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Research Article

Optimum Design, Socioenvironmental Impact, and Exergy Analysis of a Solar and Rice Husk-Based Off-Grid Hybrid Renewable Energy System

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This study examines the optimal sizing of an off-grid hybrid system comprising solar photovoltaic (PV), rice husk-based biomass, and lead-acid battery for meeting the electric demand of a rural community. Considering a selected remote village in Bangladesh as a case study, the proposed optimized system is primarily compared with the diesel generator and the micro gas turbine (MGT)-based options in techno-economic and environmental terms. The potential social benefits, such as the employment creation and the improvement in the human development index in the locality, have been investigated in this study. Moreover, the impacts of operational greenhouse gas emissions on the human health damage and the surrounding ecosystem have been examined. Additionally, an exergy analysis of the hybrid system and the components has been carried out. Results indicate that in addition to being the environmentally preferable option, the proposed PV/biomass/battery system offers a lower cost of energy of 0.314 $/kWh compared to the MGT-based system (0.377 $/kWh). Although the diesel-based system offers a marginally better economy (9.55% less energy cost), it comes with the expense of probable damages to human health and the ecosystem worth of $15,211 and $6,608, respectively, making biomass the best option with no such damages. Exergy analysis reveals higher loss from PV than biomass and 13.09% system exergy efficiency. The assessment of the social indicators testifies to the potential of promoting the human development index from its current value and the formation of 1.41 jobs to as high as 15.15 full-time permanent jobs with the installation of hybrid systems in the community.

1. Introduction

Bangladesh is a developing and densely populated nation with an estimated population exceeding 168 million within an area of about 147,570 km^2 [1]. According to the most recent account of the World Bank, about 73% of the country's energy comes from fossil fuels. However, Bangladesh, like many other countries, has a diligent concern about fossil fuel depletion at a minacious rate and the high reliance on conventional fuels for electricity generation which also has been proven detrimental to the environment. Moreover, recently, the Ukraine-Russia war caused a hike in the prices of fuel and other commodities which forced the government of Bangladesh to impose nationwide scheduled outages of electricity to save foreign reserves, leaving the population of the country in sheer distress. Adversity like that could be avoided by transitioning the country's energy sector to utilize the abundance of available clean and sustainable renewable energy resources.

The potential sources of renewable energy that can be implemented in Bangladesh include solar, wind, biomass and biogas, and hydro energy [2–7]. However, these sources of energy have some drawbacks that restrict their widespread applications. The major drawbacks of a stand-alone RE system include the relatively high initial upfront cost, the low conversion efficiency, and the requirement for greater space. However, when climatic adversity, health hazards, and energy security are concerned, renewable energy is inarguably the best option over others [8]. Still, the intermittency of these systems is a major barrier for them to emerge competitive in terms of reliability [9]. In this context, hybridization with two or more RE sources along with or without backup generators has been proven a tangible solution to supply reliable electricity [10–17].

In the relevant literature, Al-falahi et al. [18] presented a comparison between stand-alone solar and wind-based HES and concluded that the HESs combining the solar, wind, battery storage, and diesel generators could be integrated to improve the reliability and continuity of power supply in remote areas. Fadaeenejad et al. [19] have also analyzed the HESs for rural electrification and concluded that HES could be a reliable, cost-effective, and viable solution towards a sustainable energy supply. The techno-economic-environmental study conducted by Mehrpooya et al. [20] found that the price of electricity was less in PV/battery system than that of the conventional ways of power generation by diesel. They also mentioned that a reduction of 51% in CO_2 emissions could be obtained by adding the PV panels. A comparative analysis of several HESs was conducted by Muh et al. [21] in southern Cameroon. They assessed the feasibilities of a HES and found that the PV/battery/diesel/hydro system was cost-effective, with a cost of energy (COE) of 0.443 $/kWh. The optimized component sizing entails a 10 kW diesel generator set, 332 units battery, 67.3 kW PV module, 13.4 kW small hydro, and 53 kW inverter. In this configuration, a total of 170,095 kWh power is produced in a year with the percentage contribution of 57.7%, 40.5%, and 1.84% from the solar, small hydro, and diesel generators, respectively. A grid-dependent PV/wind/biomass was investigated by Ahmad et al. [22] in a remote place named Kallar in Punjab, Pakistan. They investigated the potential for power production through the HES and found that the proposed system could have the potential for electrification in remote areas with an investment of $180.2M and a COE of 0.057 $/kWh. Tun et al. [23] studied the biomass resources in South Asia, and they found that the major sources of biomass are wood residue, fuelwood, rice husk, sugarcane residue, rice straw, and coconut residue.

Through a technical and economic assessment, Tajeddin and Roohi [24] studied the feasibility of a 1.5 MW wind farm in Iran and concluded that hybridization with biomass could be an alternative solution to meet the shortfall of wind resources. Anvari et al. [25] proposed a hybrid solar-biomass with a capacity of 13.4 MW power. The results revealed that the addition of a solar system contributed to an increase of 25% and a decrease of 31% in power production and CO_2 emissions, respectively. The findings also showed that the emission of CO_2 from the proposed system was 49% lower than the comparable stand-alone biomass system. Roy et al. [26] examined a PV/WT/biomass/FC-based HES system for meeting electric and water demand for a remote location near the Sundarbans in India. Eteiba et al. [27] carried out an analysis of a PV/biomass hybrid system and suggested an effective way to design an optimized HES. Shahzad et al. [28] studied the feasibility of an off-grid hybrid PV/biomass one for the electric energy supply to the rural village in Pakistan using HOMER and reported that the HES is cost-effective and can reliably supply the energy demand. Although many studies consider energy, economics, and environmental criteria in their evaluation of the HES, very few reported the exergy analysis. A PV/wind-based hydrogen production system was evaluated based on energy, exergy, financial, and environmental parameters by Nasser et al. [29]. In another study, Nosratabadi et al. [30] analyzed a PV/wind/PEMFC-based HES considering the economic parameters along with the energy and exergy.

The sizing of HES requires careful consideration of reliability requirements, temporal resolution of climatic and load data, and the energy management algorithm [31, 32]. The inclusion of technical parameters based on the available RE resources and the economic indicators is equally important. Aziz et al. [33] investigated the techno-economic-environmental performance of a PV/diesel/battery under three different operational strategies. The costs and operational emissions are lower in the combined strategy than in the load-following and cyclic charging strategies. Samy et al. [34] examined a PV/wind/fuel cell/grid-connected HES using hybrid firefly/harmony search and particle swarm optimization techniques and found that the electricity cost (0.0628 $/kWh) is lower than the national grid (0.1 $/kWh) tariffs. An optimal HES microgrid of PV/wind/diesel/biomass is developed by Kharrich et al. [35] using the Giza pyramids construction (GPC) algorithm and reported the COE of 0.208 $/kWh. Naderipour et al. [36] analyzed PV/wind/battery using an improved grasshopper optimization algorithm (IGOA) for minimizing NPC under the loss of energy probability and reported that the proposed optimization technique offered cost reduction over the conventional GOA technique. The social indicators such as employment creation, human progress index, and land requirements along with the cost optimization were examined by Kushwaha and Bhattacharjee [37] using HOMER. However, the energy and exergy analyses and impacts on the ecology and human well-being are not reported as discussed in the present study. Kumar and Channi [38] examined a PV/biomass-based HES using HOMER for Indian rural areas and found the COE of 0.362$/kWh with a RE contribution of 35.6%. Although different techno-economic parameters are exclusively investigated in their study, the social aspects, sustainability, and the ecological factors are not reported. Ji et al. [39] investigated a PV/diesel/biomass-based system under different operational modes, and results indicated that the grid-connected option offers a cost-effective solution over a fully RE-based system. In light of the literature review, the contributions of this study are as follows:

(i) This study considers the integration of solar PV and battery with three different types of backup generators (biomass, diesel, and MGT) by turns and optimization of the resulting hybrid configurations to obtain a cost-effective HES for the remote area electrification in Bangladesh.

(ii) The nonrenewable fueled backup generators in the hybrid systems cause a significant amount of greenhouse gas (GHG) emission over the lifetime of their operation. While most, if not all, of the studies consider quantification of these emissions, those measures do not properly reflect the ultimate detrimental consequences. The present study deals with interpreting the damages caused by operational GHG emissions through the estimation of their impacts on human health and the surrounding ecosystems. Furthermore, the economic worth of such damages is also evaluated.

