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

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Received: 09.07.2023 Accepted:18.08.2023

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 of power. This research proposes such a biomass-based energy generation system, that can cater the power needs of remote areas in tropical deciduous forests. A simulation and techno-economic and environmental investigation of eight hybrid energy generation architectures have been carried out. Solar Photo Voltaic-Biomass-Storage Unit model was found to be the most appropriate system to cater the domestic, agricultural and commercial demand of a cluster of 10 villages in tropical highlands of India. This configuration proposes levelized cost of energy (0.077 $/kWh) at and computed net cost of $ 380415. 30.3% (106240 kWh/year) of power is generated by Solar Photo Voltaic and remaining 69.7% (321580 kWh/year) by Biomass generator. Environmentally, the proposed architecture predicts a cut down of Green House Gases (CO_2) emissions to mere 82 kg/year. The results can help policy makers, researchers and designers on the latest constraints as well as policies for Solar Photo Voltaic-Biomass based systems.

Keywords Renewable Energy, Hybrid Energy Systems, Biomass, Solar Photovoltaics, Green House Gases.

1. Introduction

Energy is a term that regulates the world. Growth in one leading to growth in all has led to an unimaginable hype in need and demand of energy for sectors widespread be it commercial or domestic blindly leading to superfluous exploitation of its sources towards the fulfilment of the same. Unquestionably this is proving hazardous for the environment. To reduce the dependency on natural reservoirs for energy, alternative resources act as a solution. Several factors like lower emissions, remote area expediency, declining capital and operating expenses have obligated to accentuate renewable sources for energy generation [1, 2, 3,49,50]. For now, about 23-24% of total global energy production comes from renewable resources (15.2%-hydro power, 7.5%-wind energy, 2.4%-bio power, 4.5%-solar PVs, 0.4% others) [4,51,52]. Promotion of green energy assures amplified job opportunities, expansion in infrastructure and betterment in health condition by reducing the emissions otherwise released by energy generation units [5, 6]. It has been projected that increase in the usage of renewables for energy generation to 45 % can reduce the CO_2 emission by 11% [7]. In rural terrain the naturally replenishable energy sources like sun, wind, small water bodies and biomass reserves can be utilized for electricity generation in decentralised mode to fulfil the energy needs. In developing realms like India, around 70% people are rural residents and only 18% have non interrupting electrical supply [8]. To ensure the escalation of electrification, the Government of India has launched numerous schemes like IPDS (Integrated

Power Development Scheme) (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 energy saving of 8.24 billion kWh/year with circumvented peak demand of 1,374 MW and assessed GHG emanation lessening of 5.68 Mt CO_2 /year, Gram UJALA (Mar 2021) for replacement of old bulbs with LED lamps saving 467 million kWh/year [9]. IRES (Indian Residential Energy survey) 2020 suggests that 2.4% of households in Indian subcontinent are still deprived of electricity while remaining 97.6% receive power for 20.6 hours/day on an average. This figure is still low, 18 hours/day in eastern periphery in the states of Bihar, Jharkhand, Odisha & West Bengal [10].

Erratic presence of renewable resources in remote villages is one of the major hurdles in their utilization for sustainable power generation. However, unification of two or more, such naturally occurring and imperishable means of energy production can unravel the problem of grid extension and maintenance costs, intermittency of non-conventional sources, power reliability, system performance and production costs [11, 12]. In India, the potential of renewable energy technologies [13] was documented in the early 1970's, the nation is equipped with one of the world’s most extensive programme 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 “National Wind-Solar Hybrid Policy” to promote and optimize the usage of renewables in power generation sector emphasizing on wind and solar photovoltaic units [14]. But due to sporadic distribution of wind throughout the geography, power generation demands cannot be fulfilled in all the areas. Also, India as a geography, is full of natural vegetation, which opens biomass and water-based energy systems comparatively feasible [15].

