RESEARCH PAPER

Techno-Economic-Eco Design and Investigation of Hybrid Energy Generation Systems in Tropics

Pallavi Choudhary[1] · Ashok Kumar Akella[1]

Abstract

India, being a land of diversified flora, has a promising resource of biomass, which, when utilized to its best, can cope with the elevating need for power. This research proposes a biomass-based energy generation system that can cater to the power needs of remote areas in tropical deciduous forests. A simulation and techno-economic and ecological investigation of eight hybrid energy generation architectures have been carried out. The model comprising a solar photovoltaic-biomass energy unit-storage unit was found to be the most appropriate system to cater to the domestic, agricultural, and commercial demands of a cluster of 10 villages in the tropical highlands of India. This configuration proposes the least cost of energy (0.077 \$/kWh) at a computed net cost of \$ 380,415. 30.3% (106,240 kWh/year) of power is generated by PV, and the remaining 69.7% (321,580 kWh/year) is generated by Biomass generators. Ecologically, the proposed architecture predicts a cutdown of GHG (CO_2) emissions to a mere 82 kg/year. The results can help policymakers, researchers, and designers on the latest constraints as well as policies for solar photovoltaic-biomass energy-based systems.

Keywords Renewable energy · Hybrid energy systems · HOMER · Biomass · Solar photovoltaics · Wind turbine · Small hydro power · GHG

Abbreviations

ACS	Average cost of supply
ARR	Average revenue realized
BI	Biomass
DG	Deisel generator set
GHG	Green house gases
HEGS	Hybrid energy generation system
HRES	Hybrid renewable energy system
II	Initial investment
LCE	Levelized cost of energy
LED	Light emitting diode
NREL	National renewable energy laboratory
O&M	Operation and maintenance
OC	Operating cost
PV	Photovoltaic
RF	Renewable fraction
SH	Small hydro
SU	Storage unit
TNC	Total net present cost
WE	Wind energy

✉ Pallavi Choudhary
pallavichoudhary18@gmail.com

[1] Department of Electrical Engineering, National Institute of Technology, Jamshedpur, Jamshedpur 831014, Jharkhand, India

1 Introduction

ENERGY: A term that regulates the world. From cosmic metamorphoses to molecular mutations, every natural phenomenon is an alteration of energy (Odetoye et al. 2023). Among all the available forms of energy, the most commonly utilized by mankind, has been electricity. Mediums of electricity generation were limited for ages until they were revolutionized by renewables. Various factors, viz. inaccessible landscape, higher operating and maintenance expenses, the need for lower emissions, etc. have compelled us to explore renewable options for power generation (Saini and Chauhan 2014; Sinha and Raina 2019; Dash and Bajpai 2012). As per the report published by the IEA, about 23–24% of total global energy production comes from renewable resources (15.2% hydropower, 7.5% wind energy, 2.4% biopower, 4.5% solar PVs, and 0.4% others) (Bojek 2023). Promotion of green energy assures amplified job opportunities, expansion in

infrastructure, and improvement in health conditions by reducing the emissions released by energy generation units (Saini and Chauhan 2015; Awasthi et al. 2020). It is projected that a 45% increase in the usage of renewables will reduce CO_2 emissions by 11% (Thambi 2018).

In rural terrain, naturally replenishable energy sources like sun, wind, rivulets, and biomass are available in abundance. These reserves can be utilized for electricity generation in a decentralized mode to fulfill demands around the clock. In developing realms like India, around 70% of people are rural residents, and only 18% have non-interrupting electrical supply (Kushana 2014). To ensure the escalation of electrification, the Government of India has launched numerous schemes like IPDS (Dec 2014) for strengthening of distribution systems and set up of rooftop solar panels, DDUGJY (Dec 2014) for 100% electrification of the country, SAUBHAYGA (Oct 2017) for providing electricity connections to rural and poor households, UDAY (Nov 2015) for improvement of financial and operational efficiency of DISCOMs, RDSS (July 2021) to reduce ACS-ARR gap to 0 and AT&C losses to 12–15% by 2024–25, NERPSIP (Dec 2018) for firming up of inter and intra state transmission and distribution system, UJALA (Jan 2015) for promotion of LED bulbs for domestic and street lightening applications. This has recorded an energy saving of 8.24 billion kWh/year with a circumvented peak demand of 1,374 MW and an assessed GHG emanation lessening of 5.68 Mt CO_2/year, Gram UJALA (Mar 2021) for the replacement of old bulbs with LED lamps, saving 467 million kWh/year ("PIB" 2021). IRES 2020 suggests that 2.4% of households in the Indian subcontinent are still deprived of electricity, while the remaining 97.6% receive power for 20.6 h per day on average. This figure is still as low as 18 h per day in the eastern periphery of the states of Bihar, Jharkhand, Odisha, and West Bengal (Agarwal et al. 2020).

The erroneous presence of renewable resources in remote villages is one of the major hurdles to their utilization for sustainable power generation. However, unification of two or more such naturally occurring and imperishable means of energy production can unravel the problems of grid extension and maintenance costs, intermittency of non-conventional sources, power reliability, system performance, and production costs (Naves et al. 2014; Samaoi et al. 2015). In India, the potential of renewable energy technologies (Khan 2006) was documented in the early 1970s. The nation is equipped with one of the world's most extensive programs on alternative sources of energy, and India is perhaps the only country on the global map consisting of a full-fledged and fully functioning Ministry established exclusively for non-conventional sources of power. In 2018, the Ministry launched the "National Wind-Solar Hybrid Policy" to promote and optimize the usage of renewables in the power generation sector, emphasizing wind and solar photovoltaic units (Chandel et al. 2016). But due to the sporadic distribution of wind throughout the geography, power generation demands cannot be fulfilled in all the areas. Also, India, geographically, is full of natural vegetation, which makes biomass and water-based energy systems comparatively feasible (Adhikari and Saxena 2009).

Many investigators have explored the feasibility analysis for remote electrification by means of off-grid hybrid energy generation units all-round the globe. For example, Li et al. (Zhou et al. 2020) investigated viability of various hybrid systems incorporating different battery technologies and deduced that Zn-Br batteries are more economic as compared to Li-ion and Pb-acid. Murlidhar et al. (Murlidhar et al. 2020) explored the economic and technical analysis of HRES to compute optimum solution of electricity supply to remote villages of India. Several authors (Ma and G. R et al.., 2020) studied the feasibility of hybrid systems to accomplish power generation for small village of Iran and concluded that PV-WE-BI system is optimal for the study location. Malik et al. (Malik et al. 2020) endorsed integration of biomass gasifiers with PV-WE systems for cost cutting. Chouhan recommended (Saini and Chauhan 2016) an optimized model for 48 hamlets of Chameli district of Uttarakhand, India. Dei and Batjargal (Dei and Batjargal 2022) evaluated PV-DG hybrid system for smaller loads on technical and economical parameters. Hasan et al. (Chowdhury et al. 2019) assessed PV-WE systems with diverse running strategies of grid-tied and standalone system. Panda and Dauda (Panda et al. 2023) presented a comprehensive review on researches regarding storage integrated hybrid systems, their real time operative analysis and solution policies. Lihui Xin et al. (Zhang et al. 2017) have presented MEHS structure and deduced that the model can attain best operation by using multiple energy generation characteristics. Analysis of the characteristics of three different categories of power generation utilising biomass has been attempted by the authors, furthermore they also compared the economic and applications of biomass co-combustion power generation techniques. The outcomes showed the direct fired generators had greater efficiency and high investment but are quite reasonable in large scale operations; on the other hand, power generation through gasification had less investment, greater flexibility and lower generation cost. Thus, the co-combustion power generation technique has higher efficiency as well as lesser investment cost (Wang 2010). Researcher have summarized quite a lot of topical developments in process simulation and optimization methods and tools. The range of outcomes thus obtained were also included and it was deduced that tailor-made simulations can provide better understanding of perfect

design and operation of the necessary processes and equipment involved (Stehlik 2011). Technocrats have aimed to put forward a viability study of grid connected PV and Biomass integrated system. This was proposed to enlighten Monshaet Taher village of Egypt. HOMER optimization system was designed and it was inferred that such kind of hybrid system can effectively reduce the emission levels without increasing the investments (Barakat et al. 2016). Review of many biomass-based hybrid formations with diesel, micro hybrid, solar, wind, fuel cell and geothermal energies has been done. The authors have considered anaerobic digestion and gasification-based bio electricity and have indicated that this can be the best possible alternative for energy generation off grid (Malik et al. 2021). Salehin et al. (Salehin et al. 2014) presented HRES system for isolated island in Bangladesh. Sigarchian et al. (Sg and P. R et al.., 2015) put forward the sensitivity analysis and optimization of HRES for un-electrified communities of Kenya.

In quest of an augmented hybrid energy generation system, a techno-economic and environmental analysis of an off-grid decentralized HEGS for the tropical highlands of India has been done utilizing a simulation study in HOMER. HOMER is quite user-friendly in the design and development of hybrid energy systems in both on- and off-grid modes (Sinha and Chandel 2015). Eight different architectures were considered on the basis of the local renewables available, and CO_2 emissions were also calculated for all the architectures to analyze the environmental effect. Additionally, sensitivity analysis with eight different input parameters of the proposed system has been performed to examine the impact of input variables on system LCE and TNC. A cluster of 10 remote villages (V1–V10) has been chosen as a case study from the state of Jharkhand, India. The villages are located in the tropical region of the Chhota Nagpur plateau, which is covered with dry deciduous forests. Due to this, ample amounts of biomass are available in the region throughout the year, along with ample amounts of sunlight that can be harnessed for power generation. Additionally, due to fair amount of rainfall, the region also has substantial number of water bodies to act as small hydro power generating stations. This investigation will prove to be an aid to policymakers/system designers/ researchers in choosing apposite designing constraints and verbalizing policies for decentralized off-grid HEGS in the tropical highlands and other far-flung hilly forest ranges around the world.