(iii) The hybrid system, when established in the location, has an enormous prospect of employment creation. Moreover, a significant portion of the system's generated excess electricity can be utilized to power new businesses which will contribute to enhance the quality of living in the area. This study applies indicators such as job creation (JC) and the human development index (HDI) to quantify such benefits that can be potentially created through the hybrid renewable system.

(iv) In addition to the techno-economic, environmental, and social impact analysis, this study considers a comparative energy and exergy analyses of the proposed HES. Such analysis is useful to understand the distinction between the energy available and the energy actually recovered. Moreover, the analysis provides insights into the reason for lower efficiencies of the whole system by identifying the component(s) with higher losses.

This study is structured as follows: Section 2 reports the biomass resources in the study area, Section 3 describes the methods applied for this investigation, Section 4 presents the results and discussion, and the final section provides the key outcomes of this investigation.

2. Biomass Resources in Bangladesh

Biomass is the most preferred energy source in Bangladesh because, as an agricultural country, a significant amount of waste is produced per day with an estimate of 436 t/d production from industries alone [40, 41]. According to the renewable energy policy, 10% of total power demand would be satisfied from different RE sources by 2020 [42]. However, the present RE contribution is only 0.20% other than hydropower (1.2%) [43], which epitomizes the lack of policy and institutional support for implementing RE-based power plants despite having huge renewable potential, in particular solar and biomass [2, 44]. Table 1 represents the agricultural residue production from the different crops and, subsequently, rice husk production (considering husk yield 20% of rice production) in Bangladesh. It is estimated that the rice husk has the potential for electricity generation of 19.40 TWh. The ultimate and proximate analysis of the rice husk is reported in Table 2.

The husk has an ash content of 20.26%, a carbon content of 38.83%, and a trace amount of sulphur content. The higher calorific value of the rice husk is around 15–17 MJ/kg. The proximate analysis includes the fixed carbon of 16.22% and the volatile matter of 63.52%.

There is an auto rice mill station near the selected area, which can contribute to the rice husk supply of approximately 25.68 tons/day. The average daily production of rice husk for this mill is confirmed by consulting with the rice mill owner while surveying. Figure 1 shows the monthly contribution of rice husk from the mill.

3. Materials and Methods

A widely accepted tool, hybrid optimization of multiple energy resources (HOMER), that models and integrates the combination of conventional and renewable energy systems for predicting an optimized system configuration has been used in this study. The likely significant parameters, including the electrical load, renewable energy sources (e.g., solar irradiation and biomass), techno-economic details of HES, and the type of dispatch strategy, are used as the inputs in this optimization approach. These parameters provide the basis for the HOMER to assess the different alternative scenarios both in terms of economic and technical (including physical) aspects. The hourly performance of the HES is then simulated and analyzed to come up with the lowest possible COE while satisfying the load and technical requirements. With the optimized outcomes available from HOMER, further analyses have been carried out. Figure 2 represents the framework of the method incorporated in this study.

3.1. HES Architecture. The HES proposed in this study has been targeted for the electrification of Shahaber Ghat (longitude 24°35′1″ N and latitude 88°15′43″ E), which is located around 5 km from the district headquarters of Chapai Nawabganj. The basic elements used in the studied hybrid system included a PV module, battery, biomass gasifier, and inverter, where the PV modules were used to supply baseload demand, as shown in Figure 3. The PV module and biomass gasifier are the main energy resources for the studied HES. The contributions of the converter and the battery to the overall setup are to maintain the DC/AC

Table 1: Selected agricultural residue and energy potential in Bangladesh (2018) [2, 45, 46].

Crops type	Production (tonnes)	Type of fractions	Fractions of residue (%)	Crops residue (tonnes)	Energy content (PJ)	Electricity generation (TWh)
Rice	564,17319	Straw	50	282,08660	174.57	48.50
		Husk	20	112,83464	69.83	19.40
Maize	328,8102	Stalks	200	657,6204	40.70	11.31
		Cobs	30	986,431	6.10	1.70
Wheat	109,9373	Straw	65	714,592	4.42	1.23
Jute	161,3762	Stalk	58.84	949,538	5.88	1.63
Sugarcane (trimmed)	363,8731	Bagasse	36	130,9943	8.11	2.25
Coconuts	466,975	Husk	31	144,762	0.90	0.25
		Shell	24.40	113,942	0.71	0.20
Lentils	176,633	Straw	72.46	127,988	0.79	0.22

Table 2: Proximate and ultimate analyses of rice husk [46].

Parameters	Fixed carbon (%)	Volatile matter (%)	Ash (%)	C (%)	H (%)	O (%)	N (%)	S (%)	HHV (MJ/kg)
Values	16.22	63.52	20.26	38.83	4.75	35.47	0.52	0.05	15–17

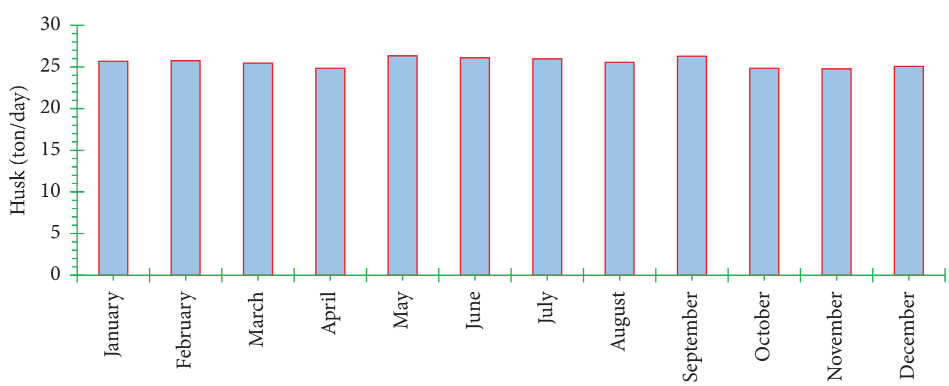

Figure 1: Monthly average rice husk production in the selected area.

energy flow and energy storage, respectively. The battery is connected to the DC bus and used to supply energy to this system when needed until it reaches the charge at its minimum level. The AC and DC buses are linked with the bidirectional inverter. The battery is charged through the PV module during the active periods (e.g., daytime for the PV module). The load and biomass gasifier unit are directly connected to the AC bus.

Figure 3 presents the conceptual layout of community electrification using the proposed hybrid renewable system (green line: AC power flow and purple line: DC power flow). The backup generator represents the three different types considered in this study, namely, biomass gasifier, diesel generator, and micro gas turbine.

The key components used in the proposed hybrid system including PV module, biomass gasifier, battery, and inverter are reported in Table 3.

3.2. Meteorological and Process Data. The account of the environmental data, such as wind speed, solar irradiation, temperature, and process data (e.g., streamflow) to the estimation of power sources, such as wind turbine, PV array, hydropower, and diesel generator, was undertaken by HOMER. The time-series data of solar irradiation for the selected site of this study are shown in Figure 4.

From the characteristic solar radiation data as shown in Figure 4, it can be anticipated that at what time and at what intensity the solar energy can be obtained at the selected location.