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. [16] investigated viability of various hybrid systems incorporating different battery technologies and deduced that Zn-Br batteries are economic as compared to Li-ion and Pb-acid. Murlidhar et al. [17] explored the economic and technical analysis of HRES to compute optimum solution of electricity supply to remote villages of India. Several authors [18] 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. [19] endorsed integration of biomass gasifiers with PV-WE systems for cost cutting. Chouhan recommended [20] an optimized model for 48 hamlets of Chameli district of Uttarakhand, India. Dei and Batjargal [21] evaluated PV-DG hybrid system for smaller loads on technical and economical parameters. Hasan et al. [22] assessed PV-WE systems with diverse running strategies of grid-tied and standalone system. Panda and Dauda [23] presented a comprehensive review on research regarding storage integrated hybrid systems, their real time operative analysis and solution policies. Lihui Xin et al. [24] 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 utilizing biomass has been attempted by the authors, furthermore they also compared the economic and applications scope of biomass co-combustion power generation techniques. The outcomes showed the direct fired generators had higher efficiency and unit investment and 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 [25]. 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 [26]. 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 not increasing the investments [27]. Critically 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 [28]. Salehin et al. [29] presented HRES system for isolated island in Bangladesh. Sigarchian et al. [30] 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 design and development of hybrid energy systems in both on and off grid mode [31]. Eight different architectures were considered based on local renewables available, and CO_2 emission was also calculated for all the architectures to analyse 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) have been chosen as a case study from the state of Jharkhand, India. The villages are located in the tropical region of Chhota Nagpur plateau covered with dry deciduous forests. Due to this ample amount of biomass is available in the region throughout the year along with the region receives ample amount of sunlight which 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 to choose 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.

2. Research Contributions

Novelties of this research gets 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 in India as a case study. c) Sizing and cost estimation of the HEGS and development of model based on demand and supply constraints was carried out. Formulation based on LCE, TNC, OC and GHG was done. d) A localised HEGS architecture based on PV-BI appended with SU has been design and simulated in HOMER. 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 resources availability. The design has been modelled and simulated for practical implementation purposes. Technical and economic investigation has been carried out to judge the feasibility of setting up of such unit and hence analysing the unit cost of electricity to be borne by the end user, capital investment required for construction, operation and maintenance expenses and lifetime of project. Such an extensive study of alternate resources for electricity generation have never been carried out for 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 help policy makers, researchers and designers on the latest constraints as well as policies for PV-BI based systems.

3. Materials and Methods

This section comprises of the methodology to design a HEGS, load estimation of the study area, resource potential assessment of the location, components of energy system required, sizing, modelling and optimization of 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 change in input variables as a part of sensitivity analysis. The is the best tool for optimization of micro system that can be employed for both on-grid and off-grid systems. HOMER develop by NREL simulates the designed architecture for 8760 hr/year and also gauges the optimized results based upon TNC [32, 48]. Fig.1 shows a typical hybrid power generation architecture that can be modelled in HOMER. Fig. 2 depicts a flow chart for methodology adopted for modelling, simulation and optimization.

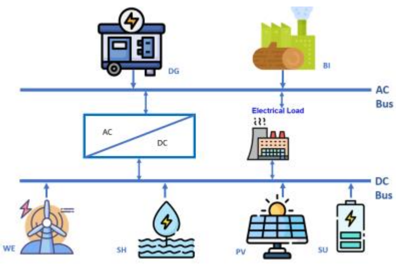

Fig. 1. Hybrid power generation architecture

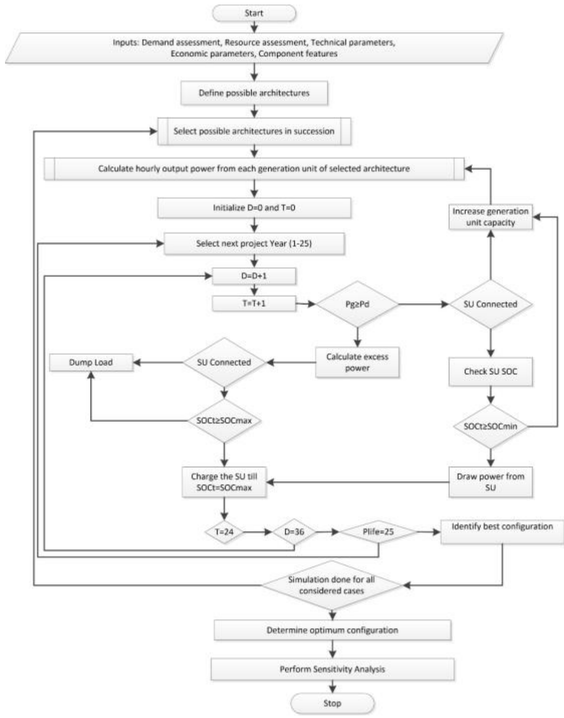

Fig .2. Flow chart of the adopted methodology

3.1. Load Estimation

10 remote villages of 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 [33].

