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Techno-economic assessment of a hybrid renewable energy storage system for rural community towards achieving sustainable development goals

S.B. Wali [a], M.A. Hannan [b,c,*], Pin Jern Ker [c], M.S. Abd Rahman [a], S.K. Tiong [c], R.A. Begum [d], T.M. Indra Mahlia [e]

[a] *Department of Electrical and Electronic Engineering, Universiti Tenaga Nasional, Kajang, 43000, Malaysia*
[b] *School of Engineering and Technology, Sunway University, Bandar Sunway, Petaling Jaya, 47500, Malaysia*
[c] *Institute of Sustainable Energy, Universiti Tenaga Nasional, Kajang, 43000, Selangor, Malaysia*
[d] *UTS Business School, University of Technology Sydney, Ultimo, NSW, 2007, Australia*
[e] *School of Civil and Environmental Eng., University of Technology Sydney, Ultimo, NSW 2007, Australia*

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ABSTRACT

Urbanization and population growth are driving carbon emissions, along with the imperative for renewable energy transition, necessitating researching the impact of hybrid renewable energy storage systems towards achieving sustainable development goals. The article presents a techno-economic assessment of a stand-alone hybrid system in a grid-deficient rural community in a developing country, Bangladesh. The optimal system sizing includes an 8.67 kW of photovoltaic, 7 kWh lithium-ion battery, 6 kW of electrolyzer, 1.8 kW fuel cell, 5 kg of hydrogen tank and 1.67 kW converter, which can achieve a net present cost of $25,099 and levelized cost of energy of 0.34/kWh. Results show hybrid system supports sustainable development goals by offering clean energy, emphasizing the need for government support, investment, and scaling in rural developing areas.

1. Introduction

The Sustainable Development Goals (SDGs) of the United Nations (UN), which were approved in 2015, present a framework consisting of 17 goals and 169 targets for global development [1]. The SDGs serve as a guideline for countries to follow for establishing a prosperous and ecologically safe future. Energy is a key facilitator in reaching the SDGs and it should be inexpensive, reliable, sustainable, and contemporary. Researchers focus on developing energy models and assessing the impact on the 169 targets of the 17 goals of SDGs. To present, efforts to include the SDGs in the energy system modelling have mostly focused on including land, energy, water, and climate in optimal modelling approaches. Energy system modelling is divided into three categories: energy economy, capacity expansion/optimization, and power systems modelling [2]. The energy economy includes supplying, converting, transporting, and using energy resources by converting them from naturally accessible forms to meet the necessary demands in an economically efficient way [3]. Capacity expansion/optimization refers to modelling energy resources considering unforeseen demand, non-zero lead times, and random cost overruns in the most cost-effective and economical, friendly way, and the modelling of power systems is used to examine the system reliability and operating parameters [4]. Within the limits and trade-offs described in the modelling approach, these models are aimed at determining the best global development pathways.

Electricity plays an important role in achieving the SDGs all around the world. A reliable, sustainable, and clean energy generation not only has a positive impact on the global economy and development but also the environment. In the recent era of industrialization, the surge in the burning of fossil fuels and the lack of fossil fuels is pushing the industry to move towards renewable energy (RE) options such as photovoltaic power (PV), wind power (WP), hydrogen storage (HS) and battery energy storage systems (BESS). Developing countries such as Bangladesh's electricity production has traditionally relied on fossil fuels (74%) and renewable energy schemes have a poor penetration in energy production (0.02%) [5]. Combusting wood, straw, leaves, dried cow dung, and kerosene releases substantial greenhouse gas (GHG) emissions into the environment. Besides this, PM 2.5 concentrations have been steadily increasing since 2010, and an estimated 100,000 people die each year because of rising air pollution [6]. The foregoing facts require

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* Corresponding author. School of Engineering and Technology, Sunway University, Bandar Sunway, Petaling Jaya, 47500, Malaysia.
E-mail address: hannan@sunway.edu.my (M.A. Hannan).

