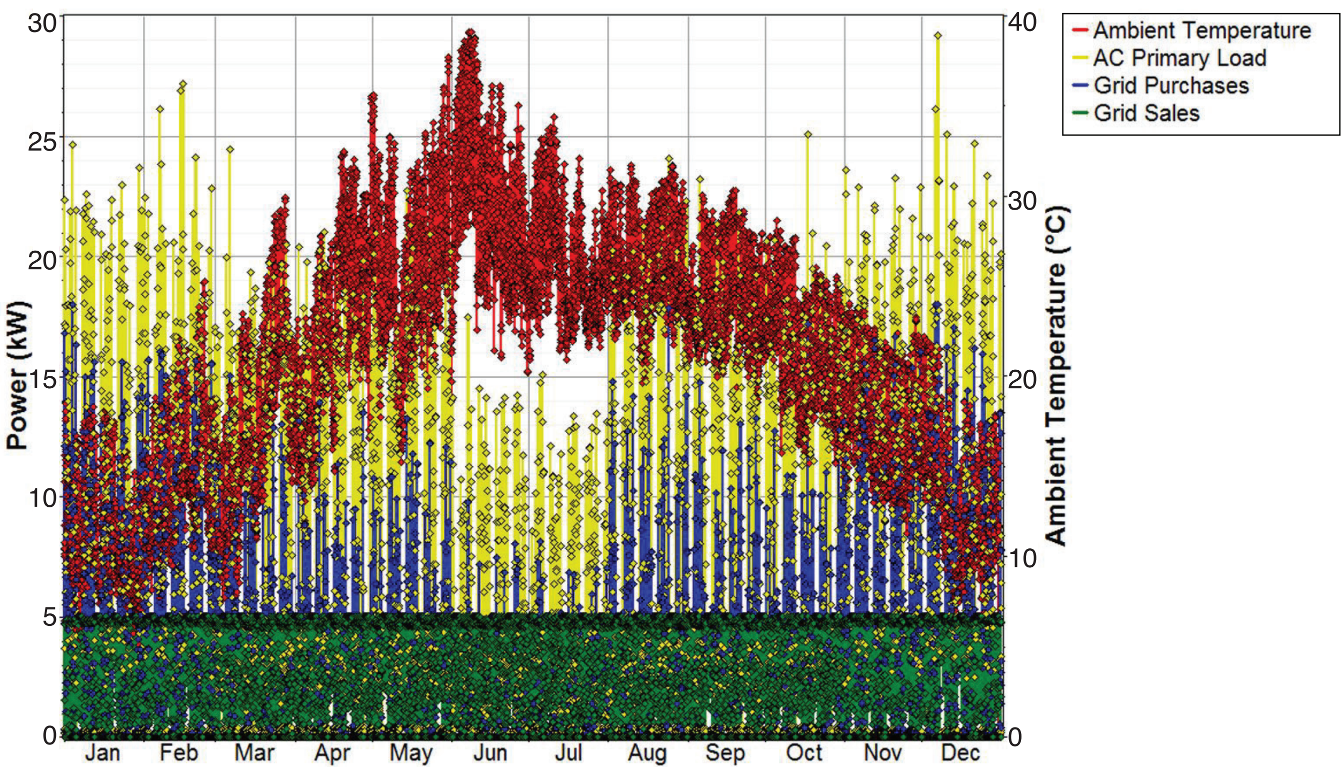

Fig. 14: Monthwise hourly grid import and export power along with load demand and ambient temperature