Table 1. Details of the study location

Parameter	Value
Country	India
State	Jharkhand
District	Seraikela Kharsawan
Geographic Location of Chandil	22.97°N 86.02°E
Total Villages considered	10
Total Population	4292
Total Households	872

For estimation of electrical power requirement of the study area, a year is categorised season wise as summer season (March-June), Rainy season (July- September) and winter season (October-February) in accordance with the electrical energy necessities and consumption outline. The pattern of load distribution on 24-hour basis was studied for 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 usage of LED (20W), fan (45W), TV (45W), etc. for each household. Agricultural demand includes power needed for rice hulling, crop threshing/fodder cutting etc. Community need are power requirements for functioning of small shops, flour mill, etc. The total energy demand of the study area is classified in four categories viz. domestic consumption (353558.1 kWh/year), agricultural consumption (17000 kWh/year), community consumption (8300 kWh/year), heat consumption (371673 kWh/year) for cooking purposes. The day-to-day energy demand of the study area has been estimated as 1472.2 kWh/d for summer season, 1293.52 kWh/d for rainy season and 1203.1 kWh/d for winter season Fig 3. Yearly power consumption of the study area is estimated as 378858.1 kWh/yr.

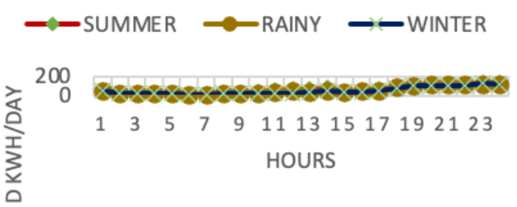

Fig. 3. Load profile of the study area

3.2. Potential Assessment

The potential assessment of renewable sources was done through an extensive survey using a set of questionnaires for data collection like cattle, agriculture residue, forest foliage, hydrological sources etc. the details of findings of survey are shown in Table 2. The study area has ample number of cattle, cow, goat, buffalo, sheep, pig, poultry whose excreta can be utilised to produce biogas and hence use for heating/cooking purpose and run a biogas generator. The total amount of biogas available in the study area is 329631.5 m^3/year which can be utilised for cooking and heating purposes. Being located in dense forest, 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 area, total amount of biomass computed is 2,68,046 kg/year from crop residue and 182189 kg/year from forest foliage. The area receives annual average daily solar insolation of 4.95 kWh/m^2/day [34]. The average temperature is 24.35° [34]. However average wind speed of is quite low, discouraging the use of wind power. The annual average has been 3.98 m/s, however in late summers and early rains the speed is as high as 4.5-5.00 m/s at some locations hence can be used for small/micro wind turbines/ aero generators [31]. The hydro power potential is available at 11 sites in 6/10 villages and is capable of generating 225494 kwh/year of energy. 6 sites have water discharge availability throughout the year, while 3 sites have discharge for 4 months, remaining 1 site for 4 months and 1 site for 1 month.

Table 2. Potential of renewable energy sources

Solar energy	**Wind energy**	**Biomass**	**Biogas**	**Small hydro power**
Annual average daily solar radiation 4.95 kWh/m^2/day	Annual average wind speed 3.98 m/s	2,68,046 kg/year from crop residue. 182189 kg/year from forest foliage	329631.5 m^3/year for cooking/heating purpose	245494 kWh/year from 11 different sites

3.3. HEGS Architectures

In this work we have considered eight different architectures involving solar PV, wind, small hydro and biomass resources with and without storage-backup genset system. The architectures include designs viz. PV-SH, PV-BI, SH-BI, PV-BI-WE-SH, BI only, PV only, PV-BI-SH, SH only. Table 3 presents the technical and economic attributes of systems used for the design of various HEGS architectures. The simulation details of all the above architectures are shown in Table 4.

Table 3. Technical and Economic Specifications of components used

Photovoltaic Unit	Value*	Wind Turbine Unit	Value*
Type	Flat Plate	Rated Capacity	1kW
Rated Capacity	1kW	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	17m
Derating Factor	85%	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	12V
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	15000 hours	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	20000 hrs
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	11kW		
Efficiency	80%		

*Data collected from local distributors

3.4. Modelling of HEGS Systems

3.4.1. Small Hydro (SH)

Based on the survey, it has been found that out of 10 villages, only 6 villages have the potential for development of small hydro power plant. These villages are V1, V2, V3, V4, V7 and V10. The potential of small hydro has been calculated using the equation (1) [35]. Where, Pg = Power Generated (kW), Q = Flow rate (m^3/sec), H = Head (m) and η = overall efficiency.

$$Pg = 9.81\, \eta Q H \tag{1}$$

3.4.2. *Wind Energy (WE)*

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 area. Equation (2) is used to compute the wind potential for a rotor diameter of 3.0 m [36].