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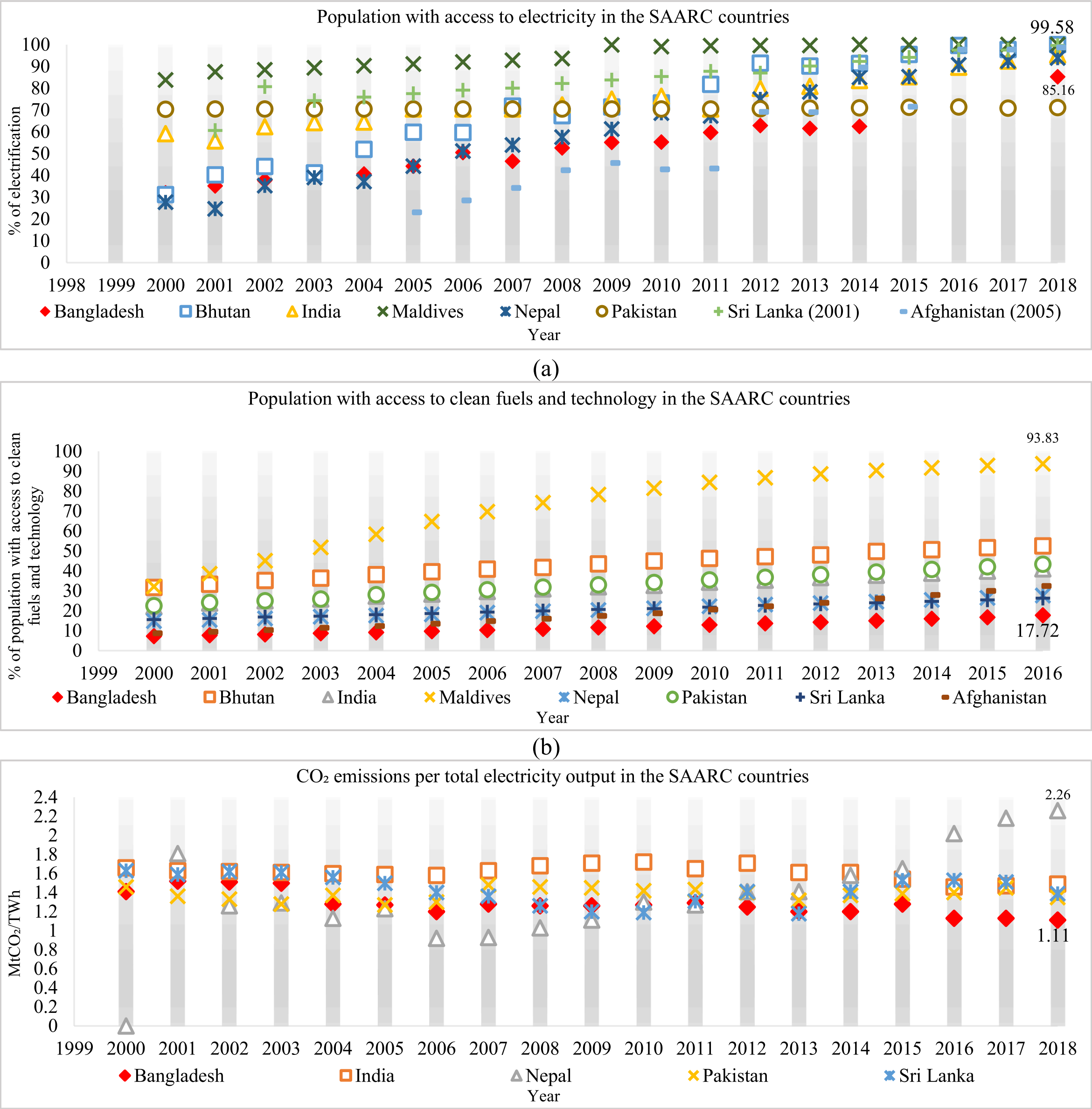
developing countries to play a pivotal role in the transition to a clean energy future.

A comparative study between the South Asian Association for Regional Cooperation (SAARC) included countries achieving various SDG targets is represented in Fig. 1 [7]. In Fig. 1(a) the country's situation until 2018 towards achieving SDG 7 target 2 indicator 9 which is "accessibility to electricity as a percentage of the population". The highest 100% of people in Bhutan have access to electricity followed by Sri Lanka with 99.58%. Only 85.16% population of Bangladesh has access to electricity. In Fig. 1 (b) the percentage of the population having access to clean fuel for cooking is shown and it can be seen that Bangladesh has the lowest 17.72% of people having access to clean fuel for cooking among the SAARC countries while the Maldives has the highest percentage (93.83%). According to Census 2011, 39.5% of people used kerosene as a source of light whereas 1% of people used it as cooking fuel. Moreover, wood and Straw/Leaf/Dried cow dung are used as cooking fuel by 34.8% and 51.2% of people respectively [8]. In Fig. 1 (c) the CO_2 emissions per total electricity output are shown and Nepal has the highest CO_2 emission (2.26 $MtCO_2/TWh$) whereas a more agriculture-oriented country like Bangladesh has the lowest (1.11 $MtCO_2/TWh$). The overall SDG index score of Bangladesh is 63.5 which is 109th in the world [9].