3.3. Load Profile. Various energy sources (i.e., biomass, kerosene, and liquefied petroleum gas) have been in use for lighting and cooking purposes in remote rural areas, including the selected site of this study, of Bangladesh. To estimate the domestic energy requirements for the selected

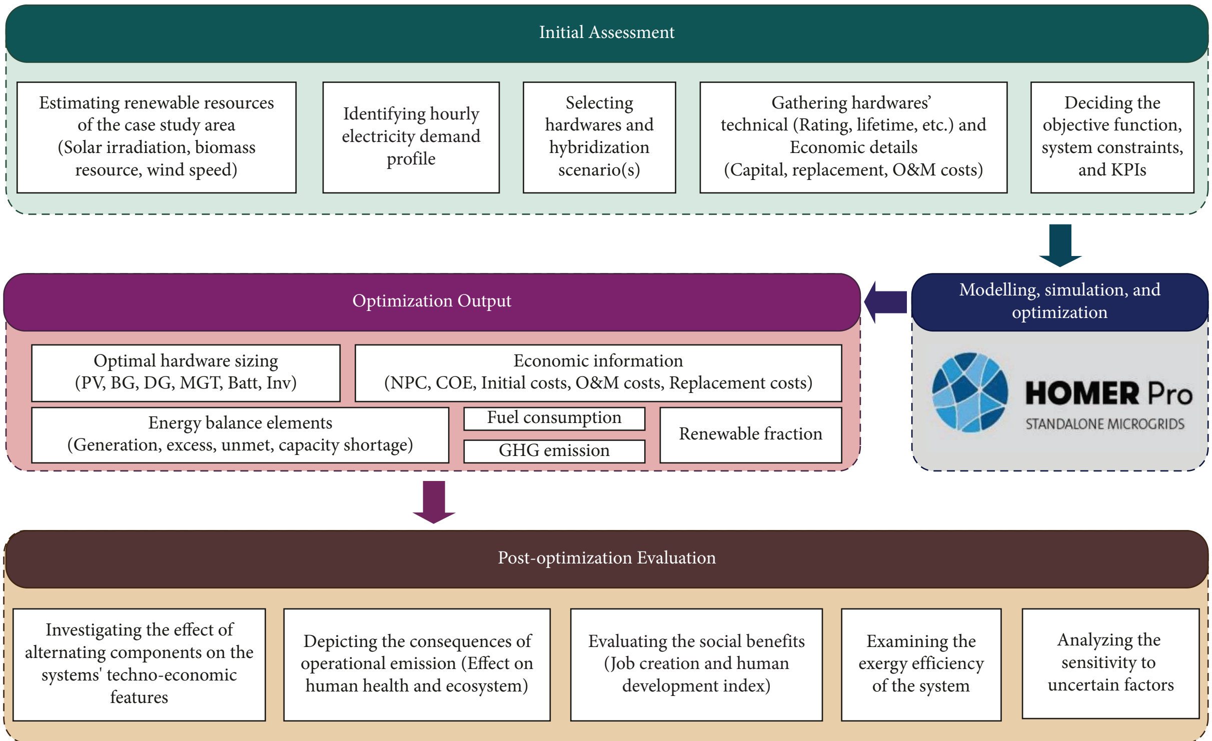

Figure 2: The methodological framework of the present study.

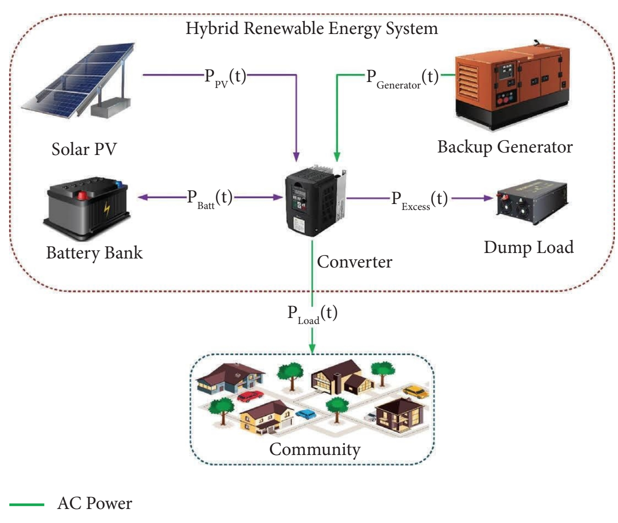

Figure 3: Conceptual layout of community electrification using the proposed hybrid renewable system.

village, a community of fifty families, each consisting of five family members, has been hypothetically modeled. The key elements of domestic loads that have been taken into consideration in this study, together with their respective annual energy demand based on the survey data, are presented in Table 4.

The load estimates shown in Table 4 are based on the necessary electrical appliances used daily by a single family. The load is determined for both the summer and winter seasons. However, for the analysis, the maximum load (summer) is considered for determining the sizing of the hardware components. The time-series data shown in Figure 5 have been used to estimate the load characteristics for the selected region.

3.4. Performance Characterization

3.4.1. System Economics. The cost of energy, COE ($/kWh), is the ratio of total annualized cost (C_A) and yearly electricity served (E_s) and can be determined using the following equation [56]:

Table 3: Technical characteristics and economic data for HRES components.

Components	Characteristics	Values
PV module [47–49]	Nominal power	327 W
	Panel efficiency	21.4%
	Derating factor	88%
	Capital cost	1300 $/kW
	O&M cost	20 $/yr
	Lifetime	25 yrs
Biomass gasifier [48]	Rated capacity	50 kW
	Capital cost	1600 $/kW
	Replacement cost	1280 $/kW
	O&M cost	0.025 $/h
	Lifetime	25000 h
Diesel generator [50, 51]	Rated capacity	50 kW
	Capital cost	370 $/kW
	Replacement cost	296 $/kW
	O&M cost	0.05 $/h
	Lifetime	15000 h
Micro gas turbine [52]	Rated capacity	50 kW
	Capital cost	2000 $/kW
	Replacement cost	2000 $/kW
	O&M cost	0.02 $/h
	Lifetime	15000 h
Battery [53]	Nominal capacity	6.91 kWh
	Nominal voltage	6 V
	Roundtrip efficiency, η_{RT}	80%
	DoD	80%
	Capital cost	1100 $/kW
	Replacement cost	1000 $/kW
	O&M cost	20 $/yr
	Lifetime	15 yrs
Inverter [54, 55]	Rated power, P_{inv}	1 kW
	Conversion efficiency, η_{inv}	95%
	Capital cost	300 $/kW
	Replacement cost	300 $/kW
	O&M cost	0
	Lifetime	15 yrs

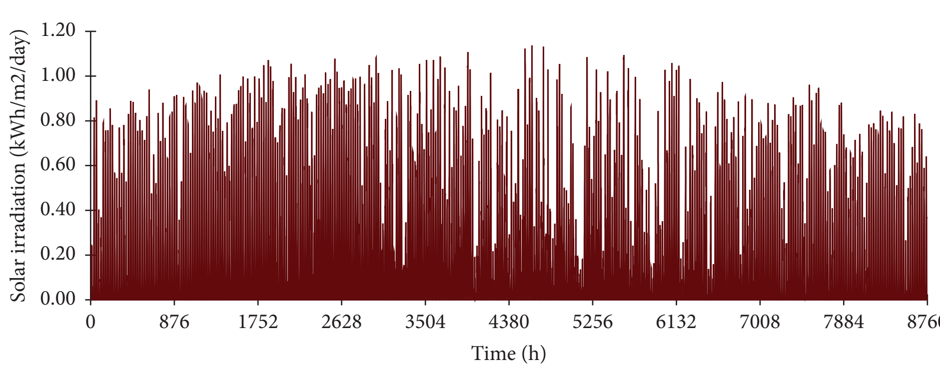

Figure 4: Time-series data of solar irradiation for the selected area.

$$COE = \frac{C_A}{E_S}. \tag{1}$$

Annualized cost is the combined form of annualized capital cost (C_{A_cap}), annualized replacement cost (C_{A_rep}), and annualized operational and maintenance cost

Table 4: Electric demand estimation for a single house in a rural village.

Load	Power rating (W)	No. in use	Summer (March–October)		Winter (November–February)	
			Operating time (h/day)	Wh/day	Operating time (h/day)	Wh/day
Light CFL	25	10	6	1,500	7	1,750
Ceiling fan	70	5	10	3,500	2	700
Table fan	25	2	4	200	0	0
Iron	1000	1	0.25	250	0.50	250
Computer	150	1	5	750	5	750
TV	100	1	6	600	8	600
Refrigerator	150	1	24	3,600	24	3,600
Water pump	750	1	0.50	375	0.50	375
Mobile charger	7	5	2	70	2	70
Grinder	500	1	0.25	125	0.25	125
Total demand				10.97 kWh/day		8.22 kWh/day

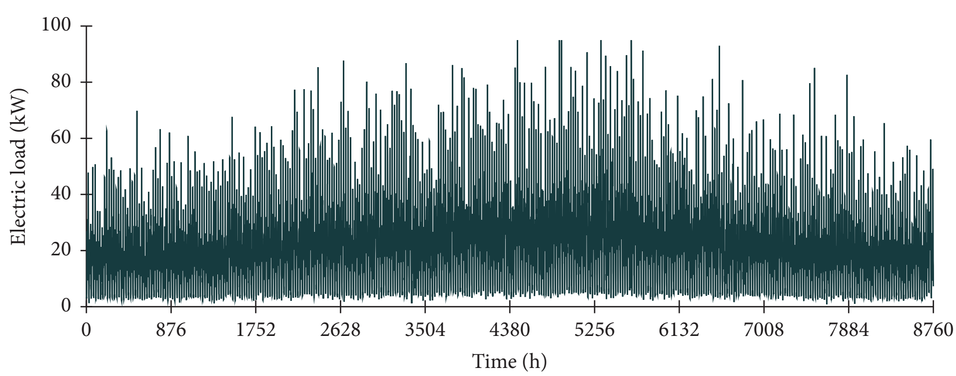

Figure 5: Time-series data of electrical load for the selected area.