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

Table 4. Simulation details of considered architectures

Architectures	SU Nos.	DG (kW)	PV (kW)	WE (kW)	SH (kW)	BI (kW)	Conv. (kW)	TNC ($)	LCE ($/kWh)	OC ($/year)	II ($)	RF (%)	Deisel ltr. /year)	Biomass (ton/year)	CO_2 Discharge Kg/Year
PV-SH	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	5351913	1.093	382809.2	403140.1	5	113030.8	0	295871.2
	3110	0	1162	0	11.0	0	191	1557998	0.318	59801.57	784912.3	100	0	0	0
	2300	210	713	0	11.0	0	189	1483791	0.303	66807.36	620137.8	98	2567.848	0	6721.638
PV-BI	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	1620294	0.331	120289.5	65249.2	75	31260.29	481	81910.61
	710	0	49	0	0.0	80	110	380414.6	0.077	18079.65	146689.6	100	0	480	82.98035
	510	210	161	0	0.0	80	98	413981.2	0.085	16980.61	194464.1	99	929.6251	362	2496.006
SH-BI	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	1628614	0.333	120870.6	66056.65	75	31295.8	483	82003.88
	700	0	0	0	11.0	80	128	391871	0.080	19511.12	139640.7	100	0	558	96.44939
	580	210	0	0	11.0	80	93	533558.4	0.109	27637.79	176270.5	95	4877.124	544	12860.6
BI only	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	902445	0.184	61489	107550	75	31296	483	82004
	720	0	0	0	0.0	80	107	383736.7	0.078	18968.93	138515.5	100	0	558	96.45612
	580	210	0	0	0.0	80	93	525298.8	0.107	27149.79	174319.5	95	4877.124	544	12860.6
PV only	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	5349087	1.092	382202.9	408152.7	5	112852.3	0	295403.9
	3660	0	985	0	0.0	0	193	1558709	0.318	55407.25	842430.9	100	0	0	0
	2300	210	712	0	0.0	0	191	1475156	0.301	66285.98	618242.9	98	2551.99	0	6680.125
SH only	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	7788636	1.590	597366.9	66165.2	0	177098.5	0	463575.8
	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	3898479	0.796	278122.8	303042.2	0	118288.5	0	309633.7
PV-BI-SH	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	1629168	0.333	120375.9	73006.2	76	31082.77	475	81444.96
	700	0	81	0	11.0	80	113	386632.4	0.079	18028.62	153567.1	100	0	435	75.1811
	510	210	159	0	11.0	80	94	421584.3	0.086	17477.22	195647.2	99	947.4583	363	2542.791
PV-BI-WE-SH	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	1632130	0.333	120565.5	73518.11	76	31116.6	474	81533.32
	700	0	82	1	11.0	80	113	389224.8	0.080	18114.09	155054.5	100	0	433	74.81998
	510	210	163	2	11.0	80	95	427454.1	0.087	17691.2	198750.8	99	946.5062	361	2540

Here, P_W= Available wind power, Cp = the coefficient of performance of the Wind turbine, ρ= Density of air (kg/m^3), D = Rotor diameter (m) and V=Velocity of wind (m/s). As the potential of wind energy in the target area is quite limited, thus small capacity systems are proposed for tapping the wind energy potential.

3.4.3. *Solar Photovoltaic (PV)*

HDKR model has been use for computation of insolation incident on the solar PV panel array. Equation (3) represents the model [36]. Here, $\overline{HT}$ is the total radiation, $\overline{Hb}, \overline{Hd}$, $\overline{Hg}$,are the beam, diffused and global radiation (kW/m2), $\overline{Rb}$ is the ratio of tilted beam radiation to horizontal beam radiation, A is index of anisotropy, β is angle of tilt (considered as 22.94°) [37] and ρ is ground reflectance. The total power generated by the panel can be mathematically expressed as equation (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/m^2), D 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).

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

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

3.4.4. *Biomass Energy (BE)*

The sizing of biomass gasifier system is done considering several parameters like efficiency (η_{BI}), operational hours/day (H_D), calorific value of fuel used (C_{BI}) and quantity of biomass available (T_Q Kg/year). the hourly generation of power using biomass gasifier system is shown in equation (5) [38].

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

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

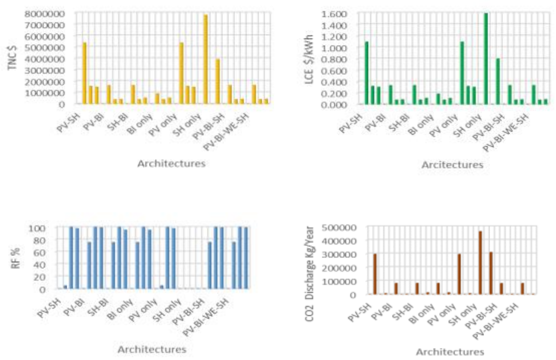

Fig. 4. TNC, LCE, RF and CO_2 discharge for various architectures

3.4.5. *Biomass Energy (BE)*

The biomass gasifier system is sized considering several parameters like efficiency (η_{BI}), operational hours/day (H_D), calorific value of fuel used (C_{BI}) and quantity of biomass available (T_Q Kg/year). the hourly generation of power using biomass gasifier system is shown in equation (5) [38].