Developing the HRES can play a significant role in helping to achieve the United Nations' SDGs by replacing or using it alongside the existing power system. HRES combines multiple energy storage technologies, such as batteries, flywheels, hydrogen storage and supercapacitors, to store and manage energy from renewable sources such as solar and wind [10]. According to Ref. [11], in achieving the SDG targets the battery energy storage system (BESS) has positive impacts on over 60 targets and negative impacts on over 22 targets. So, the implementation of an HRES system has a great potential to achieve a higher score in SDGs goals. The Advantages of HESS for rural communities in developing countries are as follows.



(a)

(b)

(c)

Fig. 1. Comparison of SAARC countries in achieving various SDG targets (a) Population with access to electricity (SDG 7.1.1) (b) Population with access to clean fuels and technology (SDG 7.1.2) (c) CO_2 emissions per total electricity output (SDG 13.2.2).

- **Improved Energy Access**: HESS can help ensure a consistent energy supply in remote and rural areas, providing access to electricity for essential services such as lighting, healthcare, and communication.
- **Increased Reliability**: HESS provides backup power during power outages and grid failures, reducing the dependence on diesel generators.
- **Environmental Benefits**: HESS helps reduce carbon emissions by promoting the use of clean and renewable energy sources.
- **Economic Benefits**: HESS can help reduce energy costs and improve energy security for rural communities, promoting economic development and poverty reduction.

Design optimization of the HRES is essential to increase exhibition and reliability, which can meet external load requirements, lower energy costs and net present costs (NPC), and reduce GHG emissions [12,13]. Although, developing an optimized HRES system for rural areas is a difficult task as factors such as site selection, techno-economic feasibility, installation cost (IC), operation cost (OC), maintenance cost (MC), load shifting, reliability, voltage and frequency regulation, BESS ageing, environmental impact, and availability of technologies can affect the system performance [10,14]. Several researchers have introduced various models and optimization methods for developing an efficient HRES system to overcome these issues. In Table 1, a few existing approaches for developing hybrid optimization models are presented.

Nojavan et al. In Ref. [23], it was shown that considering the demand response program (DRP) while constructing a microgrid, the cost is 13.34% less than the nominal condition. The total cost and loss of load expectation (LOLE) are considered the two main objective functions. The heuristic approach such as; Genetic Algorithms (GA) [19], Particle Swarm Optimization (PSO) [12], Tabu searches [24], and bat algorithms [25] is also used to optimize overall system cost, system sizing and capacity. In Ref. [19], GA is implemented to improve the performance of the distribution network by reducing the negative impact of high PV penetration. A Multi-Objective PSO (MOPSO) approach is considered in Ref. [12], and the cost is considered as the key objective function. The result shows that PV-wind-battery-based systems have less Net Production Cost (NPC) (2%) and less loss of power supply (LPSP) than the other two systems. The most renowned rule-based approach is Fuzzy logic [16] where Fossati et al. have shown a fuzzy-based energy management system (EMS) for cost and capacity optimization and the outcome shows that 3.2% of the overall cost of the microgrid can be reduced through the optimization of BESS.

The optimization using HOMER (Hybrid Optimization Model for Electric Renewable) is mostly applied to villages or remote islands [15,17]. In Ref. [15], the RE penetration is only 14% and it is concluded that, if there is a possibility of hydropower, the advantage should be taken and the system cost will reduce with it. It also concluded that penetration of RE such as PV or wind is not always the cost-effective option for a remote island. The existing energy situation and RE prospects of the developing countries are described in Ref. [26] whereas in Ref. [27], a detailed discussion on smart grid (SG) development in developed countries is presented. A model for long-term capacity planning and short-term dispatch for rural areas is presented in Ref. [28]. HOMER software is used in Refs. [5,29], and [30] for developing a hybrid system model for remote areas and analyzing the performance and economic feasibility of the model.