Novelties of this research is reflected in the following points: a) This study aims to develop a dedicated hybrid energy generation system for remote areas of dense deciduous forests in tropical highlands. b) A cluster of 10 villages was chosen for the load estimation, energy consumption pattern (including domestic, agriculture, and commercial demand), and assessment of renewable potential (small hydro, PV, wind, biomass, etc.) from Chandil, Jharkhand, India, as a case study. c) Sizing and cost estimation of the HEGS and the development of a model based on demand and supply constraints were carried out. Formulation on the basis of LCE, TNC, OC, and GHG was done. d) A localized HEGS architecture based on PV-BI appended with SU has been designed and simulated in HOMER. A technical, economic, environmental, and sensitivity analysis has been carried out.

The proposed HEGS is a custom design based on real-time constraints for both load as well as resource availability. The design has been modeled and simulated for practical implementation purposes. A technical and economic investigation has been carried out to judge the feasibility of setting up such a unit and, hence, to analyze the unit cost of electricity to be borne by the end user, the capital investment required for construction, operation, and maintenance expenses, and the life-time of the project. Such an extensive study of alternate resources for electricity generation has never been carried out at the study location. Also, the design of HEGS along with technical and economic studies for real-time implementation are some of the primary features of this work. The results can inform policymakers, researchers, and designers on the latest constraints as well as policies for PV-BI-based systems.

The article flows as follows: "Materials and Methods" delivers an outline of the methodology used; "Results and Discussion" depicts the simulation results and discussion along with sensitivity analysis. Evaluation with similar studies is covered in "Comparison with other studies," and conclusions with a future scope are described in "Conclusions and future scope."

2 Materials and Methods

This section comprises the methodology to design a HEGS, load estimation of the study area, resource potential assessment of the location, components of the energy system required, sizing, modeling, and optimization of the best architecture. HOMER is used to optimize the best possible architecture in terms of total net present cost (TNC) and the levelized cost of energy (LCE). It has also been used for the study of variation in output with changes in input variables as a part of sensitivity analysis. This is the best tool for optimizing microsystems that can be employed for both on-grid and off-grid systems. HOMER, developed by NREL, simulates the designed architecture for 8760 h/year and also gauges the optimized results based upon TNC ("http://www.nrel.gov/homer/", [Online].
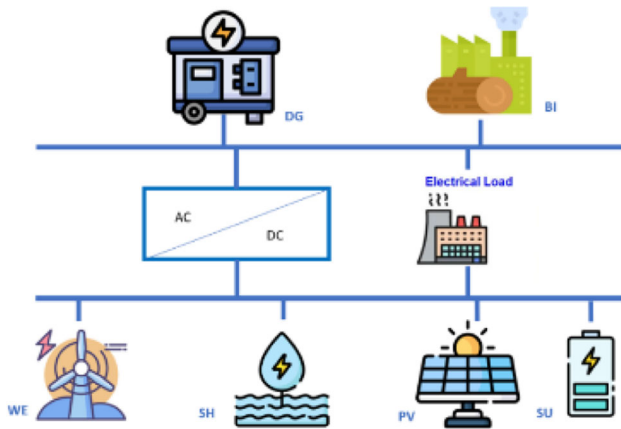
Fig. 1 Hybrid power generation architecture

2023). Figure 1 shows a typical hybrid power generation architecture that can be modeled in HOMER.

2.1 Load Estimation

10 remote villages in Chandil block in Jharkhand have been considered for the study purpose (V1–V10). The area is located on the tropical belt and is covered with dense deciduous vegetation. The details of the area are presented in Table 1 ("https:, , censusindia.gov.in, census.website, data, population-finder", [Online]. 2023).

For estimation of electrical power requirement of the study area, a year is categorized season-wise as the summer season (March–June), the rainy season (July–September), and the winter season (October–February) in accordance with the electrical energy necessities and consumption outline. The pattern of load distribution on a 24-h basis was studied for the complete year 2022. Four different energy consumption sectors were considered under the present study, viz. domestic, commercial, agricultural, and community. The domestic sector includes power consumption due to the usage of LED (20W), fans (45W), TVs (45W), etc. for each household. Agricultural demand includes power needed for rice hulling, crop threshing, fodder

Table 1 Details of the study location

S. No	Parameter	Value
1	Country	India
2	State	Jharkhand
3	District	Seraikela Kharsawan
4	Geographic location of chandil	22.97°N 86.02°E
5	Total villages considered	10
6	Total population	4292
7	Total households	872

cutting, etc. Commercial needs include power requirements for the functioning of small shops, flour mills, etc. The total energy demand of the study area is classified into four categories viz. domestic consumption (353,558.1 kWh/year), agricultural consumption (17,000 kWh/year), commercial consumption (8300 kWh/year), heat consumption (371,673 kWh/year) for cooking purposes. The day-to-day energy demand of the study area has been estimated as 1472.2 kWh/d for the summer season, 1293.52 kWh/d for the rainy season and 1203.1 kWh/d for the winter season. Figure 2 shows the 24-h load profile of the study area in all the seasons. Yearly power consumption of the study area is estimated as 378,858.1 kWh/yr.

2.2 Potential Assessment

The potential assessment of renewable energy sources was done with the help of an extensive survey using a set of questionnaires for the purpose of data collection, like cattle, agriculture residue, forest foliage, hydrological sources, etc. The details of the findings of the survey are listed in Table 2. The study area has an ample number of cattle, cows, goats, buffalo, sheep, pigs, and poultry whose excreta can be utilised to produce biogas and hence used for heating/cooking purposes as well as to run a biogas generator. The total amount of biogas available in the study area is 329,631.5 m3/year, which can be utilised for cooking and heating purposes. Being located in a dense forest belt, the study area has ample availability of forest foliage (twins, leaves, etc.) and crop residues, which can be a major source of biomass. For this location, the total amount of biomass is computed to be 2,68,046 kg/year from crop residue and 182,189 kg/year from forest foliage. The area receives an annual average daily solar insolation of 4.95 kWh/m2/day ("NREL", [Online]. Available 2023). The average temperature of the study area is 24.35° ("NREL", [Online]. Available 2023). However, the average wind speed in the study area is quite low, discouraging the utilization of wind power. The annual average has been 3.98 m/s; however, in late summer season and early rainy season, the speed is as high as 4.5–5.00 m/s at some locations, hence it can be used for small/micro wind turbine aerogenerators (Sinha and Chandel 2015). The hydropower potential is available at 11 sites and is capable of generating 225,494 kwh/year of energy. The water discharge is available throughout the year at 6 sites, while 3 sites have discharge for 4 months, 1 site for 4 months, and 1 site for 1 month.

2.3 HEGS Architectures

In this work we have considered eight different architectures involving solar PV, wind, small hydro and biomass
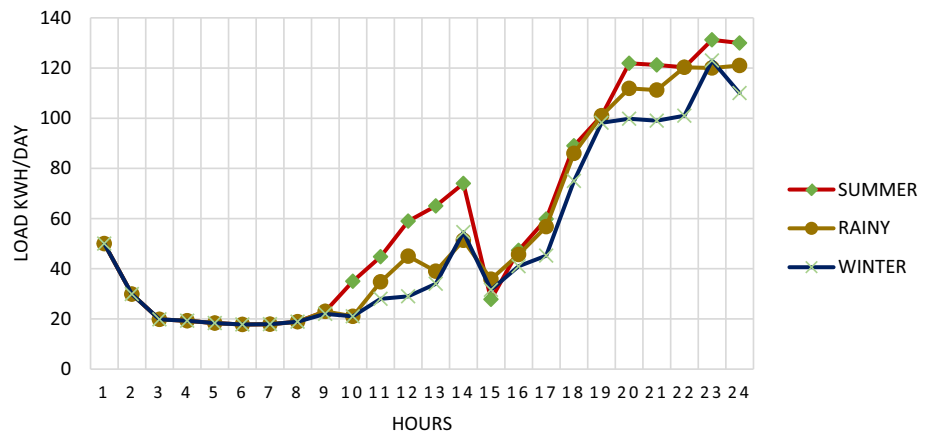
Fig. 2 Load profile of the study area

Table 2 Potential of renewable energy sources

Solar energy	Wind energy	Biomass availability	Biogas availability	Small hydro power availability
Annual average daily solar radiation 4.95 kWh/m^2/day	Annual average wind speed 3.98 m/s	268,046 kg/year from crop residue. 182,189 kg/year from forest foliage	329,631.5 m^3/year for cooking/heating purpose	245,494 kWh/year from 11 different sites

resources with and without a storage-backup genset system. The architecture includes designs, viz. PV-SH, PV-BI, SH-BI, PV-BI-WE-SH, BI only, PV only, PV-BI-SH, and SH only. The simulation details of all the above architectures are shown in Table 4. Table 3 presents the technical and economic attributes of systems used for the design of various HEGS architectures.

2.4 Modelling of HEGS Systems

The following mathematical expressions have been used for the purpose of modeling the renewable energy sources and system components.

2.4.1 Small Hydro (SH)

Based on the survey, it has been found that out of 10 villages, only 6 have the potential for the development of small hydropower plants. These villages are V1, V2, V3, V4, V7, and V10. The potential of small hydro has been calculated using the equation given as (Blume-Werry and Everts 2022):

$$Pg = 9.81\eta QH \tag{1}$$

where, Pg is power generated (kW), Q is the flow rate (m^3/sec), H is Head (m) and η is overall efficiency.