($C_{A_O\text{and}M}$). The resulting equation takes the form as follows [57]:

$$C_A = C_{A\text{-cap}} + C_{A\text{-rep}} + C_{A_O\&M}. \quad (2)$$

The total net present cost (NPC) can be expressed by the following equation [57]:

$$T_{\text{NPC}} = \frac{C_A}{\text{CRF}(i, N)}, \quad (3)$$

where capital recovery factor (CRF) is calculated by the following equation [26]:

$$\text{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}, \quad (4)$$

where N is the number of years and i is the real annual interest rate, which can be obtained from the following equation [58]:

$$i = \frac{i' - f}{1 + f}. \quad (5)$$

In (5), the nominal interest rate and the annual inflation rate are denoted by i' and f, respectively. A 2% annual inflation is used in this study. In the cost estimation, an annual interest rate of 10% has been taken into consideration throughout the expected 25 years of the project lifetime.

3.4.2. Impact on Human Health and Ecosystem. Damage to human health (DHH) is expressed in disability-adjusted life years (DALYs), which is the healthy life lost due to either premature mortality or disability caused by prevalent disease or other health issues [59]. The raise in the global mean temperature instigated by GHG emission has a damaging effect on the ecosystem (DES) as well, resulting in the loss of local species, the quantity of which integrated over a year is measured in species·yr unit [60]. The computation of DHH and DES requires estimation of the amount (kg) of different GHGs (CO_2, CO, NO_x, SO_x, etc.) emitted by the fossil fuel-run backup generators in their functional lifetime. With the characterization factors (in DALYs/kg and species·yr/kg units) available from ReCiPe2016 [60] method within the SimaPro software database, the following equation can be used for a specific type of nonrenewable generator:

$$\text{Damage}_d = \sum_e \sum_t^{8760} \text{CF}_{d,e} \times R_{e,t}, d \in \text{DHH, DES, and } e \in CO_2, NO_x, SO_x, \text{etc.} \quad (6)$$

Here, CF indicates the characterization factor, and R indicates the emission of a particular GHG over the year.

The estimated damages can be further characterized in monetary terms using the conversion factors proposed by Weidema [61]. These conversion factors essentially signify the economic valuation of the willingness of a typical society to preserve 1 DALY or 1 species·yr [61, 62]. Weidema estimated that 1 DALY is worth 74,000 $€_{2003}$, while 1 species·yr has an equivalency of 9,500,000 $€_{2003}$. Using the available currency conversion factors [63] and GDP deflator values [64], the amounts can be converted to $\$_{2021}$ units.

3.4.3. Social Sustainability

(1) Job Creation. The number of jobs created by a system having n components is determined from the following equation:

$$\mathrm{JC} = \sum_{n} f_{JC,n} \times P_n, n \in \mathrm{PV, Batt, and\ backup\ generators}, \tag{7}$$

where P is the total capacity of the component and f_{JC} is the job creation potential of that component. Job creation potential of hybrid renewable system components may vary due to the consideration of different methodologies, existing dissimilarities in regional job content, distinction in the comprehension nature of employment as direct jobs, etc. [65, 66]. Evidently, different values of job creation factors have been adopted in studies conducted prior to the present one [8, 67, 68]. In this study, the approach proposed by Ram et al. [69] has been adopted as it, among other aspects, allows for the inclusion of different elements of regional business and labor productivity through the use of employment multipliers which are based on labor productivity across different regions. The data relevant for calculating the employment factors along with the regional multipliers (SAARC region for this study) can be found in [69].

(2) Human Development Index. The hybrid renewable systems for obvious reasons generate a substantial quantity of excess energy, part of which often cannot be stored due to the storage system's charge remaining at the maximum state. Instead of dumping all of it, a portion of it, if not all, can be used to run new local businesses, small workshops, etc., by supplying it directly or storing it in a storage system of their own since the electricity consumption pattern of a community significantly influences the standard of living of the residents, such a practice will potentially contribute in improving the value of human development index [68]. The HDI has been calculated using the following equation [70]:

$$\mathrm{HDI} = 0.978 \ln\left[\frac{E_{\mathrm{load}} + \min\left(f_{\mathrm{excess}} \times E_{\mathrm{excess}}, f_{\mathrm{load}} \times E_{\mathrm{load}}\right)}{N_{\mathrm{residents}}}\right] - 0.0319, \tag{8}$$

where f_{excess} and f_{load} denote the factors that determine the maximum quantity of excess energy to be sent for utilization of the new businesses and the maximum permissible new load in comparison with the total load demands of the community, respectively.

3.4.4. Exergy Analysis

(1) PV Module. The exergy of a PV module depends on both the parameters of energy flow and the environment. The exergy efficiency of a PV module can be determined using the following equation [70]:

$$\eta_{\mathrm{ex},PV} = \frac{E_{x,\mathrm{out}}(t)}{E_{x,\mathrm{in}}(t)}, \tag{9}$$

where $E_{x,\mathrm{in}}(t)$ is the input exergy of solar irradiance and $E_{x,\mathrm{out}}(t)$ is the exergy output of a PV system. The exergy input and output can be found in (10) [70, 71] and (11) [70], respectively, whereby $T_{\mathrm{amb}}(t)$ and T_{sun} are the atmospheric and the sun temperature, respectively, and $E_{x,\mathrm{ther,PV}}$ is the thermal exergy loss from the PV surface to the atmosphere can be calculated using the following equations:

$$E_{x,\mathrm{in}}(t) = \left[1 - \left(\frac{4}{3}\right)\left(\frac{T_{\mathrm{amb}(t)}}{T_{\mathrm{sun}}}\right) + \left(\frac{1}{3}\right)\left(\frac{T_{\mathrm{amb}}(t)}{T_{\mathrm{sun}}}\right)^4\right] \times G(t) \times \mathrm{A}, \tag{10}$$

$$E_{x,\mathrm{out}}(t) = E_{x,\mathrm{elec}}(t) - E_{x,\mathrm{ther,PV}}(t), \tag{11}$$

$$E_{x,\mathrm{ther,PV}}(t) = Q(t) \times \left[1 - \frac{T_{\mathrm{amb}}(t)}{T_{\mathrm{PV}}(t)}\right], \tag{12}$$

where $Q(t)$ is the heat transfer from the module to the atmosphere and can be calculated using the following equation:

$$Q(t) = U(t) \times A \times \left(T_{\mathrm{PV}}(t) - T_{\mathrm{amb}}(t)\right). \tag{13}$$

The overall heat transfer coefficient (U) of a PV module is the sum of the convection and radiation loss, and (14)–(16) are used to determine the convective heat transfer coefficient [72] and radiative heat transfer coefficient [73], respectively.

$$U(t) = h_{\mathrm{conv}}(t) + h_{\mathrm{rad}}(t), \tag{14}$$

$$h_{\mathrm{conv}}(t) = 2.8 + 3 \times W_s(t), \tag{15}$$

$$h_{\mathrm{rad}}(t) = \epsilon \times \sigma \times \left(T_{\mathrm{sky}}(t) + T_{\mathrm{PV}}(t)\right)\left(\mathrm{T}_{\mathrm{sky}}^2(\mathrm{t}) + \mathrm{T}_{\mathrm{PV}}^2(t)\right), \tag{16}$$

where σ refers to the Stefan–Boltzmann constant (5.67×10^{-8} W/m^{2}K), ϵ refers to the emissivity of the panel (0.9), and $T_{sky}(t)$ refers to the sky temperature ($T_{sky}(t) = T_{amb}(t) - 6$) [73].