A hydrogen energy storage system (HESS) utilizes hydrogen to store and manage energy from RES, such as solar and wind power and then converts it into hydrogen through a process called electrolysis, which splits water molecules into hydrogen and oxygen. The hydrogen is then stored and can be used later, when needed, to generate electricity through a fuel cell (FC). The advantages of using hydrogen as a storage system include high energy density, flexibility, high efficiency, longevity and environmental friendliness [31,32]. The HESS system is used in Refs. [18,20,21,33] to perform a techno-economic analysis. In Ref. [18], a grid-connected system consisting of PV, FC and batteries is modelled using dynamic modelling (DM), Elman Neural Network (ENN)-based controller, Takagi-Sugeno-Kang based fuzzy gain tuner and Virtual Flux Oriented Control (VFOC) for controlling the power flow between the different HRES system. In Ref. [20], a PV-WT–FC–based system is simulated and a techno-economic assessment is provided considering LCOE using the FPA. A CPVT-WT-Biomass–HS–BESS-based off-grid HRES is modelled in Ref. [21] for driving an Electric vehicle charging station (EVCS) using the PVSyst, HOMER software. Basu et al. have presented three different configurations using the HOMER [33] and the optimal hybrid system configuration includes PV, WT, HS and converter with an LCOE of 0.3387$/kWh.

In this regard, five stand-alone HRES systems with various configuration components are developed for a rural village in a developing country, Bangladesh. A techno-economic and environmental assessment are presented for each configuration and the most optimum, cost-effective and environmentally friendly configuration is nominated for the specific location, Finally, the impact of the proposed optimal HRES system in achieving the SDG’s goals for the rural community of a developing country are briefly discussed. For the simulation, HOMER pro is used for system configuration and village load assessment because it enables the analysis of various system configurations, considering multiple energy sources, storage technologies, and economic factors in

Table 1
A few of the existing studies on the HRES system.

Ref.	Year	Mode	Location	Modelling components	Methods	Research gaps
[15]	2014	Off-grid	India	HP-PV-WT-DG-BESS	HOMER	Techno-economic analysis for the rural communities is presented where systematic demand assessment and stakeholders’ influence are needed to consider.
[16]	2015	–	–	DG-WT + BESS	GA + FLC	Both EMS and battery lifetime modelling for MG are presented. Although, the PV is considered and DG’s environmental impact is not mentioned.
[17]	2017	Grid-connected/off-grid	India	PV-Biomass-DG-BESS	HOMER	The NPC and LCOE for both grid-connected and off-grid modes are considered and grid-connected seems to have a better solution if the 7.5 km with 169 kW/d load. Detailed load profiling and CO_2 emission reduction are needed.
[18]	2018	Grid-connected	–	PV-FC-BESS	DM + ENN + VFOC + FLC	The experimental setup in the FPGA/dSPACE platforms for verification of effectiveness and viability can be proposed.
[19]	2018	Grid-connected	–	PV-BESS	GA	DIgSILENT with Matlab is used to perform the techno-economic and environmental analysis. Although the degradation of battery life is not analyzed.
[20]	2019	Off-grid	Iran	PV-WT-FC	flower pollination algorithm (FPA)	The environmental impact of HS and DG is not included in the article.
[21]	2020	Off-grid	Qatar	CPVT-WT-Biomass–HS–BESS	PVSyst + HOMER + EES	An off-grid EC charging station is developed to minimize cost and rapid battery degradation using RES. Even though, the post-processing of the heat loss produced by CPV/T is not included.
[22]	2022	Off-grid	Iran	PV-WT-BESS-CHP based DG-Boiler	HOMER	Techno-economic analysis to achieve SDG is presented. Although the system with the lowest LCOE has only 37.1% RF leads to high CO_2 emission.

both off-grid and on-grid scenarios and provides valuable insights for decision-making and policy formulation towards sustainable energy solutions. The novelty of this research lies in the comprehensive assessment of the feasibility of the stand-alone HRES system in achieving SDGs. Firstly, a real-time load profile of a rural village is created with extensive analysis and assessment of the overall demand during weekdays and weekends for two different seasons. Secondly, five different system configurations are developed considering the availability of renewable sources. Thirdly, considering the same load profile a comparative techno-economic assessment between LIB and LAB is presented. A comparative techno-economic assessment between the HS-based system and the HS-BESS-based system is also presented. Fourthly, based on the economic and environmental impact the optimal system is chosen. Fifthly, a comparison between the proposed system with various configurations as well as with the existing study is presented. Finally, the benefits of the HRES system to society, the economy, and the environment are described and assessed the impact of the proposed system in achieving the SDGs goals. The main contributions of this study are as follows.

- An economic and environmental impacts analysis regarding different system configurations of renewable sources.
- Provides a comparative performance analysis between the proposed optimal system and existing configurations.
- Evaluates the socio-economic and environmental advantages, along with potential challenges, of the proposed HRES system.
- An impact assessment of the proposed HRES system towards achieving the SDGs.