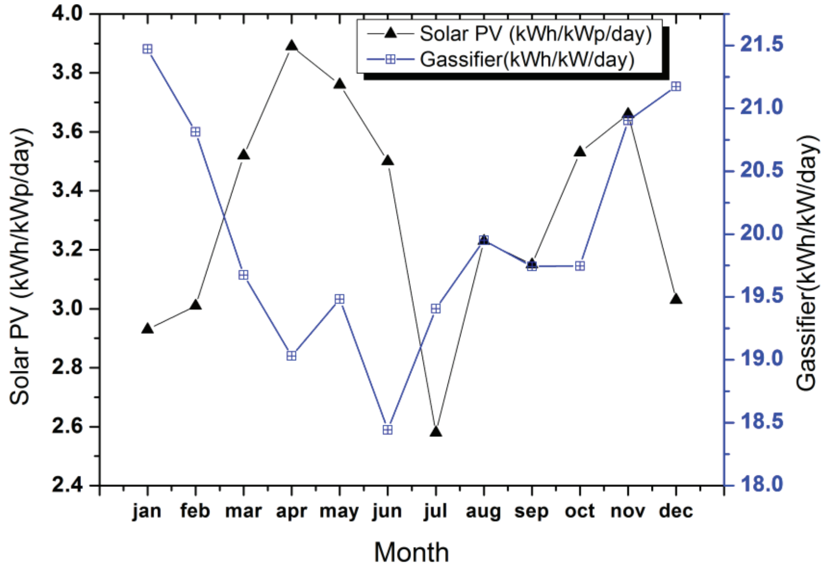

Figure 15: Power generation from PV and Biomass system

The most optimized system (PV/BM/grid) generates 59.7 MWh/year at 0% power shortage and 83% renewable fraction. A diesel generator power system with 30% efficiency, 16000 hours lifetime and 25% minimum load ratio will be required to fulfill the same load demand, which consumed 10563 liters of diesel per year and emitted the 27.8 Mt of CO_2 per annum. The calculated value of the CO_2 generated is obtained by considering that each liter of diesel fuel consumed by diesel engine produces about 2.6 kg of CO_2 [46,21].

4. Conclusion

In the present study, a feasibility analysis of on-grid integrated biomass-based hybrid energy system configurations, i.e., PV/BG/grid, BG/grid, and only grid in the western Himalayan region has been conducted. The primary goal behind this study was the use of unutilized pine needles biomass production in hilly regions of western Himalayan territory to contribute to the worldwide fight against global warming. The natural degradation of pine needles in the forests would emit the same amount of carbon as the burning of the pine needles in the gasifier to produce electricity.

Pine needles are also fired hazards to the forests due to the presence of a high amount extremely inflammable of resin contents. Which leads to the destruction of an enormous amount of photosynthesizing green vegetation. It is noted that no such research study with realistic inputs (latest equipment market prices, unutilized pine needles as biomass and real-time hourly energy consumption and location-specific renewable resources data) has been conducted in the western Himalayan area earlier. The important conclusions are drawn from this study as follows:

- The resource assessment results revealed that the location of the study has good power generation potential through the use of solar PV and BG systems. The area of the investigation has a low wind profile, so that small/micro/pico/ nanoscale wind turbines with lower cut-in speed (1–1.5 m/sec) may be more useful for generating power. Which is not only increases the generation percentage and renewable fraction but also further reduces the overall generation cost of the system.
- Among all the simulated configuration, PV/BM/grid analysis is found to be optimum with 11 kW_p of PV array, 5 kW biomass gasifier, 7 kW converter, and 18 kW grid without any capacity shortage to meet the energy demand 88 kWh/day for study location.
- The economic analysis found that the optimum configuration is achieved at a minimum value of LCOE $0.102 per kWh (29% and 7% lower than Case 2 and Case 3 respectively) with estimated

TNPC $42,081 (29% and 7% lower than Case 2 and Case 3 respectively) and 83% renewable fraction.

- The total power generation from optimum configuration is found to be 59.7 MWh/year, where biomass gasifier contributes uppermost 36.4 MWh/year (61%) followed by PV (22%) and grid (17%).
- The CO_2 emission analysis also has been done and concludes that the proposed system saves 27.8 Mt of CO_2 per year compared to only diesel system.

Practical use of unutilized biomass in hilly regions will not only aid in protecting the environment, but it will also help achieve the renewable energy goal of India as well as employment for local communities. Small-scale biomass-based hybrid systems can play a significant role because of their higher reliability, low generation costs, and environmentally friendly nature for power generation models in western Himalayan regions as well as other locations. In which there is also plenty of surplus biomass at a cheaper cost. Moreover, the output of such kind of analyses gives a general proposal of best practices or guidelines for future programs/projects in the western Himalayan region.

A further follow-up simulation study with a sensitivity analysis can be done to analyze the effect of variation of input parameters on the output side and to obtain the most critical parameters. The practical implementation based on simulation could also be a follow-up study to understand practical challenges and solutions.

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Appendix 1.