2.4.2 Wind Energy (WE)

A wind speed of 4 m/s has been considered to estimate the wind potential and unit cost of energy from wind resources in the target study area. Expression (2) is used to compute the wind potential for a rotor diameter, D, of 3.0 m; here D = 2*R (R = radius of the rotor) (Kusiak et al. 2009).

$$P_W = \frac{\pi}{8} Cp\rho D^2 V^3 Watts \tag{2}$$

Here, P$_W$ is available wind power (watt), Cp is the coefficient of performance of the Wind turbine, ρ is density of air (kg/m^3), D is rotor diameter (m) and V is the velocity of wind (m/s). As the potential of wind energy in the target area is quite limited, small-capacity systems are proposed for tapping the wind energy potential.

2.4.3 Solar Photovoltaic (PV)

HDKR model has been use for computation of insolation incidents on the solar PV panel array. Equation (3) represents the model (Shukla et al. 2015).

$$\overline{HT} = (\overline{Hb} + \overline{Hd}A)\overline{Rb} + \overline{Hg}\rho\frac{(1 - cos\beta)}{2}$$
$$+ \overline{Hd}\left\{\frac{(1 + cos\beta)}{2}(1 - A)\left[1 + sin^3(\frac{\beta}{2})\right]\right\} \tag{3}$$

Here, $\overline{HT}$ is the total radiation, $\overline{Hb}, \overline{Hd}, \overline{Hg}$ are the beam, diffused and global radiation (kW/m^2), $\overline{Rb}$ is the ratio of tilted beam radiation to horizontal beam radiation, A is

Table 3 Technical and economic specifications of components used in architecture

Photovoltaic unit	Value*	Wind turbine unit	Value*
Type	Flat Plate	Rated capacity	1 kW
Rated capacity	1 kW	Initial investment	$1170
Initial investment	$195.2	Replacement cost	$1170
Replacement expenses	$195.2	O&M cost/year	$88
O&M cost/year	$10	Hub height	17 m
Derating factor	80%	Unit lifetime	20 Years
Unit lifetime	25 Years		
Diesel genset unit	**Value***	**LA storage unit**	**Value***
Initial investment	$292.7	Rated capacity	1kWh
Replacement expenses	$292.7	Voltage	12 V
O&M Cost/hour of operation	$0.2	Initial investment	$170.7
Fuel expense/ litre	$1.1	Replacement expenses	$109.7
Min. load ratio	25%	O&M cost/year	$1.3
Unit lifetime	15,000 h	Unit lifetime	10 Years
		String size	10
		Nominal capacity	83.4 Ah
		Min. charge state	40%
Converter unit	**Value***	**Biomass genset unit**	**Value***
Initial investment	$121.9	Initial investment	$487.8
Replacement expenses	$121.9	Replacement expenses	$487.8
O&M cost/year	$6.1	O&M Cost/hr	$0.1
Efficiency	95%	Lifetime	20,000 h
Inverter lifetime	10 Years	Min. Load ratio	50%
Rectifier relative capacity	100%		
Hydro turbine unit			**Value***
Initial investment			$1951
Replacement expenses			$1951
O&M Cost/year			$488
Lifetime			25 Years
Pipe head loss			15%
Capacity			11 kW
Efficiency			80%

*Data collected from local distributors

index of anisotropy, β is angle of tilt (considered as 22.94°) (Choudhary and Akella 2022) and ρ is ground reflectance. The total power generated by the panel can be mathematically expressed as Eq. (4) (Masrur et al. 2021).

$$P_{PV} = R_{PV} Df \left(\frac{\overline{HT}}{HN} \right) [1 + \alpha(T_{PV} - T_S)] \qquad (4)$$

Here, P_{PV} is the total power generated by the panel (kW), R_{PV} is rated power of the panel (kW), HN is the insolation incident at test conditions(kW/m²), Df is the derating factor (%), α temperature coefficient (%/°C), T_{PV} is the temperature of solar cell (°C) and T_S is temperature of solar cell at test conditions (°C).

2.4.4 Biomass Energy (BI)

The sizing of biomass gasifier systems is done considering several parameters like efficiency (η_{BI}), operational hours/day (H_D), calorific value of fuel used (C_{BI} kJ/kg) and quantity of biomass available (T_Q Kg/year). The hourly generation of power using biomass gasifier system is shown in expression ((5)Malik et al. 2021).

$$P_{BI} = \frac{T_Q * C_{BI} * \eta_{BI} * \delta}{860 * 365 * H_D} \qquad (5)$$

P_{BI} is the total energy generated (kWh) and δ is the time step of 1 h.

2.4.5 Backup Genset (DG)

Deisel generator station have been employed to provide a backup supply. The rate of consumption of diesel can be computed using expression (6) (Malik et al. 2021).

$$C = F_C * R_{DG} + F_S * P_{DG} \qquad (6)$$

Here, F_C is coefficient of fuel curve intercept, R_{DG} is rated capacity of diesel generator station (Litres), F_S is the slope of the fuel curve and P_{DG} is the diesel generator output power (watt).

2.4.6 Storage (SU)

The power generated by renewable means cannot be matched with the demand, many times surplus power generation takes place, which has to be stored for usage during scarcity. Battery banks are included in the system to fulfil this purpose. When electricity generation exceeds demand, the surplus power stored in the battery bank is mathematically expressed as (7) and (8) (Malik et al. 2021).

$$E_B(t) = E_B(t-1) + E_X(t) * \eta_B * \eta_C \qquad (7)$$

$$E_X(t) = [E_{AG}(t) + E_{DG}(t) * \eta_C] - E_D(t) \qquad (8)$$

Here, $E_X(t)$ denotes the surplus energy from resources, $E_B(t-1)$ signifies the capacity of battery bank in the earlier stage, $E_{AG}(t)$ is generator output power, $E_{DG}(t)$ is power from a DC source, η_B is battery charging efficiency, η_C denotes converter efficiency. If the demand is greater than the generated power, scarcity is introduced and the storage bank will discharge to satisfy the same. The expressions (9) and (10) can be used for the computation of the storage capacity of battery bank.

$$E_B(t) = (1 - \upsilon) * E_B(t-1) - \left[\frac{E_{DD}(t)}{\eta_{DB} * \eta_C}\right] \qquad (9)$$

$$E_{DD}(t) = E_D(t) - [E_{AG}(t) + E_{DG}(t) * \eta_C] \qquad (10)$$

Here $E_{DD}(t)$ is the total deficit energy requirement, υ is the self-discharging rate/ hour and η_{DB} is the battery discharging efficiency.

2.4.7 Environmental and Economic Attributes

Various economic and environment-based parameters have been considered for the computation of TNC and LCE of all architectures. TNC, theoretically, is the total sum of all present figures of all the lifetime expenses minus the present value of all life time revenue. TNC and LCE can be calculated by expression (11) (Raji et al. 2021) & (12) (Turkdogan 2021).

$$TNC = ANC * \left[\frac{(1+R)^N - 1}{R * (1+R)^N}\right] \qquad (11)$$

$$LCE = \frac{ANC}{E_{AC}} \qquad (12)$$

Here, ANC is annualised cost (\$/year), R is the interest rate (%), N is life time of project (year) and E_{AC} is the AC load (kWh/year).

The CO_2 emission by the system is estimated by quantification using Eq. (13). It is considered that 1 g of CO_2 consists of 0.2962 g of carbon, thus 1 g of carbon is contained by 3.367 g of CO_2 (Al-Rawashdeh et al. 2023).

$$TE = 3.367 * Q_E * HV * Cf * CE_f \qquad (13)$$

Here, Q_E is the amount of diesel/fuel used in Ltrs., HV the heating value of fuel in MJ/Ltr., Cf denotes the oxidised carbon fraction, and CE_f is emission factor of carbon measured in ton carbon/TJ.

Renewable fraction (RF) is the percentage of energy generated by renewable sources and is mathematically expressed as (14) (Bahgaat 2023). Here P_{DG} is the diesel generator output power and P_{RS} is the power generated by renewable source (Figs. 3, 4 and 5).

$$RF = \left(1 - \frac{\sum P_{DG}}{\sum P_{RS}}\right) * 100 \qquad (14)$$

3 Results and Discussions

This section demonstrates the technical, economic, social and environmental aspects derived from the situation results of all the considered architectures.

3.1 Simulation and Optimization Outcomes

Eight different architectures of HEGS have been simulated in HOMER and the outcomes have been tabulated in Table 4. For each architecture four different cases have been studied with SU-DG, with SU without DG, with DG without SU and without SU-DG. A relative assessment of simulated finest configurations is achieved considering the following parameters: TNC, LCE, OC, II, RF, energy generation, SU life, Capacity shortage, total emission, fuel consumption, rectifier losses; with more emphasis on LCE, total CO_2 emission, and TNC.