2. Modelling of the HRES system

The research aims to provide an optimized model for the electrification of rural villages and reduce the current CO_2 emission. The overall research is divided into 3 stages such as 1) Initial assessment 2) simulation and system optimization 3) post-economic analysis and decision. The research was conducted in a rural village named Sutabria in Bangladesh. Initially, the energy consumption units, as well as the load points and load duration, are identified. After that, a load profile of the overall village load consumption in different seasons is created. In the second stage, five different configurations of the HRES model are developed, and a comparative and techno-economic analysis is performed followed by a post-economic analysis. A detailed outline of the research is shown in Fig. 2.

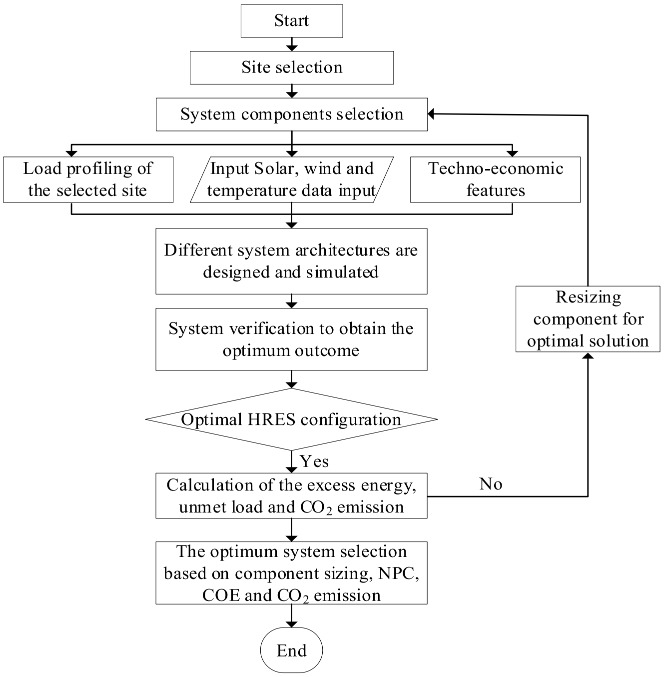


Fig. 2. The overall outline of the research.

2.1. Study area

The proposed HRES configurations are modelled for an off-grid remote village named Sutabaria (Latitude 22°16′ N and Longitude 90°43′ E), which is situated on the banks of the Komolakanto River with an area of 4.802 km^2. According to the Bangladesh Bureau of Statistics [34], the total population is 2838 whereas the total number of households is 675. According to the Rural Electrification Board (REB), Bangladesh, there is no active grid connection with the village [34].

2.2. Village load assessment

In southeast Asia, kerosene is considered the main energy source along with other sources such as burning wood, cow dung, crop residue, etc. [35]. To develop the system, the key factor is to estimate the actual energy consumption of the selected area. Considering the current load profile information available in state government documents for related remote areas, the energy load requirement of the selected area is carefully orchestrated. To acquire a more accurate assumption of the demand data, we have also consulted with experts from utilities, residents, and personal judgments. Because of its geological location, the weather condition is varied. The energy consumption has been calculated separately for two distinct seasons, summer (March to October) and winter (November to February) whereas January is considered the coolest month and June is considered the warmest month. Not only have the necessary utilities for energy consumption in households, schools, and industrial and commercial purposes been considered, but also the user patterns, operation hours in different seasons, and load points are carefully estimated. In this study, the village load is classified into two categories such as domestic loads which include all the household energy consumptions (light, fan, TV, etc.), and other loads which include agricultural loads (pumps), shops, small manufacturing units (such as milk processing plants, cottage industries, and cold storage), and a post office.

The estimated load are used to create the daily load profile for each month for the selected area as shown in Fig. 3(a). From the Sutabaria village load assessment, it can be calculated that the annual average load is 1209.2 kWh/day, whereas the daily average load is 50.38 kW. The Peak load is considered 161 kW and the load factor is 0.31. The optimization operation is conducted for 8760 h. The load profile is categorized into four categories according to the summer and winter seasons such as weekdays of January, the weekend of January, weekdays of June, and the weekend of June as shown in Fig. 3(b).