Modelling equations used in HOMER

(a) *Solar radiation and PV module modeling*

The HDKR (Hay, Davies, Klucher, Reindl) model [47] is used to calculate the incident solar radiation at PV array, given by Eq. (1)

$$G_T = R_b\left(G_b + G_d A_i\right) + G_d\left(1 - A_i\right)\left(\frac{1+\cos\beta}{2}\right)\left[1 + f\sin^3\left(\frac{\beta}{2}\right)\right] + G\rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{1}$$

where, G_b, G_d, G are the beam radiation (kW/m^2), diffusion radiation (kW/m^2) and global horizontal at earth surface (kW/m^2) respectively, A_i denotes the anisotropy index, R_b is the ratio of beam radiation at a tilted surface to beam radiation on a horizontal surface, f is used for horizon brightening= $\sqrt{\frac{G_b}{G}}$, β is the slope of the surface (^{0}), ρ_g represents ground reflectance (%). The PV modules power generation on an optimum tilt angle is estimated in HOMER by using the following equation (2):

$$P_{pv} = Y_{pv} D_{pv}\left(\frac{G_T}{G_n}\right)\left[1 + \alpha_p\left(T - T_{ref}\right)\right] \tag{2}$$

where, P_{pv} is the power generation from PV array (kW), Y_{pv} represents the rated capacity of PV array at standard test conditions (kW), D_{pv} symbolizes the PV de-rating factor (%), G_T is the solar radiation incident on the PV array in the current time step (kW/m^2) calculated by Eq. (1), G_n is the incident radiation at standard test conditions (kW/m^2), α_p denotes the temperature coefficient of power (%/°C), T is the PV cell temperature in the current time step (°C), T_{ref} characterizes the PV cell temperature under standard test conditions.

(b) *Wind turbine model*

HOMER calculates the output power of the wind turbine in a particular hour in three steps.

1. The hourly wind speed data are used to calculate wind speed at the hub height using either the logarithm profile or the power-law profile. The hub height of the turbine is directly proportional to the wind speed according to the wind speed profile given by Eq. (3)

$$\frac{V}{V_r} = \left(\frac{H}{H_{ref}}\right)^{\alpha} \quad (3)$$

α is a power-law exponent, which is given by

$$\alpha = \frac{0.37 - 0.088\ln\left(V_{ref}\right)}{1 - 0.088\ln\left(\frac{H_{ref}}{10}\right)} \quad (4)$$

where,

V = wind speed at height H (m/s)
H = hub height (m)
V_r = wind speed at reference height H_{ref}
V_{ref} = reference wind speed (m/s)
H_{ref} = reference height (m)

2. The wind turbine maximum output power is calculated using equation [48]

$$P_{max} = 0.5\rho A C_p \left[V/\omega_m\right]^3 \times \omega_m^{\ 3} \quad (5)$$

Where P_{max} (kW) is the maximum power generated by a wind turbine. ρ is the density of the air (kg/m^3), A is the swept area, C_p is the coefficient of a wind turbine, ω_m is the rotor speed (rad/sec), V is the linear speed of the wind (m/s).

(c) *Biomass energy*

The biomass gasifier size depends on some critical factors such as biomass quantity (T) at the location, the calorific value of biomass (CV_{BM}), hours of operation per day (H_{BM}), time step (Δt) and overall biomass gasifier system efficiency (η_{BMGS}).

Gasifier hourly energy generation (E_{BMGS}) is calculated by using Eq. (5) [49].

$$E_{BMGS}\left(t\right) = \frac{T\left(kg/y\right) \times CV_{BM} \times \eta_{BMGS} \times \Delta t}{365 \times 860 \times H_{BM}} \quad (5)$$

(d) *Economical parameters*

The Homer simulates different system configurations according to the input parameters and finds the optimal solution from various combinations according to total net present cost (TNPC). The total net present cost is calculated using the following equation:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF\left(i,N\right)} \quad (11)$$

where, $C_{ann,tot}$ is the total annualized cost ($/year). *CRF* denotes the capital recovery factor and calculated by Eq (12).

$$CRF\left(i,N\right) = \frac{i\left(1+i\right)^N}{\left(1+i\right)^N - 1} \quad (12)$$

where, i = interest rate (%), N = project lifetime (years)

The levelised cost of energy (LCOE) calculation has been done with the help of the following equation

$$LCOE = \frac{C_{ann,tot}}{E_{prim,AC}} \quad (13)$$

where $E_{prim,AC}$ is the AC primary load served (kWh/year)