(2) Biomass Gasifier. The exergy efficiency of a biomass gasifier is obtained using the following equation [74]:

$$\eta_{ex,BG} = \frac{P_{BG}(t)}{\dot{E}x_f(t)}. \tag{17}$$

The exergy rate, $\dot{E}x_f$, of input fuel is determined using (18) [74], whereby LHV is the lower heating value of biomass, ω is the moisture content and the biomass parameter, and β is calculated using (19) [74].

$$\dot{E}x_f(t) = \left[\left(\text{LHV} + \omega h_{fg}\right)\times\beta + 9.417S\right], \tag{18}$$

$$\beta = 0.1882\frac{H}{C} + 0.061\frac{O}{C} + 0.0404\frac{N}{C} + 1.0437. \tag{19}$$

4. Results and Discussion

The present study explores the feasibility of using PV/biomass/batt by analyzing the different factors affecting the financial, social, and environmental benefits. In achieving this, the stand-alone PV/biomass/batt option is compared with the PV/diesel/batt and PV/MGT/batt ones. The effects of variation of different hardware components and the husk price on the COE are also discussed. The impact of the energy system on human health, the ecosystem, the job creation of the rural areas, and the human development index are extensively analyzed.

4.1. Effects of Different Prime Movers. A comparative analysis of the stand-alone system is carried out by considering three different prime movers and the PV-only system with the lead-acid battery. Three different backup sources (biomass gasifier, diesel generator, and MGT) are compared based on the technical, monetary, and environmental points of view. These hybrid options are further compared with the PV/batt only while meeting the same load. An overview of the optimized results from different system configurations is presented in Table 5.

Results presented in Table 5 indicate that the COE and NPC for the PV/biomass/batt system are 0.314 \$/kWh and \$631,710, respectively. This hybrid renewable option entails of 83.30 kW rated PV module, two 50 kW biomass gasifiers, 470 kWh battery capacity, and 32.10 kW inverter. The biomass generator is used to satisfy 46% of the total load demand (186,150 kWh/yr), whereas PV supplies 54% of the load requirements. The hybrid system has a renewable fraction of 100% and generates an excess energy fraction of 8% only of the total energy generation. More importantly, the system does generate any harmful emissions to the atmosphere. In the PV/biomass/batt-based system, larger capital investment is required for the biomass gasifier (45%), whereas capital costs for the PV module, battery, and converter need 31%, 21%, and 3% of total capital investment, respectively (Figure 6(a)). The replacement and operating costs are mostly needed for the gasifier and the battery, and the resource cost is for purchasing the rice husk biomass.

The PV/diesel/batt option has the lowest COE and NPC of 0.284 \$/kWh and \$572,909, respectively. As reported in Table 5, this system has a slightly lower COE than that of PV/biomass/batt (0.314 \$/kWh) one. This is because the capital investment of the diesel-based hybrid option (Figure 6(b)) is inferior to the biomass gasifier system (Figure 6(a)). However, the resource cost for the PV/diesel/batt option is found to be significantly higher (54% of total NPC) than the PV/biomass/batt. This is due to the higher diesel fuel cost than the biomass cost. The PV/diesel/batt system generates excess energy of 15,566 kWh/yr (7% of total energy generation). However, the RE fraction for this system is much lower (46%) compared to the biomass-based option. Although the cost is slightly lower for the PV/diesel/batt system than the PV/biomass/batt one, the environmental emissions are substantially higher in the former system, and the biomass-based system does not generate any emissions.

The COE (0.377 \$/kWh) and NPC (\$758,726) for PV/MGT/batt are higher than the PV/biomass/batt and PV/diesel/batt ones (Table 5) due to the more substantial capital investment for the MGT-based system (Figure 6(c)). Since the efficiency and power output of MGT are lower than the similar capacity of diesel and biomass generators [75, 76], the MGT-based system has a higher PV and battery capacity than the other two systems. Therefore, the renewable contribution (82%) for the MGT system, as well as the excess energy generation, is higher in the MGT-based system than diesel-based one. However, the environmental emissions generations are almost half in PV/MGT/batt one than that of the PV/diesel/batt.

In summary, the higher resource cost of the PV/diesel/batt system reflects the cost-effective application of PV/biomass/batt, where the diesel fuel cost is high. However, the total investment cost throughout the project lifetime for the PV/diesel/batt system is lower than the other systems studied. Islam et al. [77] found that the COE for the PV/biomass/batt option was 0.201 \$/kWh. However, they consider a discount rate of 6%, and the capital cost for the biomass gasifier was 1100 \$/kW. In this context, the COE for the PV/biomass/batt of the present study is comparable, considering the above economic values. As the gasifier runs on the biomass, the PV/biomass/batt system necessarily does not release any CO_2 to the environment.

In contrast, the diesel-based and MGT systems generate 106,310 kg/yr and 53,119 kg/yr of CO_2, respectively (Table 6). In relation to the RE penetration, the PV/biomass/batt and PV/batt systems have 100% renewable penetration, whereas the MGT-based hybrid option has the RE penetration of 82% still representing a much higher penetration than that of the diesel-based hybrid one (only 46%). The excess energy generation from the PV/biomass/batt system (17,572 kWh/yr) is comparable with the PV/diesel/batt one but fewer than the MGT-based hybrid option. The above analysis indicates the superiority, both from techno-economic, social, and ecological viewpoints, of the PV/

Table 5: Optimized sizing of using different backup sources of HES.

Characteristics	PV/biomass/batt	PV/diesel/batt	PV/MGT/batt	PV/batt
COE ($/kWh)	0.314	0.284	0.377	0.602
NPC ($)	631,710	572,909	758,726	1,210,926
PV capacity (kW)	83.30	60.5	118	417
Generator capacity (kW)	2 × 50	2 × 50	2 × 50	—
Battery capacity (kWh)	470	173	767	2,321
Inverter capacity (kW)	32.10	41.20	47	118
Renewable fraction	100	46	82	100
PV energy (kWh/yr)	134,280	97,491	190,785	672,094
Generator set energy (kWh/yr)	85,186	114,112	47,787	—
Fuel usage (l/yr)	267 tons/yr	40,616	20,153	—
Excess energy (kWh/yr)	17,572 (8%)	15,566	27,304	452,430
Unmet load (kWh/yr)	0	0	0	130