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

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

3.4.6. *Backup Genset (DG)*

Deisel generator station have been employed for providing a backup supply. The rate of consumption of diesel can be computed using equation (6). Here, F_C is coefficient of fuel curve intercept, R_{DG} is rated capacity of diesel generator station, F_S is slope of fuel curve and P_{DG} is the diesel generator output power.

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

3.4.7. *Storage Unit (SU)*

The power generated by renewable means cannot be resonated with the demand, many a 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 equation (7) and (8) [19].

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

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

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 more than generated power, the scarcity is introduced hand the storage bank will discharge to satisfy the same. The equations (9) and (10) can be used for computation of the storage capacity of battery bank. Here E_{DD} (t) is total deficit energy requirement, υ is self-discharging rate/ hour and η_{DB} is the battery discharging efficiency.

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

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

3.4.8. *Environmental and Economic Attributes*

Various economic and environment-based parameters have been considered for computation of TNC and LCE of all architectures. TNC is the total sum of all present figures of all the lifetime expenses minus present value of all lifetime revenue. TNC and LCE can be calculated by equations (11) & (12) [39].

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

$$LCE = \frac{ANC}{E_{AC}} \tag{12}$$

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 using equation (13) [40].

$$TE = \sum_{t\epsilon T} \sum_{n\epsilon N} E_n P_{gt} \tag{13}$$

Here, TE is the total emission, E_n stands for the CO_2 emitted by the n^{th} unit in time t (kg/MWh) and P_{gt} is the amount of power generated by conventional sources in period t (MWh). CO_2 emission leads to carbon pricing and reduces the LCE further hence modifying the process of its estimation (14) [47]. In order to calculate the amount of CO_2 reduction, emission factor for base system has been employed as 0.277 $kgCO_2$/kWh [47]. Renewable fraction (RF) is the percentage of energy generated by renewable sources and is mathematically expressed as equation (15) [41].

$$LCE = \frac{ANC - C_{CO2}}{E_{AC}} \tag{14}$$

$$RF = \left(1 - \frac{\sum P_{DG}}{\sum P_{RS}}\right) * 100 \tag{15}$$

4. Results and Discussions

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

4.1. 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 ($7.78 M), LCE (1.59$/kWh) and Emission (463576 kg/year) is higher as compared to that when SU is present along with. The values of TNC ($1483791) and LCE (0.303 $/kWh) are better when both SU-DG are present in the architecture, but the CO_2 emission is 6722 kg/year. On the other hand, if only 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 [42, 43, 44]. The OC of this configuration is $ 66807 which is lowest among all. In Architecture 2 (PV-BI) configuration has been considered, PV-BI-SU has best results among all the cases with LCE as low as 0.077 $/kWh, TNC $ 380415 and OC 18080 $/year. The RF here is 100% and CO_2 emission of 83 kg/year. Only PV-BI is not feasible and rest both cases PV-BI-DG and PV-BI-SU-DG have comparatively higher LCE and TNC. Architecture 3 (SH-BI) gives 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 $/kWh) but TNC ($ 391871), OC (19512 $/year) 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 $/kWh) for the study area but TNC ($ 383737), OC (18969 $/year) and CO_2 emission (96.5 kg/year) are slightly higher than its PV appended counterpart. 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 having 0.30 $/kWh LCE and 1475156 $ TNC, however the fuel used is 2552 ltr/year and RF is 98.1 % so higher CO_2 discharge is expected. Architecture 6 (SH only) also provides feasible solution only when SU-DG or at least DG unit is appended to the system providing 0.79 $/kWh LCE and 3898479 $ TNC. This is because the area does not have enough flowing water resources available throughout the year. Only 11 Hydro power potential point are available out of which 6 sites have discharge round the year rest are season dependent. Architecture 7 (PV-BI-SH) is one of the promising configurations when added with a storage unit SU. This design provides estimate of 0.079 $/kWh LCE and 386632 $ TNC with 100% RF which is best among all the considered configurations. OC of the system is 18029 $ and CO_2 emission is just 76 kg /year which depicts 99.5% reduction as compared to conventional sources. The SU consists of 71 strings of 10 batteries each with 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 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 results that amalgamation of PV-BI-WE-SH configuration with SU provide the winning metrics with 389225 $ TNC, 0.080 $/kWh LCE, 18115 $/ year OC and 155055 $ II. 433 ton of biomass is 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 counterpart. The reason being requirement of high-capacity energy generation units to satisfy the demand without SU which in turn increases the operational-maintenance expenses. Analysing the results, it can be concluded that architecture 2, PV-BI-SU has 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 [45]. The CO_2 discharge reduction (~99%) is also promising for this configuration. Moreover, comparing the four architectures it has been deduced that the maximum share power generation is borne by BI (~ 69.7 %) followed by PV (~30.3%), WI and SH generate quite low amount of electricity that too is not functional throughout the year. Hence set up of SH and WI units requires more capital with low payback hence cannot be considered feasible. Hence 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 implementation of proposed system. In future, with the government backing and amendment in policies, such type of systems could be a striking choice for local publics. Hence, remaining analysis is done for architecture 2.