2.3. Resource assessment

To develop a suitable cost-effective environment-friendly HRES system for the rural area, PV, WT, BESS, DG, and HS are considered. For the main RE resources, PV and WT are considered. However, due to the unreliability of renewable energy (RE), using a DG as a backup power generator in combination with BESS-based systems improves system stability [29]. The monthly average solar radiation (SR), wind, and temperature data have been acquired from NASA (National Aeronautics and Space Administration) [36]. The monthly solar radiation data for a whole year is shown in Fig. 4 (a), where it can be illustrated that the highest average solar radiation is in April (5.65 $kWh/m^2/day$) followed by March (5.57 $kWh/m^2/day$) whereas the highest clearness index was found in December (0.623). The months in the winter season (Nov–Feb) have the highest average clearness index (0.602) than summer (Mar–Oct) (0.448). Fig. 4 (b) illustrates that July has the highest wind speed of 6.56 m/s and the average wind speed for a year is 4.72 m/s. The

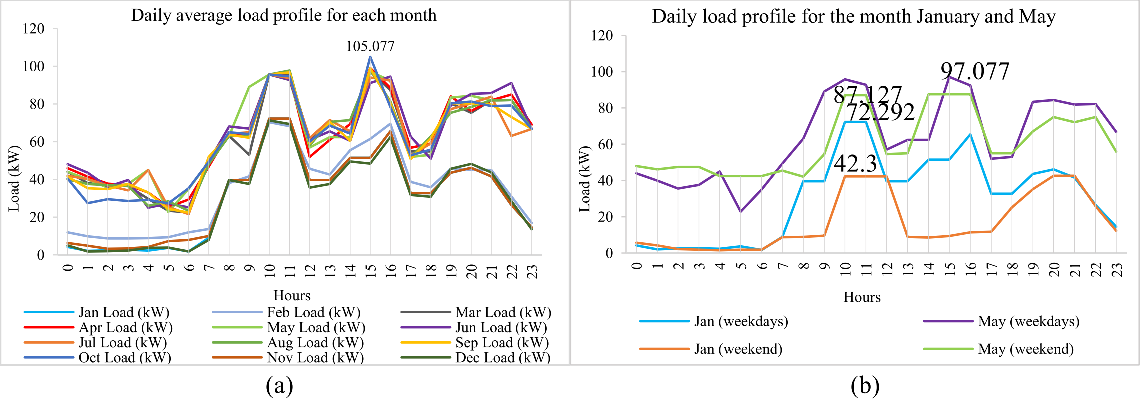


Fig. 3. Load profile of the rural community (a) daily average load profile for each month (b) from the month of January and June.

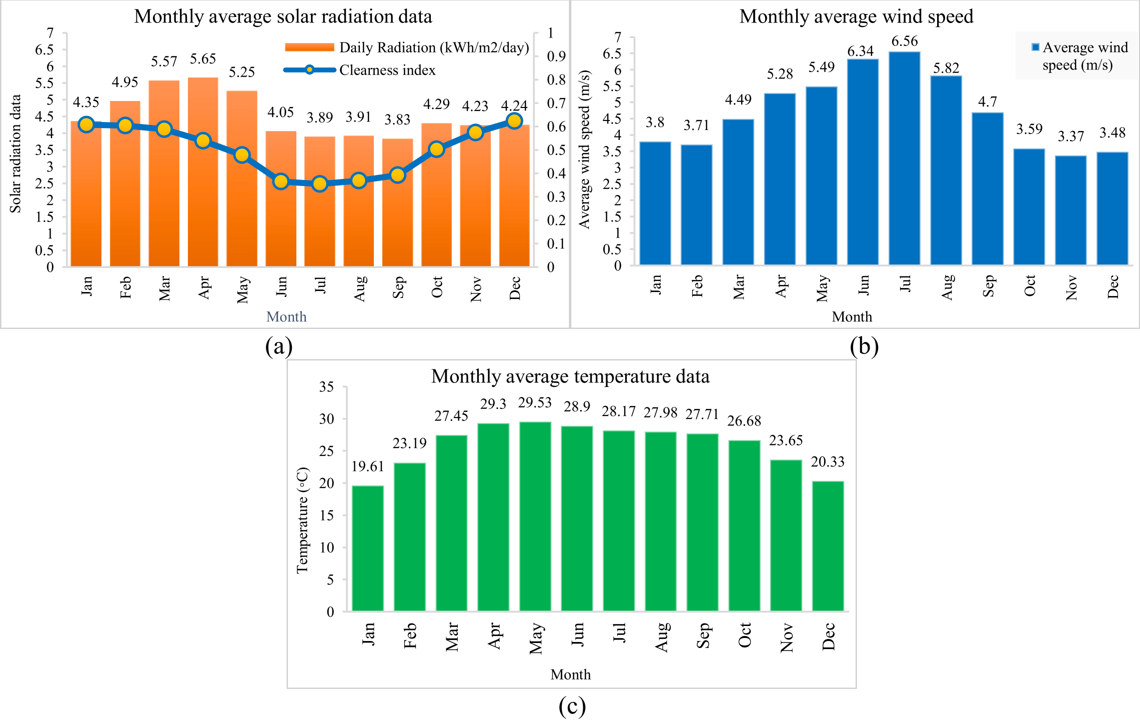


Fig. 4. Monthly average (a) solar radiation (b) wind speed and (c) temperature for a year.

average wind speed in summer (5.284) is greater than in the winter season (3.59). Fig. 4 (c) shows the monthly average temperature data from where it can be illustrated that the warmest month is June (29.53 °C) whereas the coolest month is considered January (19.61 °C). The average temperature in the summer is 28.215 °C and the average temperature in winter is 21.695 °C).