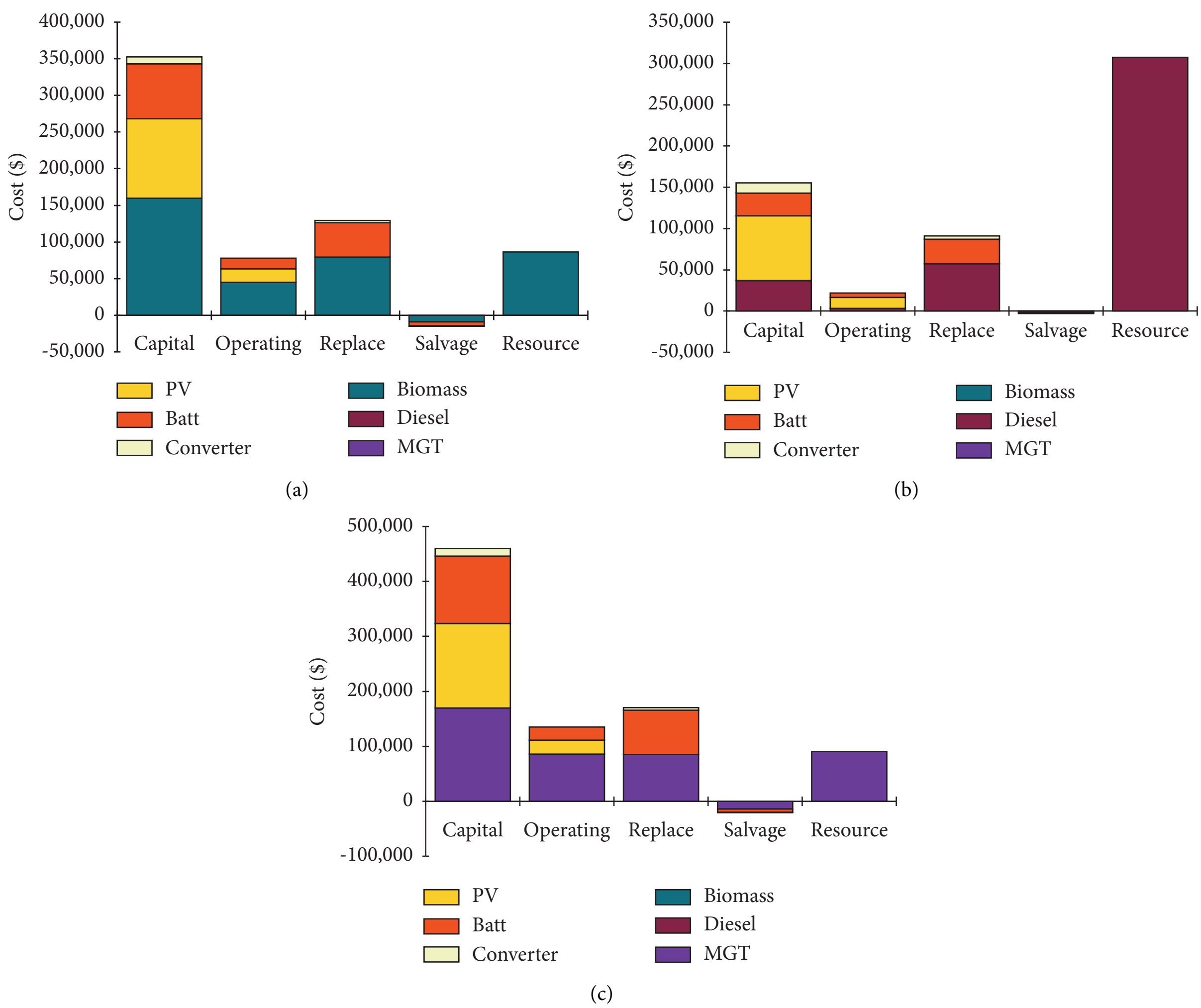

Figure 6: NPC breakdown of the hybrid systems: (a) PV/biomass/batt, (b) PV/diesel/batt, and (c) PV/MGT/batt.

biomass/batt system over the other options studied. Figure 7 illustrates the time-series data to show how the load demand is met using different system components. The results show that the biomass gasifier is used to meet electricity when PV and battery are unable to supply power.

4.2. Implications on Human Health and Ecosystem. As presented in Table 6, only the diesel generator and MGT-based systems emit GHGs, while it is significantly higher for diesel-based ones compared to MGT. Consequently, the PV/diesel/batt system inflicts more damage to human health

Table 6: Environmental pollutants from HES.

Pollutants	PV/biomass/batt	PV/diesel/batt	PV/MGT/batt	PV/batt
CO_2 production (kg/yr)	—	106,310	53,119	—
CO production (kg/yr)	—	674	129	—
Unburned hydrocarbon (kg/yr)	—	29.2	0	—
Particulate matter (kg/yr)	—	40.4	3.65	—
SO_x (kg/yr)	—	260	132	—
NO_x (kg/yr)	—	539	271	—

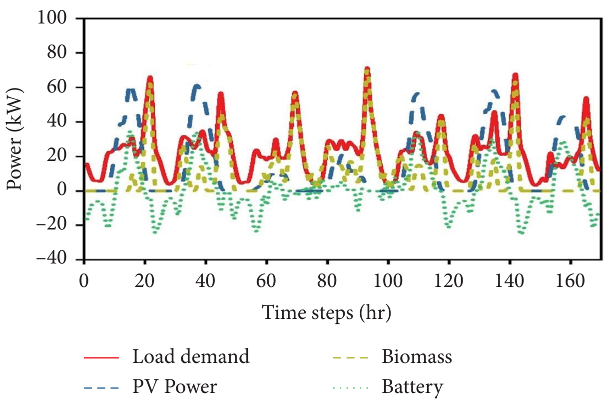

Figure 7: Time-series data showing the share of energy from different components of PV/biomass/batt system meeting the load requirements.

(1.25$E-01$ DALYs) and ecosystem (4.22$E-04$ species·yr) than PV/MGT/batt (5.19$E-02$ DALYs and 2.12$E-04$ species·yr), as it can be seen in Figure 8(a). To a typical society, such extent of damage to human health is worth \$6331 to as high as \$15,211, while for the ecosystem, it is within \$3312-\$6608 (Figure 9(b)). With the proposed biomass-based system emitting zero carbon in operation, such damages can be averted.

4.3. Social Benefits Created. The total number of permanent full-time jobs created by the hybrid systems is presented in Figure 10(a). An apparent trade-off in the job creation quantity can be noticeable from the results, as the higher number of jobs are created by the systems involving higher sizing of the components for meeting the same load (PV/batt system with 15.15 jobs for example), something that is less appreciable in hybrid systems for numerous reasons. At the expense of 10.56% more energy cost, the PV/biomass/batt creates two more jobs (3.41 jobs) than the PV/diesel/batt system (1.41 jobs). Although the PV/MGT/batt system creates 1.6 jobs more than PV/biomass/batt, it comes with around a 20% increase in the energy cost.

Figure 10(b) depicts the HDI values for the community implementing different hybrid system scenarios. There are 250 persons residing in the community with a total of 186,150 kWh/yr of load demand. Using these values, the current HDI value of the community has been calculated to be 0.6148, which is depicted by the dotted vertical line. In this scenario, all the new loads will essentially be covered by the total load demand of the community. To compute the HDI values when the hybrids are installed, it was assumed that the new loads will not be greater than 50% of the total load demands, i.e., $f_{\text{load}} = 0.5$ (refer to (8)), and 50% of the total excess energy will be utilized to supply the new loads ($f_{\text{excess}} = 0.5$). As it can be seen in the figure, each of the systems incurs some extent of increase in the HDI values, higher for those having greater sizing and more excess energy. Such a scenario substantiates the hybrid system's potential of enhancing the living standard of the concerned community while providing a reliable electricity supply.

4.4. Energy and Exergy Analyses. Figure 9 represents the outcomes of the energy and exergy analyses of the PV/biomass/batt hybrid system. As it can be observed in Figure 9(a), solar energy accounts for 64.27% of the total energy input to the system, only 16.89% of which could be recovered as useful energy where the rest is lost due to reflectance and the conversion to thermal energy. In the biomass gasifier, this loss is estimated as 80.27% of the total energy content of the biomass. In the case of the hybrid system as a whole, about 82.26% of total energy input is lost where 8.43% of the total recovered energy is lost in battery and converter action. Exergy flow in the system, presented in Figure 9(b), shows an obvious resemblance to the energy flow scenario. However, some differences can also be noticeable. Slightly lower PV input accounts for the dead state condition where higher biomass exergy content is due to the additional exergy in moisture, required in the chemical reaction. The combined influence of such difference results in an overall exergy input higher than that of energy. Around 83% of exergy input to the hybrid system is lost, of which around 61% is from PV. In the output exergy, the contribution from biomass is similar to that of energy. However, thermal exergy loss in PV (11) causes a reduction in the overall output exergy and the total useful exergy from the system. The energy and exergy efficiency values are presented in Figure 9(c). Having no thermal conversion involved, battery and converter efficiencies are similar for energy and exergy. Reflecting the discussion, biomass efficiencies are higher than PV, and the overall system exhibits energy and exergy efficiencies of 16.24% and 13.09%, respectively.