4.2. Techno-economic and Environmental Analysis of Architecture 2 (PV-BI-SU)

PV-BI-SU configuration is found to be optimum for the study area. Fig 5-7 shows the pattern of power generation from both the sources against the demand and the state of charge of storage unit. 69.7 % of power is generated by biomass and remaining 30.3 % is accounted by PV unit generating 427820 kWh/year against the demand of 378624 kWh/year, unmet load being 231 kWh/yr. which is merely 0.06%. In rainy season, the PV output is low and is available only during the daytime, rest of the load is met BI generation system. It can be seen during night power is supplied by the SU. During summer season, large amount of solar insolation can be used for energy generation and same can been in the Fig. 6. Most of the load during daytime is met by PV only and during night BI feeds the demand. Quite good amount of excess electricity is produced during the time period of year that can be stored for future use. In winter season, again PV functions better during the sunshine hours meeting maximum share of load and rest is fulfilled by the BI and SU. The SOC varies 40-100% throughout the year with higher variation in winter as compared to summer.

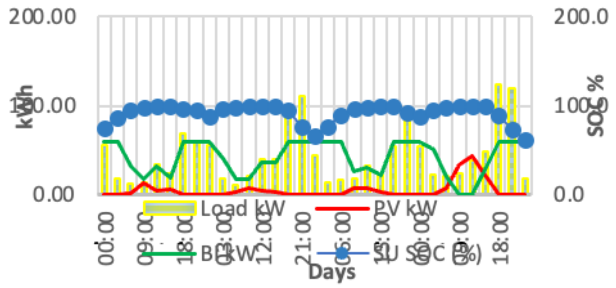

Fig. 5. Power generation pattern -rainy season weekday

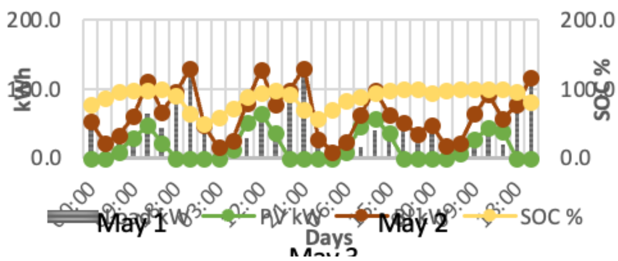

Fig. 6. Power generation pattern-summer season

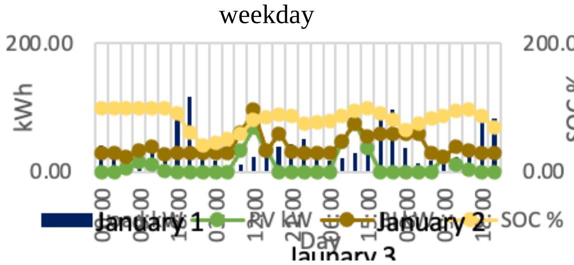

Fig. 7. Power generation pattern-winter season weekday

The capacity of PV unit is 48.6 kW while that of BI is 80 kW and 110 kW converter is used implementing Cycle charging electrical dispatch strategy. For storage purpose, 71 strings of 10 units, 1 kWh LA batteries have been used. Fig. 8 shows the monthly average power generation by architecture 2 involving PV-BI system. Substantial amount of energy can be generated by PV system in the month of Jan – May, dur to clear sky and large amount of sunshine available. This value is quite less 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 most promising architecture for the study area is shown in Fig. 9. 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.