Simulation and optimization results of Architecture 1 (PV-SH) hybridization shows that the design is not feasible in the absence of SU-DG, however if only DG is present the TNC, LCE and emissions are higher as compared to those when SU is present. The values of TNC (\$1,483,791) and LCE (0.303 \$/kWh) are better when both SU-DG are
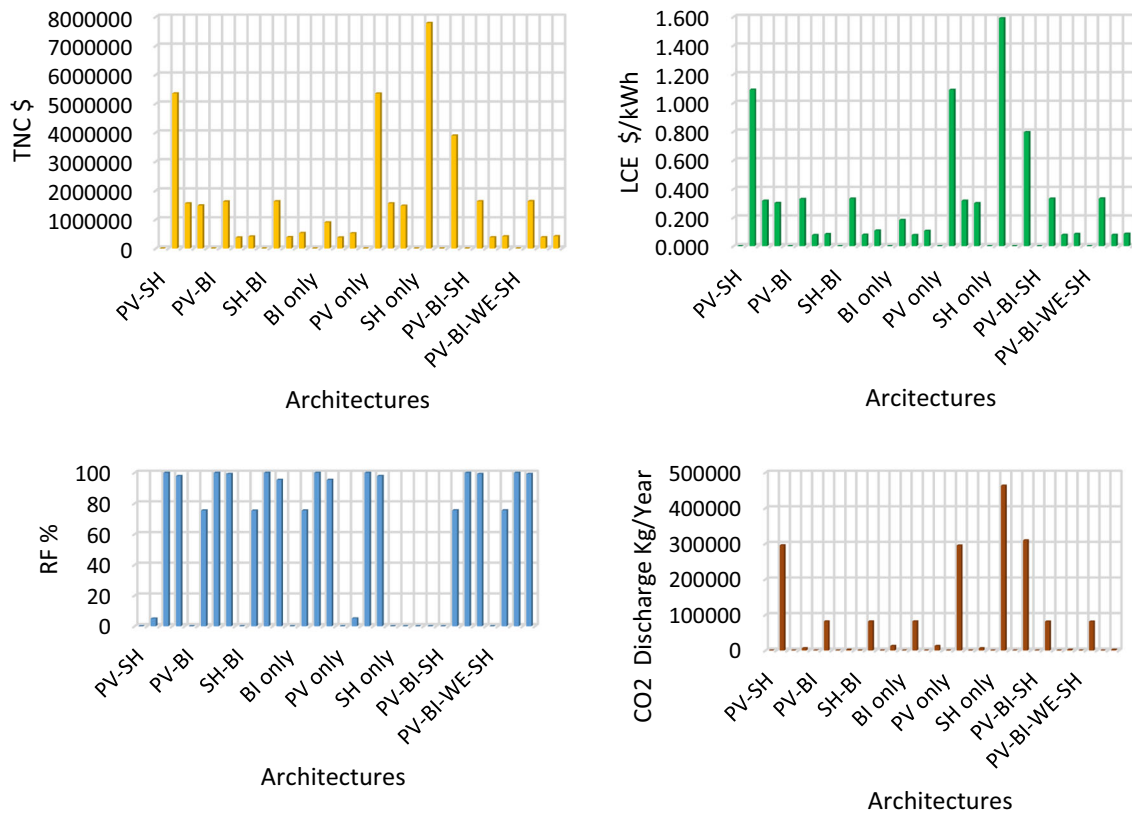
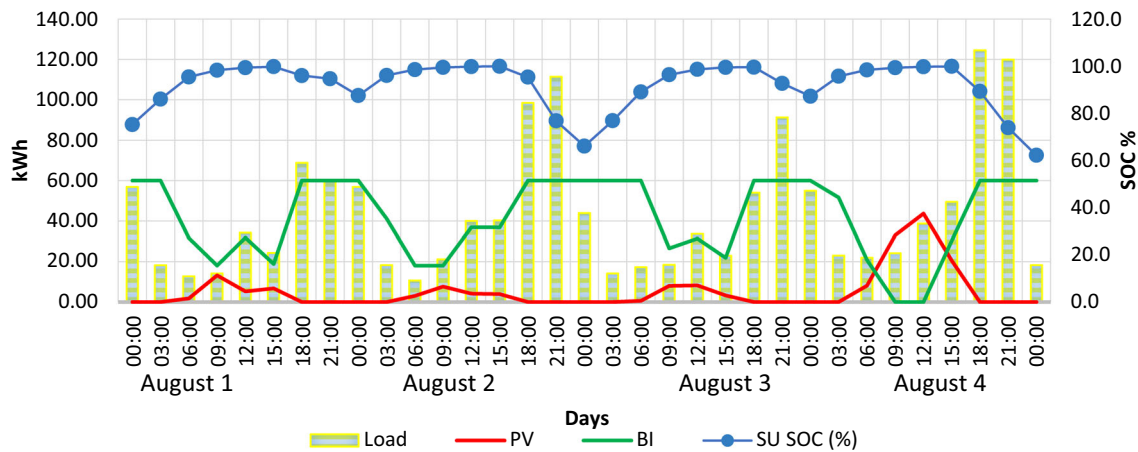**Fig. 3** TNC, LCE, RF and CO_2 discharge for various architectures

Fig. 4 Power generation pattern for a weekday in rainy season

present in the architecture, but the CO_2 emission is 6722 kg/year. On the other hand, if only the SU configuration is considered, the most optimal solution is obtained with 100% RF, CO_2 emission is reduced to 0. 49.3% of excess electricity is produced and 100% demand is met (Syahputra and Soesanti 2020; Kusakana and Munda 2009; Oladigbolu et al. 2020). The OC of this configuration is $ 66,807 which is the lowest of all. In the Architecture 2 (PV-BI) configuration has been considered, PV-BI-SU has

the best results among all the cases, with LCE as low as 0.077 $/kWh, TNC $ 380,415 and OC 18080 $/year. The RF here is 100% and the CO_2 emission of 83 kg/year. Only PV-BI is not feasible, and remaining both cases (PV-BI-DG and PV-BI-SU-DG) have higher LCE and TNC comparatively. Architecture 3 (SH-BI) gives a feasible solution for SH-BI-SU, SH-BI-DG and SH-BI-SU-DG cases. SH-BI-SU provides a comparable solution in terms of LCE (0.080 $/kWh) but TNC ($ 391,871), OC (19,512 $/year)
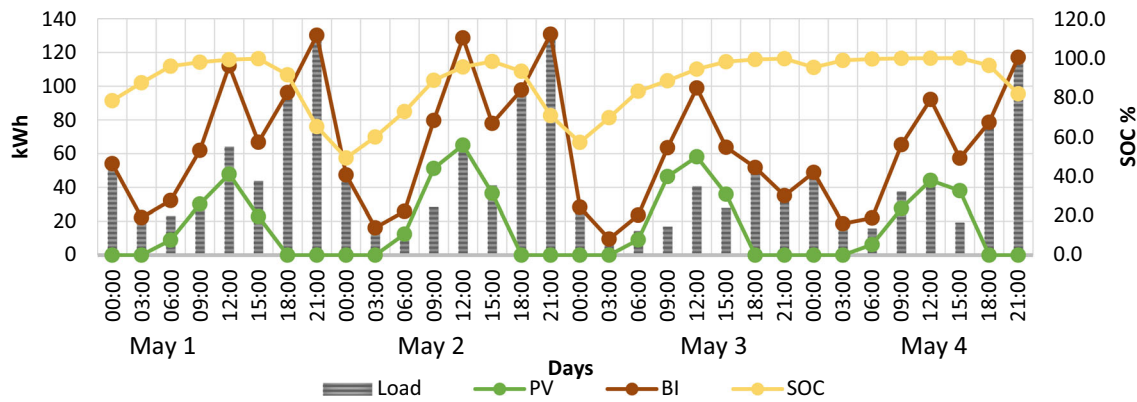
Fig. 5 Power generation pattern for a weekday in summer season

and CO_2 emission (97 kg/year) are comparatively higher. Architecture 4 (BI only) is not capable of meeting the required load for BI only; however BI-SU configurations can be a solution due to low LCE (0.078 $/kWh) for the study area but TNC ($ 383,737), OC (18,969 $/year) and CO_2 emission (96.5 kg/year) are slightly higher than their PV appended counterparts. Architecture 5 (PV only) is also not suitable for meeting the total demand of study area without appending SU-DG system. The most feasible design is PV-SU-DG, which has 0.30 $/kWh LCE and 1,475,156 $ TNC, however the fuel used is 2552 ltr/year and RF is 98.1% so a higher CO_2 discharge is expected. Architecture 6 (SH only) also provides feasible solution only when SU-DG or at least DG units are appended to the system, providing 0.79 $/kWh LCE and 3,898,479 $ TNC. This is because the area does not have enough flowing water resources available throughout the year. Only 11 Hydro power potential points are available, out of which 6 sites have discharge round the year; the rest are season dependent. Architecture 7 (PV-BI-SH) is one of the promising configurations when added to a storage unit SU. This design provides an estimate of 0.079 $/kWh LCE and 386,632 $ TNC with 100% RF, which is best among all the considered configurations. The OC of the system is 18,029 $, and CO_2 emissions are just 76 kr/year, which represents a 99.5% reduction as compared to conventional sources. The SU consists of 71 strings of 10 batteries, each with a 120 V rating, and is expected life is 10 years. 17.2% of power is generated by PV, 78.2% is generated by BI and the rest, 4.6% is generated by SH. Architecture 8 integrates all the renewable sources (PV-BI-SH-WE) with and without SU-DG addition. It can be inferred from the simulation results that amalgamation the of PV-BI-WE-SH configuration with SU provides the winning metrics with 389,225 $ TNC, 0.080 $/kWh LCE, 18,115 $/ year OC, and 155,055 $ II. 433 tons of biomass are used per year, which reduces the CO_2 discharge by 99%.

It can be inferred from Table 4 that architectures involving SU are quite economical as compared to their without-SU counterparts. The reason is the requirement of high-capacity energy generation units to satisfy the demand without SU, which in turn increases operational-maintenance expenses. Analysing the results, it can be concluded that architecture 2, PV-BI-SU, has the most promising energy solution for the study area as compared to architecture 4,6, and 8. It has lowest TNC, LCE, OC and II among the 4. The LCE is quite low as compared to other works in the literature available and is comparable to grid tariff (0.07 $/kWh) of the area ("JBVNL" 2023). The CO_2 discharge reduction ($\sim$ 99%) is also promising for this configuration. Moreover, comparing the PV-BI-SU, BI-SU, PV-BI-SH-SU and PV-BI-SH-WE-SU architectures, it is deduced the BI ($\sim$ 69.7%) and PV ($\sim$ 30.3%) have the maximum share in generation of power, while WI and SH generate a very low amount of electricity and are not functional throughout the year. Hence, set up of SH and WI units requires more capital with a low payback hence cannot be considered feasible. Thus, there is a potential for development of economical and green HEGS in these regions. A decentralized system, including PV-BI-SU, can be the best substitute of conventional energy generation mediums since both the resources are available in ample amount in this region. Moreover, due to comparable LCE, rural consumers can easily be convinced for the implementation of the proposed system against grid. In the coming time, with government backing and amendment to policies, such type of systems could be a striking choice for home-grown public. Thus, the remaining analysis is done for architecture 2.