3. Simulation and modelling of the HRES system

The key purpose of the system is to provide electricity to an agri-based rural community in developing countries. In this regard, five different system off-grid system configuration is modelled where the main components are PV, WT, BESS, HS (HT, FC and electrolyzer) and converter. Another goal of the system is to produce hydrogen from the RE resources to reduce the overall CO_2 emission and to help sustain the intermittent nature of RES. The modelling and simulations of the five configurations are; PV-WT-Lithium-ion batteries-converter, PV-WT-Lead acid (LA) batteries-converter, PV-WT–HS–Converter, and PV-WT-Lithium-ion batteries–HS–converter as shown in Fig. 5. The HOMER software is employed to determine the most feasible electrical load component sizes and most optimal configurations considering the NPC and LCOE.

3.1. PV system

The PV module of the proposed HRES generates DC electricity approximately proportional to the incident SR. Therefore, the PV derating factor and temperature have a detrimental impact on the total DC electricity generated. For the PV module, Peimar SG290MFB is considered with $640 per kW capital cost (CC) and replacement cost (RC), $10 per year operation and maintenance (O&M) cost, and 20 years of a lifetime [37]. As PV power output is heavily influenced by the weather and environmental conditions, for the proposed system Peimar SG290PFB is considered. According to Ref. [36], a surge of 0.1%/°C of temperature LCOEfficient will occur in the yearly energy production by a PV. Equation (1) is used to estimate the hourly production rate of the PV system.