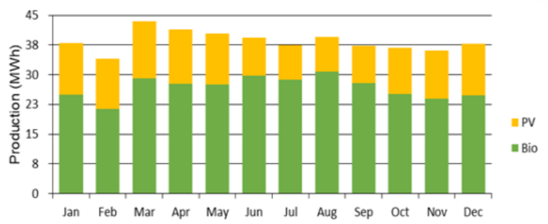

Fig. 8. Monthly energy generation share of PV-BI in architecture 2

However, the PV array has operation-maintenance cost of about 18080 $ due to necessity 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 107070 $. Thus, improvement in storage technology and lifetime could further result in cost cutting of overall system cost. The analysis of environmental benefits suggested that the proposed system produces a cleaner environment due to minor discharge. Fig. 10 shows the % share of various discharge materials comparing the proposed architecture to the base architecture (DG only system).

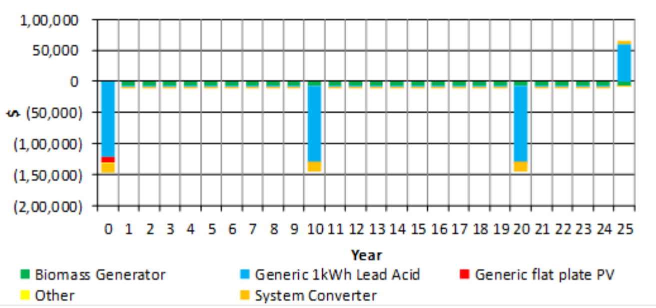

Fig. 9. Nominal cash flow of proposed architecture

4.3. Sensitivity Analysis of Architecture 2 (PV-BI-SU)

Sensitivity analysis has been done for the proposed architecture 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 load, PV derating factor, annual interest rate, biomass rate, BI lifetime, gasification ratio, and annual capacity shortage Fig. 12-17.

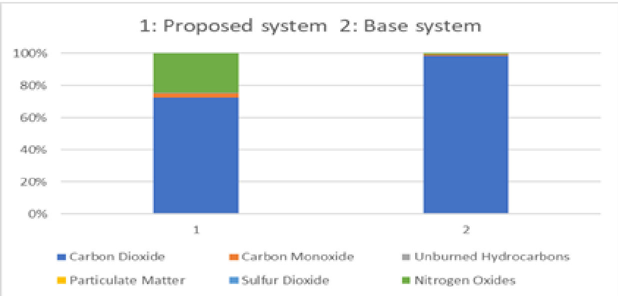

Fig. 10. % share of emissions proposed vs base architecture

The proposed HEGS has to be developed to compensate the variation in demand. Fig. 11 shows the variation of load from 1037.96 to 1050 kWh/d and simultaneous deviations in TNC and LCE. It is worth noticing that load variation has greater effect on TNC as compared to LCE. The derating factor of PV array should by high for better power generation. Hence its variation has to be studied for optimal system design. The effect of change in derating factor on TNC and LCE has been depicted in Fig. 12. Both the parameters decrease with increasing derating factor. The price of Biomass also affects the systems economics adversely as the major generation is done using BI system. Fig. 13 shows the changes in TNC and LCE with price of biomass. Capacity shortage is important factor for an improved system. To judge the system performance capacity shortage has been varied from 0% to 30% and has been estimated that TNC and LCE drop down with increasing capacity shortage % Fig. 14. Upon variation in nominal discount rate (from 6% to 15%), the LCE was directly proportional while TNC was inversely proportional Fig. 15. BI life time and gasification ratio affects the system performance as both should be high for viability. The replacement cost can decrease the TNC and this can be done by increasing the operation lifetime. BI gasification ratio on the other hand is related to efficiency of the system. Hence these factors are studied and inverse proportionality has been discovered for both TNC and LCE Fig.16.