3.1.1 Techno-Economic and Environmental Analysis of Architecture 2 (PV-BI-SU)

PV-BI-SU configuration is found to be optimum for the study area. Figure 6–8 shows the pattern of power

Table 4 Simulation details of considered architectures

| Architectures	SU Nos	DG (kW)	PV (kW)	WE (kW)	SH (kW)	BI (kW)	Conv. (kW)	Strategy	TNC ($)	LCE ($/kWh)	OC ($/year)	II ($)	RF (%)	Diesel ltr./year	Biomass (ton/year)	CO_2 Discharge Kg/Year
PV-SH	0	0	0	0	0.0	0	0	0	0	0.000	0	0	0	0	0	0
	0	210	1667	0	11.0	0	102	CC	5,351,913	1.093	382,809.2	403,140.1	5	113,030.8	0	295,871.2
	3110	0	1162	0	11.0	0	191	CC	1,557,998	0.318	59,801.57	784,912.3	100	0	0	0
	2300	210	713	0	11.0	0	189	LF	1,483,791	0.303	66,807.36	620,137.8	98	2567.848	0	6721.638
PV-BI	0	0	0	0	0.0	0	0	0	0	0.000	0	0	0	0	0	0
	0	210	5	0	0.0	80	1	CC	1,620,294	0.331	120,289.5	65,249.2	75	31,260.29	481	81,910.61
	710	0	49	0	0.0	80	110	CC	380,414.6	0.077	18,079.65	146,689.6	100	0	480	82.98035
	510	210	161	0	0.0	80	98	LF	413,981.2	0.085	16,980.61	194,464.1	99	929.6251	362	2496.006
SH-BI	0	0	0	0	0.0	0	0	0	0	0.000	0	0	0	0	0	0
	0	210	0	0	11.0	80	1	CC	1,628,614	0.333	120,870.6	66,056.65	75	31,295.8	483	82,003.88
	700	0	0	0	11.0	80	128	CC	391,871	0.080	19,511.12	139,640.7	100	0	558	96.44939
	580	210	0	0	11.0	80	93	CC	533,558.4	0.109	27,637.79	176,270.5	95	4877.124	544	12,860.6
BI only	0	0	0	0	0.0	0	0	0	0	0.000	0	0	0	0	0	0
	0	210	0	0	0.0	80	0	LF	902,445	0.184	61,489	107,550	75	31,296	483	82,004
	720	0	0	0	0.0	80	107	CC	383,736.7	0.078	18,968.93	138,515.5	100	0	558	96.45612
	580	210	0	0	0.0	80	93	CC	525,298.8	0.107	27,149.79	174,319.5	95	4877.124	544	12,860.6
PV only	0	0	0	0	0.0	0	0	0	0	0.000	0	0	0	0	0	0
	0	210	1687	0	0.0	0	127	CC	5,349,087	1.092	382,202.9	408,152.7	5	112,852.3	0	295,403.9
	3660	0	985	0	0.0	0	193	CC	1,558,709	0.318	55,407.25	842,430.9	100	0	0	0
	2300	210	712	0	0.0	0	191	LF	1,475,156	0.301	66,285.98	618,242.9	98	2551.99	0	6680.125
SH only	0	0	0	0	0.0	0	0	0	0	0.000	0	0	0	0	0	0
	0	210	0	0	11.0	0	7	CC	7,788,636	1.590	597,366.9	66,165.2	0	177,098.5	0	463,575.8
	0	0	0	0	0.0	0	0	0	0	0.000	0	0	0	0	0	0
	1320	210	0	0	11.0	0	102	CC	3,898,479	0.796	278,122.8	303,042.2	0	118,288.5	0	309,633.7
PV-BI-SH	0	0	0	0	0.0	0	0	0	0	0.000	0	0	0	0	0	0
	0	210	32	0	11.0	80	6	CC	1,629,168	0.333	120,375.9	73,006.2	76	31,082.77	475	81,444.96
	700	0	81	0	11.0	80	113	CC	386,632.4	0.079	18,028.62	153,567.1	100	0	435	75.1811
	510	210	159	0	11.0	80	94	LF	421,584.3	0.086	17,477.22	195,647.2	99	947.4583	363	2542.791
PV-BI-WE-SH	0	0	0	0	0.0	0	0	0	0	0.000	0	0	0	0	0	0
	0	210	28	1	11.0	80	7	CC	1,632,130	0.333	120,565.5	73,518.11	76	31,116.6	474	81,533.32
	700	0	82	1	11.0	80	113	CC	389,224.8	0.080	18,114.09	155,054.5	100	0	433	74.81998
	510	210	163	2	11.0	80	95	LF	427,454.1	0.087	17,691.2	198,750.8	99	946.5062	361	2540
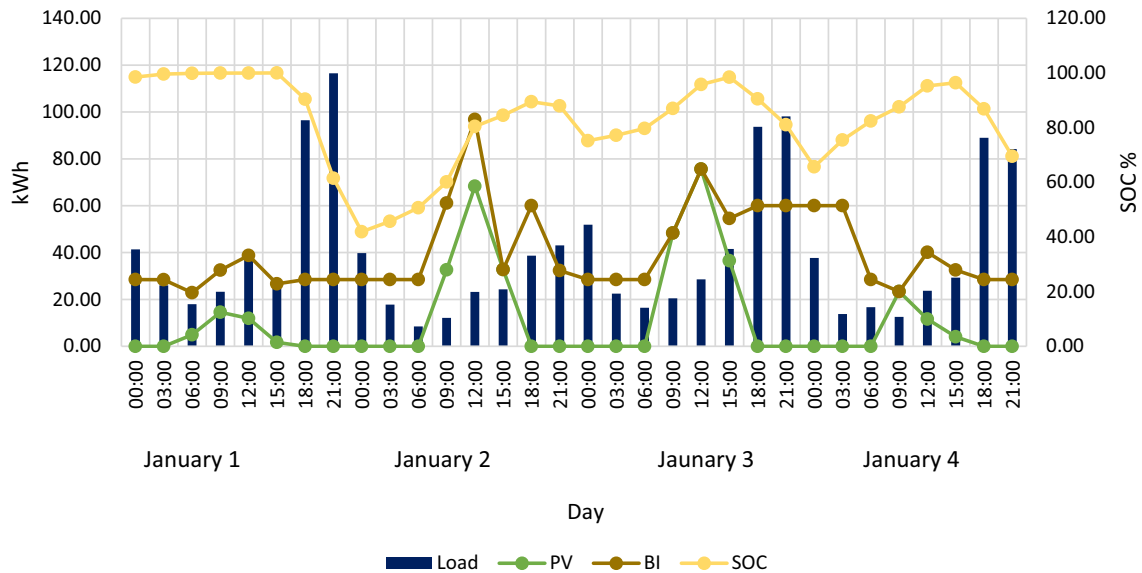
Fig. 6 Power generation pattern for a weekday in winter season

generation from both the sources layered over the demand and the state of charge of storage unit. 69.7% of power is generated by biomass, and remaining 30.3% is accounted for by PV units, generating 427,820 kWh/year against the demand of 378,624 kWh/year and the unmet load being 231 kWh/yr, which is merely 0.06%. In the rainy season, the PV output is low and is available only during the daytime; the rest of the load is met BI generation system. It can be seen that during the night, power is supplied by the SU.

In the summer season, a large amount of solar insolation can be used for energy generation, as can be seen in the Fig. 5. Most of the load during the day is met by PV only, and during the night, BI feeds the demand. A good amount of excess electricity is produced during this time period of the year that can be stored for future use. In the winter season, PV functions better during the sunshine hours, meeting maximum share of the load, and rest is fulfilled by the BI and SU. The SOC varies 40–100% throughout the year, with higher variation in winter because of increased load demand and lower power generation due to less sunshine hours and low biomass availability in winter as compared to summer and rainy seasons. The capacity of the PV unit is 48.6 kW, while that of the BI is 80 kW, and a 110 kW converter is used to implement the cycle charging electrical dispatch strategy. For storage purposes, 71 strings of 10 units of 1 kWh LA batteries have been used.

Figure 7 shows the monthly average power generation by architecture 2 involving PV-BI system. Substantial amount of energy can be generated by the PV system in the months of Jan – May, due to the clear sky and large amount of sunshine available. This value is quite low during the

rainy season in the months of Jun, Jul and Aug. due to cloudy weather.

Nominal cash flow for a period of 25 years of the most promising architecture for the study area is shown in Fig. 8. The cash flow analysis shows that BI has the highest capital and replacement cost; it has to be replaced when a lifetime (20,000 h) is completed. However, the PV array has an operation-maintenance cost of about 18,080 $ due to the necessity of periodical cleaning. The replacement cost, too, has a significant share in the overall cost analysis of the system. In the proposed architecture, SU has the biggest share of 107,070 $. Thus, improvements in storage technology and lifetime could further result in a reduction in overall systems costs.

During the analysis of environmental benefits, it was found that the proposed system produces a cleaner environment due to minor discharge during energy generation procedure. These pollutants harm the ecosphere to a great extent, so efforts are required to reduce the discharge of such gases. The carbon dioxide percentage in the atmosphere is higher as compared to other gases, so reducing it is more important so as to reduce the carbon footprint. Figure 9 shows the % share of various discharge materials comparing the proposed architecture to the base architecture (DG only system).