4.5. Sensitivity Analysis. In this section, the effects of uncertainty or changes in the model inputs, such as solar irradiation, economic parameters, or future biomass fuel price, on the optimization results are analyzed. In this study, the obtained results are further extended to identify the

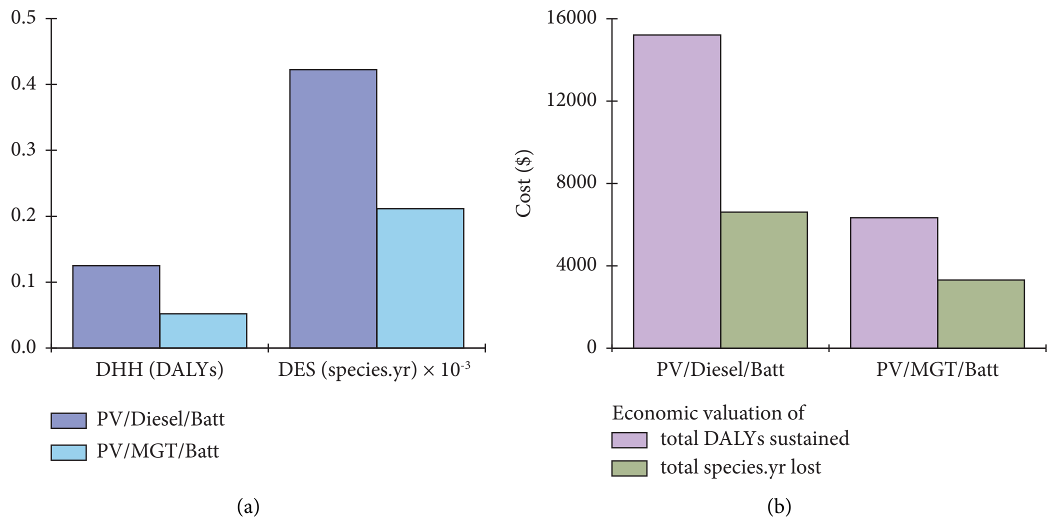

FIGURE 8: Impact of GHG emission on human health and the ecosystem: (a) the estimated damages and (b) the monetary valuation of the damages.

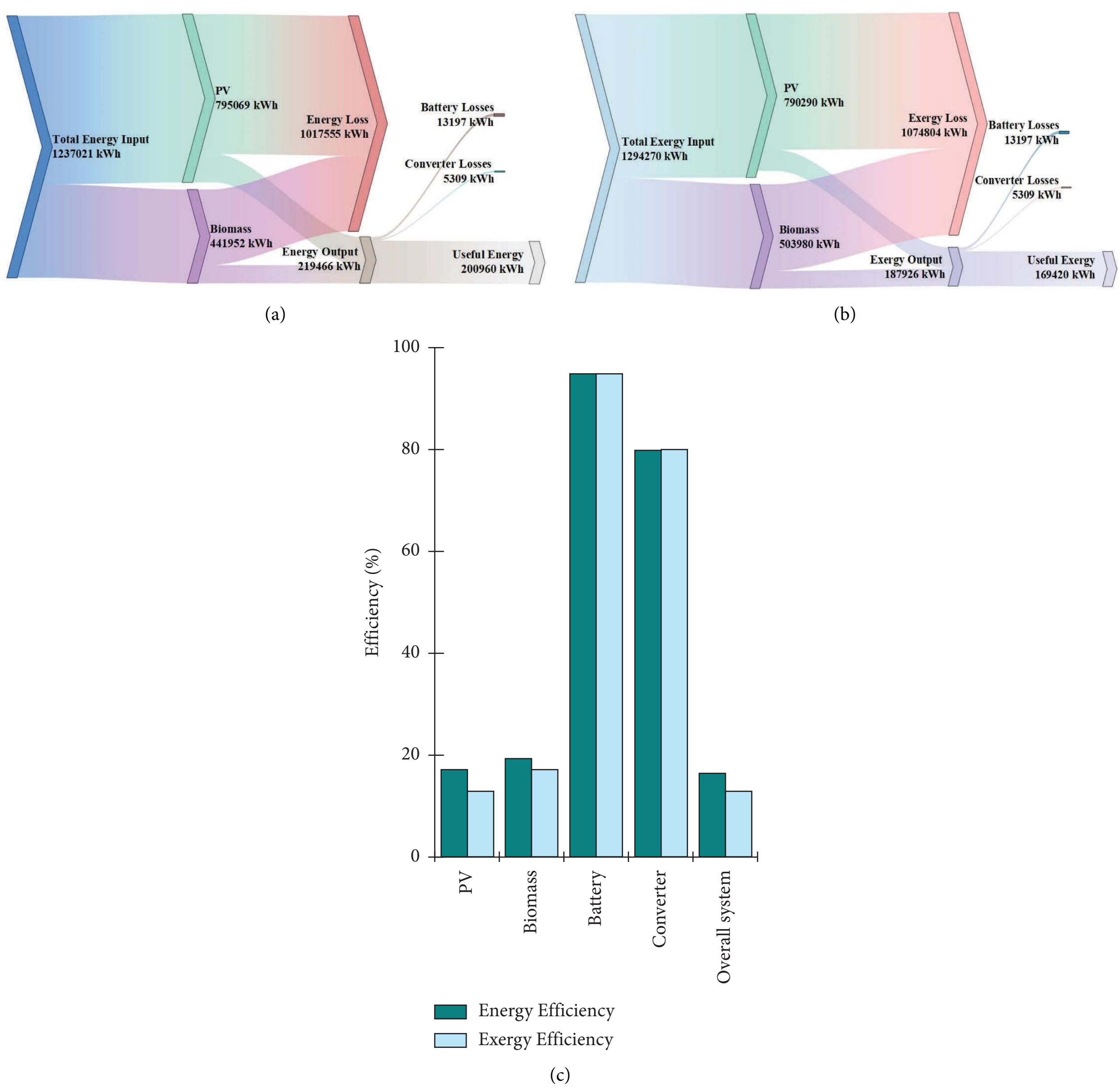

FIGURE 9: Energy and exergy analyses of the proposed hybrid renewable system: (a) energy flow of the system, (b) exergy flow of the system, and (c) energy and exergy efficiencies of the components and the entire system.

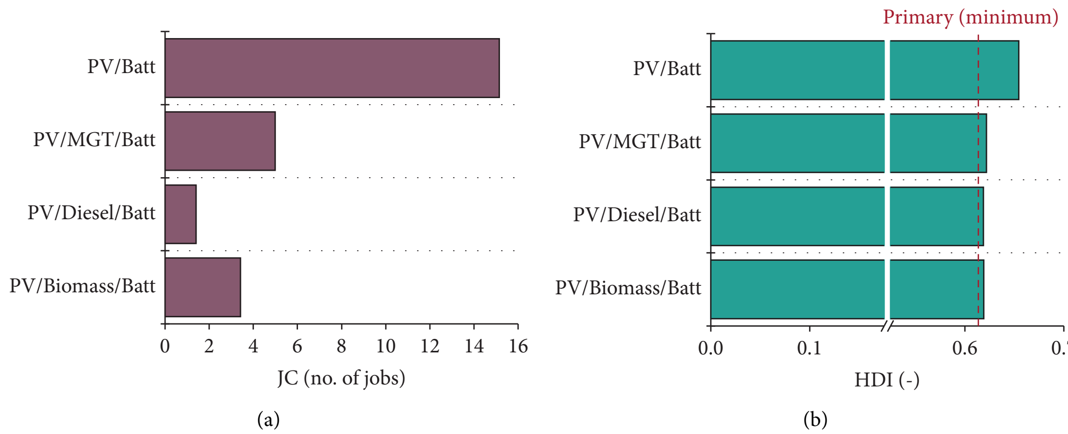

Figure 10: Social benefits created the hybrid systems: (a) number of jobs created and (b) human development index. The dotted vertical line in (b) indicates the value of HDI in the absence of the hybrid systems.