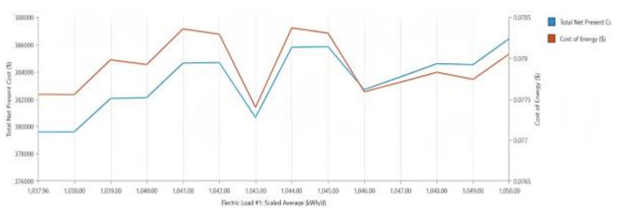

Fig. 11. Effect of load on TNC and LCE

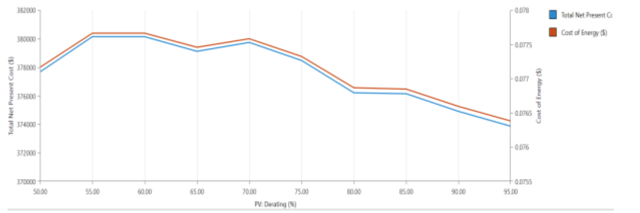

Fig. 12. Effect of PV derating factor on TNC and LCE

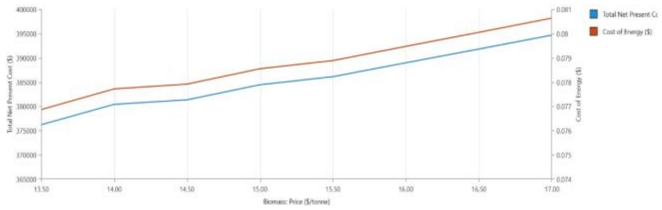

Fig. 13. Effect of Biomass price on TNC and LCE

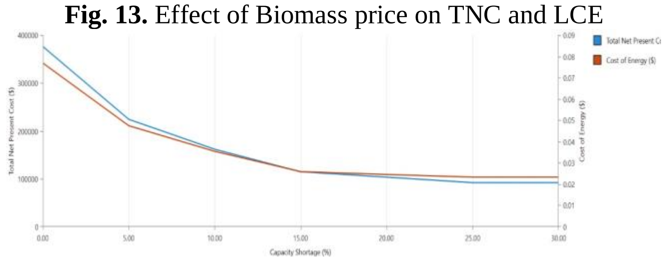

Fig.14. Effect of Capacity shortage on TNC and LCE

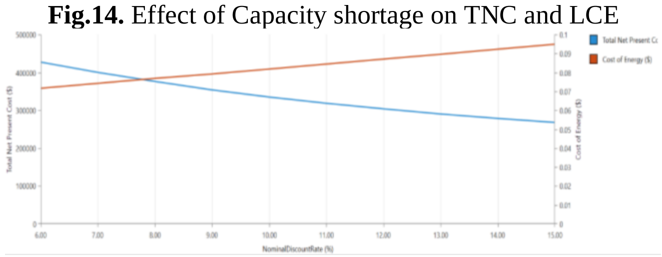

Fig.15. Effect of Discount rate on TNC and LCE

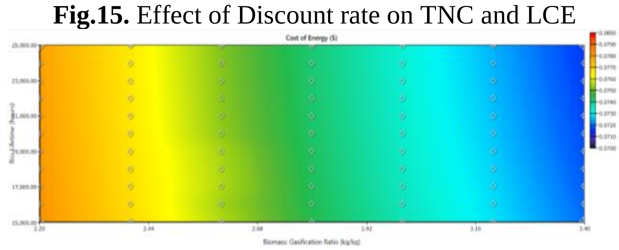

Fig.16. Effect of BI life and gasification ratio on TNC

5. Comparison with Available Literature

This section focusses on 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 feasible both in terms of economic and environmental metrics.

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	[28]

3.	North-West Iran	PV-BI-FC	0.163	361	[18]
4.	Chamarajanagar district, India	PV-WE-BI-FC	0.214	724.83	[17]
5.	Uttarakhand, India	PV-BI-SH-SU	0.09	1569	[20]
6.	Nampula, South Africa	PV-BI	0.33	81	[46]
7.	Monshaet Taher, Egypt	GRID-PV-BI	0.09	2340	[27]
8.	Adorsho Char, Bangladesh	PV-BI-DG	0.22	181	[29]
9.	Garissa, Kenya	PV-WE-BI	0.25	200	[30]

6. Conclusion

In this work eight hybrid energy generation models have been studied technically, economically and environmentally with 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 purpose. Following are the concluding remarks of this study: a) 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. However, wind energy potential is not much promising. b) Eight hybrid models have been analysed and PV-BI-SU was found to be the most appropriate 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% (106240 kWh/year) of power is generated by PV and remaining 69.7% (321580 kWh/year) by Biomass generator. The most optimal architecture suggests most promising LCE of 0.077 $/kWh at a TNC of $ 380415, II of $ 146690 and OC of $18080. These figures are far more competitive as compared to other models present in the literature. c) Environmental analysis suggests that the total GHG emission by proposed system is quite low i.e., 99 % less than diesel model. d) Sensitivity analysis suggests that the proposed architecture is more sensitive for annual discount rate, price of biomass, capacity shortage and gasifier lifetime.

The proposed HEGS has confirmed techno-economic-environmental 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, hamper of green vegetation and obviously will prove to be an excellent key to the alternate energy target of India and create employment for locals. Furthermore, such research provides an insight for future biomass-based studies and deployment in tropical areas. Simulation of on-grid HEGS for the region is also required along with practical implementation to understand the practical challenges and explanations.

Nomenclature

ACS	Average Cost of Supply
ARR	Average Revenue Realized
BI	Biomass Energy
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 Energy
RF	Renewable Fraction
SH	Small Hydro Energy
SU	Storage Unit
TNC	Total Net present Cost
WE	Wind Energy

Acknowledgements

The Authors are thankful to Department of Electrical Engineering, National Institute of Technology Jamshedpur, for all the support and assistance to carry out the research.

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