3.1.2 Sensitivity Analysis of Architecture 2 (PV-BI-SU)

Sensitivity analysis have also been done for the proposed architecture in order to examine the uncertainty of proposed HEGS. Numerous input parameters were varied to analyse the impact on TNC and LCE of the proposed system. The input constraints considered were variation in

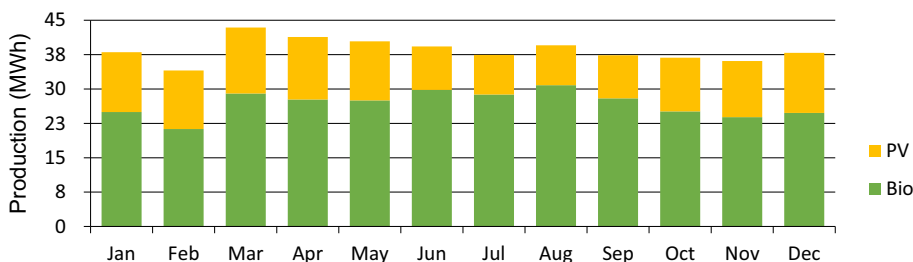**Fig. 7** Monthly energy generation share of PV-BI in architecture 2

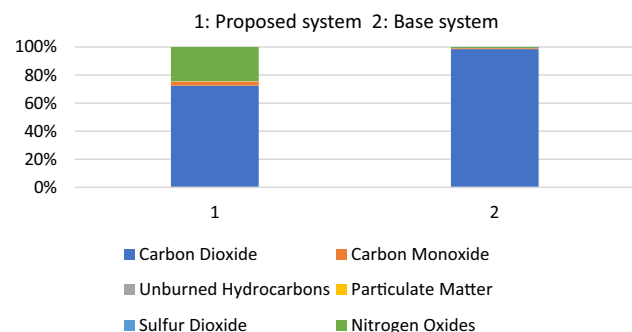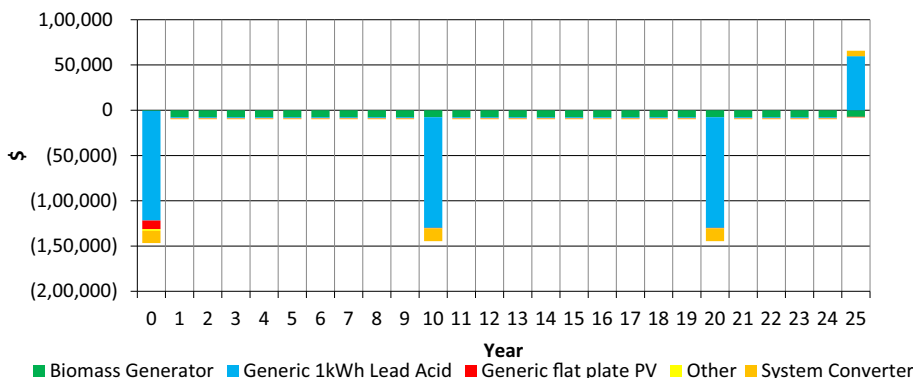**Fig. 8** Nominal cash flow of proposed architecture

Fig. 9 % share of emissions proposed vs base architecture

load, PV derating factor, annual interest rate, biomass rate, BI lifetime, gasification ratio, and annual capacity shortage. The impact of these variations is shown in Fig. 10–15.

The proposed HEGS has to be developed in order to compensate for the variation in demand over a period of time. Figure 10 shows the variation of load from 1037.96 to 1050 kWh/d, and simultaneous deviations in TNC and LCE has been estimated. It is worth noticing that load variation has greater effect on TNC as compared to LCE. The derating factor of a PV array should be high for better power generation. Hence, its variation has to be studied for optimal system design. The effect of a change in derating factor on TNC and LCE is depicted in Fig. 11. Both parameters decrease with an increasing derating factor. The price of Biomass also affects the system's economics adversely, as the major generation is done using the BI system. Figure 12 shows the changes in TNC and LCE as the price of biomass varies. A Capacity shortage is another

important factor for an improved system. To judge the system performance, capacity shortage has been varied from 0 to 30% and it has been estimated that TNC and LCE drop down with increasing capacity shortage % as shown in Fig. 13. Upon variation in nominal discount rate, it has been seen that the LCE was directly proportional while the TNC was inversely proportional as the discount rate was varied from 6 to 15% as shown in Fig. 14. BI life time and gasification ratio also affect the system performance, as both should be high for viability. The replacement cost can cut down on the TNC, and this can be done by increasing the operation lifetime. BI gasification ratio, on the other hand, is related to the efficiency of the system. Hence, these factors are studied, and inverse proportionality has been discovered for both TNC and LCE as per Fig. 15.

4 Comparison with Available Literature

This section focusses on the comparison of results obtained from similar studies available in the literature with the proposed HEGS. This comparison of LCE of similar architectures at different locations are shown in Table 5. It can be seen that the LCE of proposed architecture is quite promising and competitive among all. Thus, for the considered study location, the proposed system is quite feasible both in terms of economic and environmental metrics.
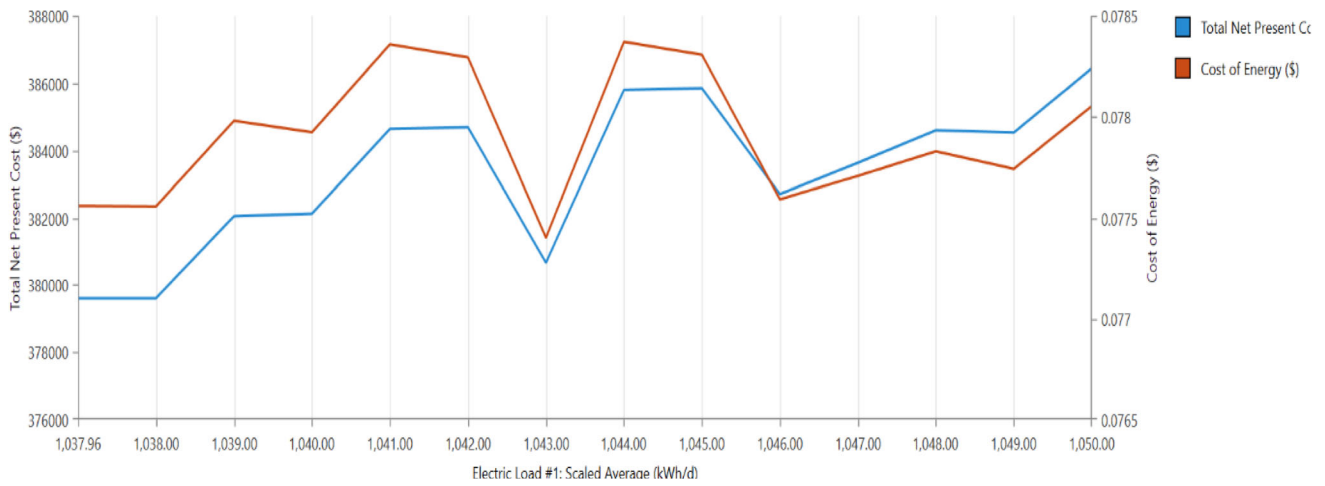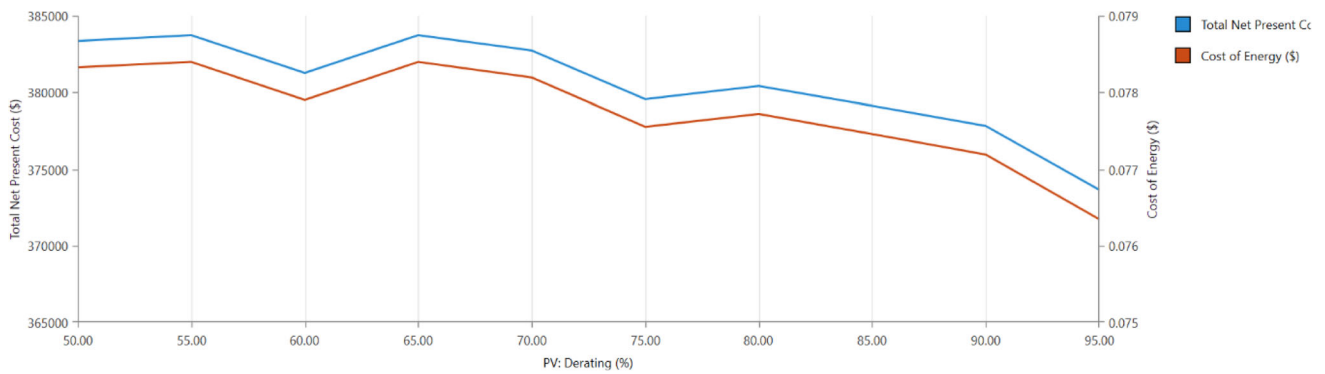
Fig. 10 Effect of load on TNC and LCE