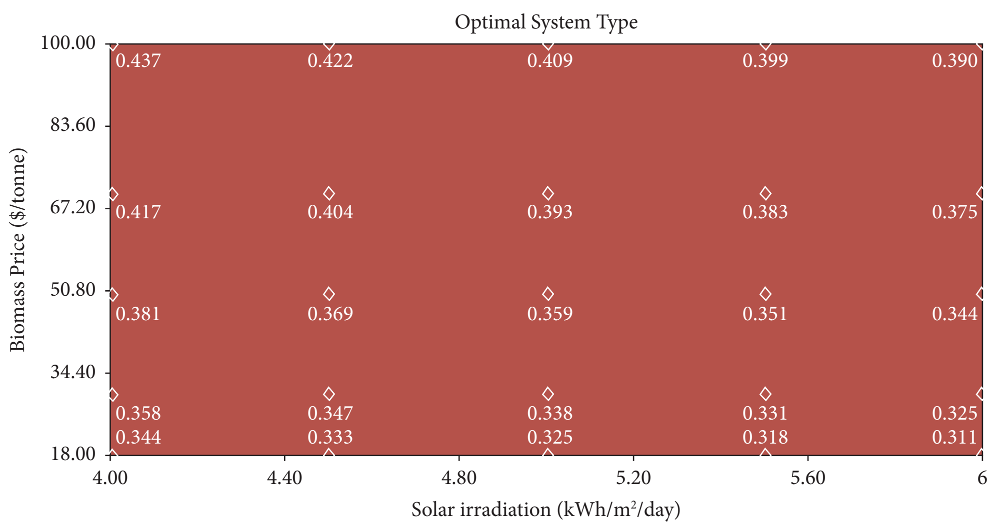

Figure 11: Effects of solar irradiation and biomass price on the COE for PV/biomass/batt system.

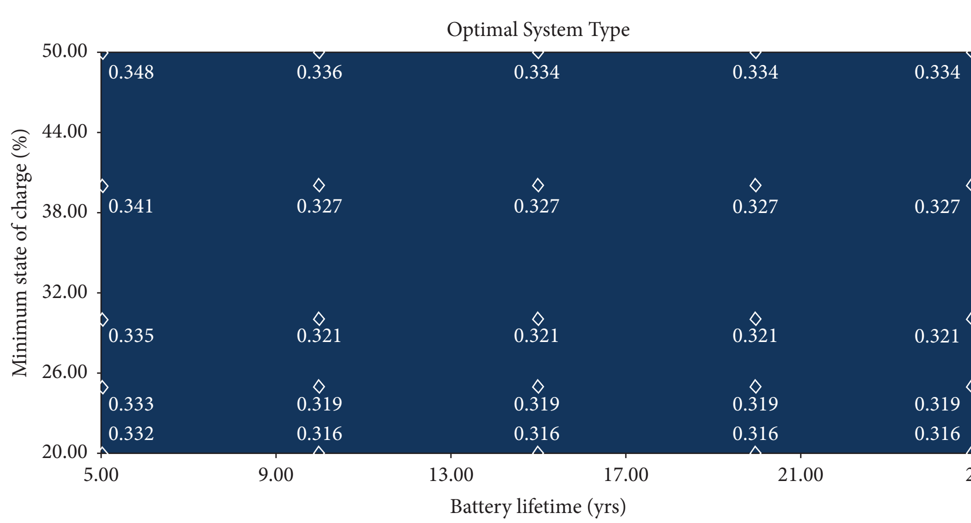

Figure 12: Effects of battery lifetime and minimum state of charge on the COE for PV/biomass/batt system.

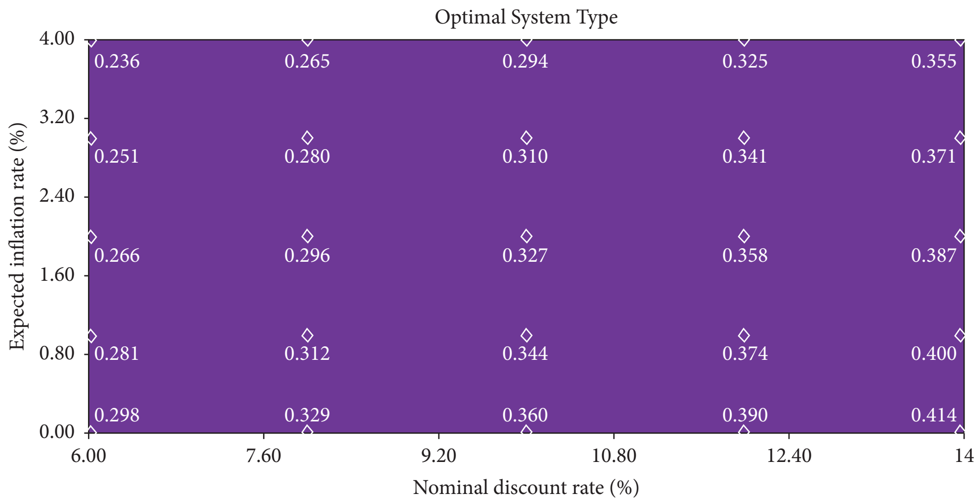

Figure 13: Effects of nominal discount rate and inflation rate on the COE for PV/biomass/batt system.

effects of the change in various parameters, mainly the solar irradiation and rice husk price, as reported in Figure 11. It can be seen from Figure 12 that the biomass (rice husk) price and the solar irradiation have significant effects on the COE. The lowest cost (0.31 \$/kWh) is achieved at a biomass price of 18 \$/ton and solar irradiation of 6 kWh/m^2/day. The COE grows to 0.344 \$/kWh at a biomass price of 50 \$/ton with the same solar irradiation. However, when the solar irradiation decreases from 6 kWh/m^2/day to 5 kWh/m^2/day, the COE rises to 0.359 \$/kWh at a biomass price of 50 \$/ton.

Figure 13 depicts the effects of the discount rate and inflation rate of the unit energy costs (the baseline rate: 10% discount rate and 2% inflation rate). It is clear from Figure 13 that the COE increases from 0.298 \$/kWh to 0.36 \$/kWh when the discount rate rises from 6% to 10% at the zero-inflation rate. The cost is decreased when the inflation rate increases with the same discount rate as reported in Figure 13.

The sensitivity analysis is further extended to analyze the effects of battery lifetime and minimum state of charge (SOC) of LA battery on the COE, as reported in Figure 13. The LA has to maintain at least 20–40% minimum state of charge for its longevity [78, 79]. As seen in Figure 13, battery lifetime has insignificant effects on the COE. The COE slightly decreases from 0.332 \$/kWh to 0.316\$/kWh at the minimum SOC of 20%. As the minimum SOC increases, the COE rises due to the larger capacity battery that is required to satisfy the load demand.

5. Conclusions

The present study analyses a stand-alone PV/biomass/batt for the sustainable remote village electrification in Bangladesh. The stand-alone hybrid PV/biomass/batt configuration is compared with the hybrid PV/diesel/batt and the PV/MGT/batt ones. Along with techno-economic features, the social sustainability and the impact on human health and the ecosystem have been discussed. The key findings of this study are summarized as follows:

(i) The COE for the hybrid PV/diesel/batt system (0.284 \$/kWh) turns out to be slightly lower than that of the PV/biomass/batt (0.314 \$/kWh) one. However, the former generates a significant amount of operational CO_2 (106,310 kg/yr). Although the PV/MGT/batt-based hybrid option produces half of the CO_2 than the PV/Diesel/Batt system, the COE is much higher than the latter.

(ii) With no operational greenhouse gas emission, the PV/biomass/batt system can potentially save maximum damages of $1.25E-02$ DALYs and $4.22E-04$ species yr, respectively, on human health and the ecosystem compared to the diesel-based system which has been characterized as the most damaging option. Economically, such extent of damage can be worth \$15,211 and \$6,608, respectively, to the society.

(iii) All the renewable-based hybrid scenarios cause appreciable improvements in the present value of the human development index. Moreover, the proposed biomass-based system holds the potential to create 3.41 jobs in the community, while diesel, MGT, and PV-only systems can create 1.41, 4.98, and 15.15 jobs, respectively. The trade-off of sizeable hardware in achieving better social benefits renders the necessity of consideration of social indicators as objectives of optimization.

(iv) According to the exergy analysis, around 83% of the total input cannot be utilized, in which PV contribution is 61%. Consequently, biomass efficiencies are found higher than PV. The overall system exhibits energy and exergy efficiencies of 16.24% and 13.09%, respectively.

(v) The sensitivity analysis indicates that the overall capital cost has notable effects on the COE, with no or little effect on the rice husk price. Also, battery lifetime has minimal effect on the values of COE.

This study highlights the potential of cost-effective electrification based on hybrid renewable energy systems which can be both environmentally benign and socially sustainable. The outcomes from this study can be beneficial in promoting and incentivizing renewable expansion in developing countries around the world. Further research can be enhanced by considering the power quality, stability, and different reliability indices for the microgrid application.

Data Availability

The data used for the optimization will be available with corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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