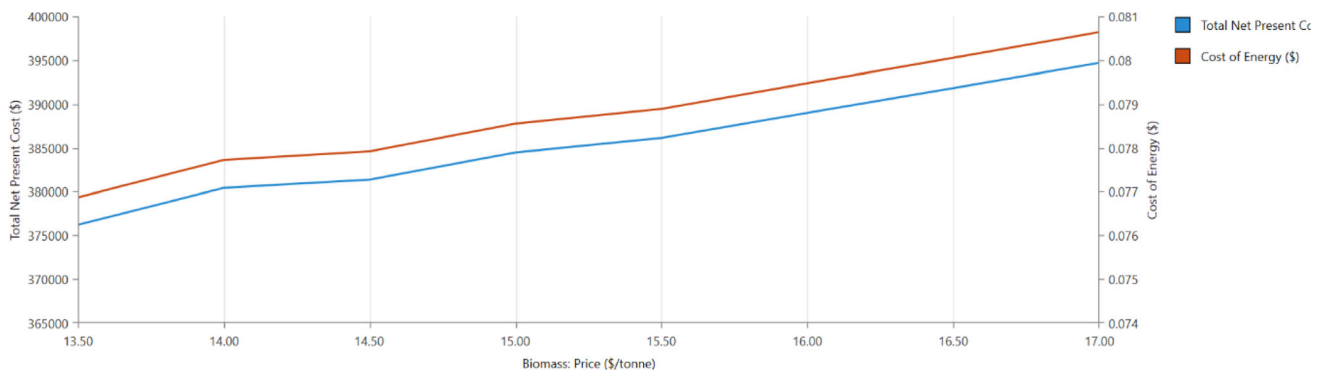**Fig. 11** Effect of PV derating factor on TNC and LCE

Fig. 12 Effect of Biomass price on TNC and LCE

5 Conclusion

In this work, eight different hybrid energy generation models have been studied technically, economically and environmentally with the combination and absence of storage and backup genset unit for a cluster of 10 villages located in the tropical plateau region of India. The most economical and optimal architecture has been identified for implementation purposes. Following are the concluding remarks of this study:

i. In tropical highlands, the resource assessment of renewable means exposed that, due to deciduous vegetation ample amount of unutilized biomass reserves are present; moreover, the area receives ample amount of sunlight for PV utilization as well.
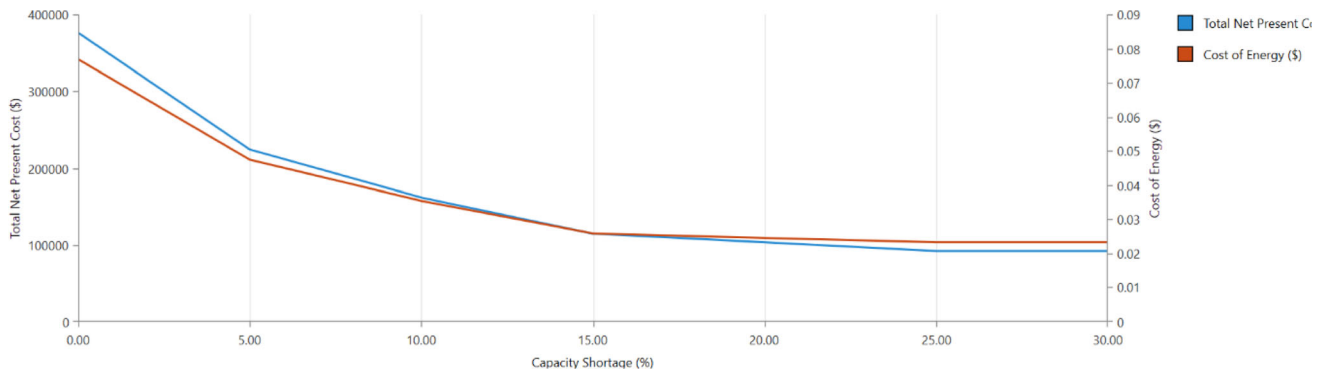
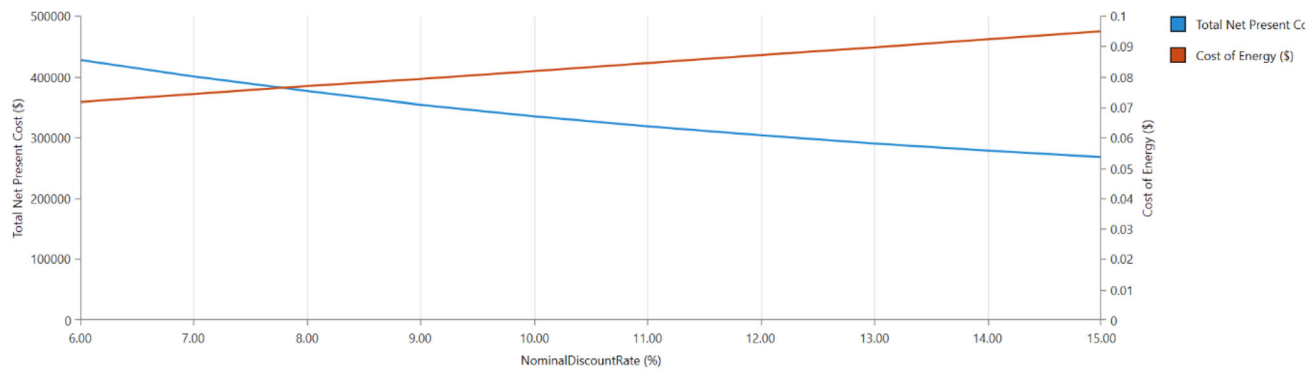**Fig. 13** Effect of Capacity shortage on TNC and LCE

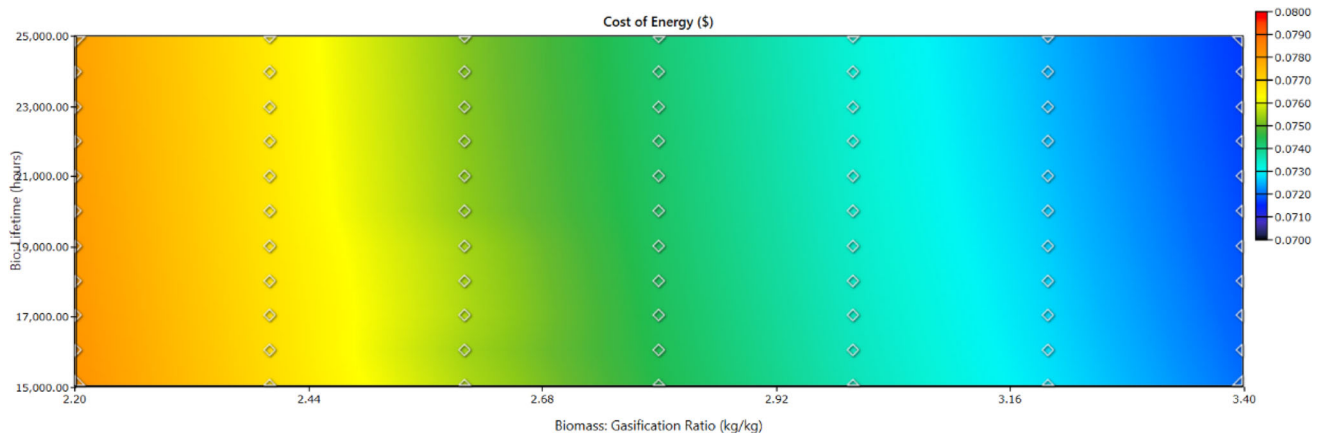**Fig. 14** Effect of Discount rate on TNC and LCE

Fig. 15 Effect of BI life and gasification ratio on TNC

However, wind energy potential is not very promising.

ii. Eight different hybrid models have been analysed, and PV-BI-SU was found to be the most appropriate one for implementation in the study area to ensure 100% electrical supply in domestic, agricultural and commercial sectors. For a cluster of 10 villages, the optimum model consists of PV of 48.6 kW, BI of 80 kW, converter of 110 kW and 710 unit of 1kWh LA batteries. 30.3% (106,240 kWh/year) of power is generated by PV and the remaining 69.7% (321,580 kWh/year) is generated by Biomass generators.

iii. The optimal architecture suggests the most promising LCE of 0.77 $/kWh at a TNC of $ 380,415, II of $ 146,690, and OC of $18,080. These figures are far more competitive as compared to other models present in the literature.

iv. Ecological analysis suggests that the total GHG emissions of the proposed system are quite low i.e. 99% less those of a diesel model.

Table 5 Comparison of LCE of proposed system with similar architectures

S.No	Location	Architecture	LCE ($/kWh)	Load (kWh/day)	Reference
1	Chandil, India	PV-BI-SU	0.077	1037.96	Proposed
2	Hamirpur, India	PV-BI	0.18	87.6	Malik et al. 2021)
3	North-West Iran	PV-BI-FC	0.163	361	Ma and G. R et al.., 2020)
4	Chamarajanagar district, India	PV-WE-BI-FC	0.214	724.83	Murlidhar et al. 2020)
5	Uttarakhand, India	PV-BI-SH-SU	0.09	1569	Saini and Chauhan 2016)
6	Nampula, South Africa	PV-BI	0.33	81	Garrido and Brito 2016)
7	Monshaet Taher, Egypt	GRID-PV-BI	0.09	2340	Barakat et al. 2016)
8	Adorsho Char, Bangladesh	PV-BI-DG	0.22	181	Salehin et al. 2014)
9	Garissa, Kenya	PV-WE-BI	0.25	200	Sg and P. R et al.., 2015)

v. Sensitivity analysis suggests that the proposed architecture is more sensitive when the annual discount rate, price of biomass, capacity shortage, and gasifier lifetime are varied.

The proposed decentralized HEGS has confirmed techno-economic-ecological feasibility in remote area of tropical highlands. Utilization of enormous reserves of biomass available in dense forests will not only minimize the GHG discharge but also help in curtailment of forest fires and hamper of green vegetation, and obviously will prove to be an excellent key to the alternate energy target of India and create employment for local resides as well. Furthermore, such research also provides insight for future biomass-based studies and implementation in tropical areas of Indian subcontinent and other parts of the world with similar landscape. Simulation of on-grid HEGS for the region is also required, along with practical implementation, to understand the practical challenges and explanations.

Declarations

References

Adhikari D, Saxena R (2009) Biomass based energy fuel through biochemical routes: a review. Renew Sustain Energy Rev 13(1):167–178

Agarwal S, S. Mani, A. Jain and K. Ganeshan, "State of Electricity Access in Indi: Insights from the India Residential Energy Survey (IRES 2020)," Council on Energy, Environment and Water., New Delhi, 2020.

Al-Rawashdeh H, Al-Khashman OA, Arrfou LM, Gomaa MR, Rezk H, Shalby M, Louzazni M (2023) Different scenarios for reducing carbon emissions, optimal sizing, and design of a stand-alone hybrid renewable energy system for irrigation purposes. Int J Energy Res. https://doi.org/10.1155/2023/6338448N

Awasthi M, Sinha S, Malik P (2020) Study of grid integrated biomass-based hybrid renewable enrgy systems for Himalayan terrain. Int J Sustain Energy Plan Manage 28:71–88

Bahgaat NK (2023) Estimation of renewable energy systems for mobile network based on real measurements using HOMER software in Egypt. Sci Rep 13:16713. https://doi.org/10.1038/s41598-023-43877-2L

Barakat S, Samy M, Magdy B, Wael I (2016) Feasibility study of grid connected PV-Biomass integrated energy system in Egypt. Int J Emerg Electr Power Syst 17(5):519–528

Blume-Werry E, Everts M (2022) Hydropower. In: Hafner, M., Luciani, G. (eds), The Palgrave Handbook of International Energy Economics, Palgrave Macmillan, Cham, 2022. https://doi.org/10.1007/978-3-030-86884-0_8

Bojek P (2023) Renewable electricity: More efforts needed," [Online]. Available: https://www.iea.org/reports/renewable-electricity. Accessed 15 June 2023

Chandel S, Srivastava R, Sharma V, Ramasamy P (2016) Overview of the initiatives in renewable energy sector under the national action plan on climate change in India. Renew Sustain Energy Rev 54:866–876

Choudhary P and Akella A, (2022) Tilt angle optimization for maximization of solar irradiance for a Photo- Voltaic panel for Chandil, Jharkhand, Journal of Engineering Research, pp. 1–15

Chowdhury N, Hossain CA, Longo M (2019). State of art on possibility and optimization of solar PV-wind hybrid system. In: 2019 International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST) (pp. 598-601). IEEE.

Dash V, Bajpai P (2012) Hybrid renewable energy systems for power generation in standalone applications: a review. Renew Sustain Energy Rev 16(5):2926–2939

Dei T, Batjargal N (2022) Technical and economic evaluation of micro solar PV/ diesel hybrid generation system for small demand. Int J Renew Energy Develop 11(4):1101–1112

Garrido H, Brito M (2016) Feasibility of KUDURA hybrid generation system in Mozambique: sensitivity study of the small-scale PV-biomass and PVdiesel power generation hybrid system. Renew Energy 92:47–57

"http://www.nrel.gov/homer/," [Online]. [Accessed 30 6 2023].

"https://censusindia.gov.in/census.website/data/population-finder," [Online]. [Accessed 30 6 2023].

"JBVNL," [Online]. Available: https://jbvnl.co.in/tariff.php. [Accessed 29 6 2023].

Khan B (2006) Non-conventional energy resources. Tata McGraw Publishing Company Limited, New Delhi

Kusakana K, Munda JL, Jimoh AA (2009). Feasibility study of a hybrid PV-micro hydro system for rural electrification. In: AFRICON 2009 (pp. 1-5). IEEE..

Kushana K (2014) Techno-economic analysis of offgrid hydro kinetic based off grid energy systems for onshore/remote area in South Africa. Energy 15(68):947–957

Kusiak A, Zheng H, Song Z (2009) On-line monitoring of power curves. Renewable Energy 34(6):1487–1493. https://doi.org/10.1016/j.renene.2008.10.022

Li C, Zhou D, Wang H, Lu Y, Li D (2020) Techno-economic performance study of stand-alone wind/diesel/battery hybrid system with different battery technologies in the cold region of China. Energy 192:116702

Malik P, Awasthi M, Sinha S (2020) Study on an existing PV/wind hybrid system using biomass gasifier for energy generation. Pollution 6(2):335–346

Malik P, Awasthi M, Sinha S (2021) Techno-economic and environmental analysis of biomass-based hybrid energy systems: a case study of a Western Himalayan state in India. Sustain Energy Technol Assess 45:101189

Masrur H, Konneh KV, Ahmadi M, Khan KR, Othman ML, Senjyu T (2021) Assessing the techno-economic impact of derating factors on optimally tilted grid-tied photovoltaic systems. Energies 14:1044. https://doi.org/10.3390/en14041044

Muljadi E, Butterfield C (2001) Pitch-controlled variable-speed wind turbine generation. IEEE Trans Ind Appl 37(1):240–246

Naves D, Silva C, Connors S (2014) Design and implementation of hybrid renewable energy systems on micro-communities: a review on case studies. Renew Sustain Energy Rev 31:935–946

"NREL," [Online]. Available: https://nsrdb.nrel.gov/. [Accessed 30 6 2023].

Odetoye OA, Olulope PK, Olanrewaju OM, Alimi AO, Igbinosa OG (2023) Multi-year techno-economic assessment of proposed zero-emission hybrid community microgrid in Nigeria using HOMER. Heliyon 9(9):e19189

Oladigbolu JO, Ramli MAM, Al-Turki YA (2020) Optimal design of a hybrid PV solar/micro-hydro/diesel/battery energy system for a remote rural village under tropical climate conditions. Electronics 9(9):1–22

Panda A, Dauda A, Hua HC, Tan R, Aviso K (2023) Recent advances in the integration of renewable energy sources and storage facilities with hybrid power systems. Clean Eng Technol 12:100598

"PIB," Dec 2021. [Online]. Available: https://pib.gov.in/Pressrelease share.aspx?PRID=1778914. [Accessed 30 6 2023].

Rad MAV, Ghasempour R, Rahdan P, Mousavi S, Arastounia M (2020) Techno-economic analysis of a hybrid power system based on the cost-effective hydrogen production method for rural electrification, a case study in Iran. Energy 190:116421

Raji L, Zhigilla YI, Wadai JR (2021) Using homer software for cost analysis of stand-alone power generation for small scale industry in nigeria: a case study lumatec aluminium products. Int J Appl Technol Res 2(2):90–102

Saini R, Chauhan A (2014) A review on integrated renewable energy system based power genration for standalone applications: configurations, stprage options, sizing methodologies and control. Renew Sustain Energy Rev 38:99–120

Saini R, Chauhan A (2015) Renewable energy based off-grid rural electrification in Uttarakhand State of India: technology options, modelling method, barriers and recommendations. Renew Sustain Energy Rev 51:662–681

Saini R, Chauhan A (2016) Discrete harmony search-based size optimization of integrated renewable energy system for remote rural areas of Uttarakhand state in India. Renew Energy 94:587–604

Salehin, S., Islam, A. S., Hoque, R., Rahman, M., Hoque, A., & Manna, E. (2014, May). Optimized model of a solar PV-biogas-diesel hybrid energy system for Adorsho Char Island, Bangladesh. In: 2014 3rd International Conference on the Developments in Renewable Energy Technology (ICDRET) (pp. 1-6). IEEE.

Samaoi M, Abdelkafi A, Krichen L (2015) Optimal sizing of standalone photovoltaic/wind/hydrogen hybrid system supplying a desalination unit. Sol Energy 120:263–276

Shukla KN, SarojRangnekar K, Sudhakar, (2015) Comparative study of isotropic and anisotropic sky models to estimate solar radiation incident on tilted surface: a case study for Bhopal, India. Energy Rep 1:96–103. https://doi.org/10.1016/j.egyr.2015.03.003

Sigarchian SG, Paleta R, Malmquist A, Pina A (2015) Feasibility study of using a biogas engine as backup in a decentralized hybrid (PV/wind/battery) power generation system–Case study Kenya. Energy 90:1830–1841

Sinha S, Chandel S (2015) Prospects of solar photovoltaic–micro-wind based hybrid power systems in western Himalayan state of Himachal Pradesh in India. Energy Convers Manage 105:1340–1351

Sinha S, Raina G (2019) Outlook on the Indian scenario of solar energy strategies: policies and challenges. Energ Strat Rev 24:331–341

Stehlik P, (2011) Modelling, simulation and optimization in waste/Biomass-to- energy processes. In: IEEE International Conference on modelling, simulation and applies automation, 2011.

Syahputra R and Soesanti I, (2020) Planning of Hybrid Micro-Hydro and Solar Photovoltaic Systems for Rural Areas of Central Java, Indonesia," Journal of electrical and computer engineering, pp. 1–16, 2020.

Thambi SBAFO, (2018) India's Energy and Emissions Outlook: Results from India energy model," [Online]. Available: http://pure.iiasa.ac.at/id/eprint/15536/1/India%E2%80%99s-Energy-and-Emissions-Outlook.pdf.. [Accessed 20 6 2023].

Turkdogan S (2021) Design and optimization of a solely renewable based hybrid energy system for residential electrical load and fuel cell electric vehicle. Eng Sci Technol, Int J 24(2):397–404. https://doi.org/10.1016/j.jestch.2020.08.017

Vendoti S, Muralidhar M, Kiranmayi R (2021) Techno-economic analysis of off-grid solar/wind/biogas/biomass/fuel cell/battery system for electrification in a cluster of villages by HOMER software. Environ Dev Sustain 23:351–372

X. Wang, (2010) Comparative Analysis of Biomass Power Generation," In: IEEE Power and Energy Engineering Conference, Asia-Pacific

Zhang X, Lihui W, He J, Jing TL, Zong F (2017) A multiobjective robust scheduling optimization mode for multienergy hybrid system integrated by wind power, solar photovoltaic power, and pumped storage power. Math Prob Eng 2017:1–15