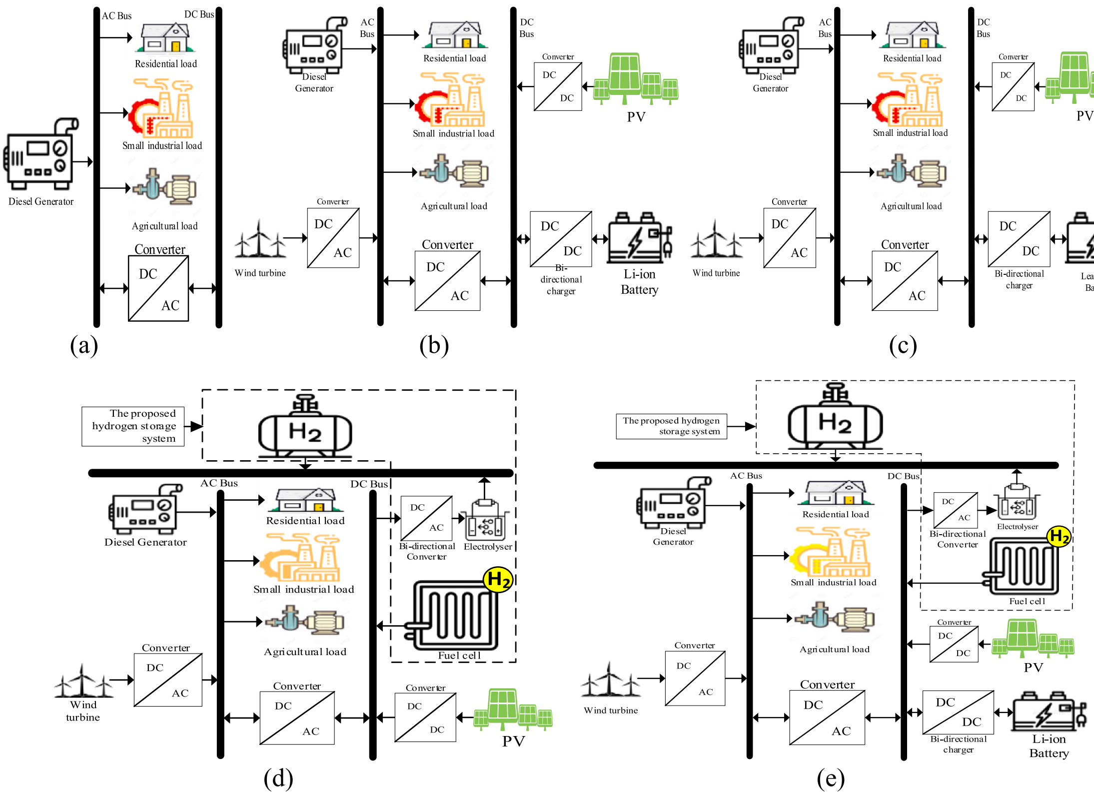


Fig. 5. The configurations of the HRES system (a) DG-only (b) PV-WT-DG-LIB-CONV-based system (c) PV-WT-DG-LAB-CONV-based system (d) PV-WT-DG–HS–CONV-based system, and (e) PV-WT-DG–HS–LIB-CONV-based system.

$$P_{PV} = Y_{PV} F_{PV} \left(\frac{I_T}{I_S}\right) [1 + \alpha_P (T_C - T_S)] \tag{1}$$

Where, Y_{PV} and F_{PV} are considered as the rated capacity (kW) and derating factor (%). I_T and I_S is denotes as the solar and incident radiation (kW/m^2) respectively whereas α_P is the temperature coefficient. T_C and T_S are the cell temperature at present (°C) and standard time (25 °C) respectively. If the output power of each PV system is ρ_{PV}, the power provided by (N) number of solar modules will be;

$$P_{PV} = N_{PV} \times \rho_{PV} \tag{2}$$

3.2. Wind turbine system

For the modelling of the WT system, Generic 1 kW WT was chosen with $7000/kW of CC and RC, $70 of O&M cost, 20 years of lifetime, and 17 m hub height considered for the system. The WT performance is calculated using linear interpolation at locations recorded to generate the power curve. The power generation of the WT under various conditions can be denoted as follows [38]:

$$P_w = \begin{cases} P_r x\left[\{U(t^3) - U_{ci}^3\}/\{U_r^3 - U_{ci}^3\}\right], U_{ci} \le U \le U_r \\ P_r, U_r \le U \le U_{c0} \\ 0, U_{c0} \le U \le U_{ci} \end{cases} \tag{3}$$

for the WT system, the hub height wind speed can be calculated as,

$$U_{hub} = U_{anem} (H_{hub}/H_{anem})^{\alpha} \tag{4}$$

where, U_{hub} and U_{anem} are the wind speed at hub height and anemometer height respectively whereas H_{hub} and H_{anem} are the hub height and anemometer height of the WT respectively. In the analysis, the WT design is presumed to have an overall loss factor of 2.3%.

3.3. Battery energy storage system

In a microgrid, BESS is primarily utilised to aid the RES in maintaining a constant voltage in the case of a power imbalance between generation and consumption. Moreover, the usage of BESS is critical for optimal utilization of the available RERs and also for improving grid stability and reliability. To develop the optimal configuration of HRES components, two different BESS system was utilized to observe the impact of BESS charging and discharging over the NPC and LCOE. Both Generic 1 kWh Li-Ion and Generic 1 kWh Lead Acid were utilized separately with the main PV-WT-Converter-based system. The Generic 1 kWh Li-Ion was considered with a CC of $550/kW, an RC of $550/kW, an O&M cost of $10/operation hour, and 15 years of a lifetime whereas Generic 1 kWh LA battery was considered with a CC of $300/kW, the RC of $300/kW, O&M cost of $10/operation hour, and 15 years [39]. In the proposed system, both input and output powers are required for charging or discharging. The total energy stored equals the sum of available (Q_1) and bound (Q_2) energies. The battery energy (Q_{bat}) and state of charge (B_{SOC}) at time t are shown as:

$$Q_{bat} = Q_{bat,0} + \int_0^t V_{bat} I_{bat} dt \tag{5}$$

$$B_{SOC} = Q_{bat}/Q_{bat,max} \times 100\% \tag{6}$$

3.4. Electrolyzer

An electrolyzer is a device used in hydrogen storage systems to produce hydrogen through a process called electrolysis. Electrolysis is the process of using an electric current to separate water into hydrogen and oxygen. The resulting hydrogen can be stored and utilized as a fuel source [31]. Electrolyzer is an important component of hydrogen storage systems as they provide a clean and renewable source of hydrogen fuel. By using RES, such as solar or wind power, to power the electrolyzer, the hydrogen produced can be considered a clean and sustainable fuel source. Hydrogen is produced by an electrolyzer using demineralized water and solar power during the day and stored in a compressed and pressurised tank until needed. For the system modelling, the capital and replacement cost of $1250, O&M cost of $120 and efficiency of 85% with a lifespan of 15 years are considered.

3.5. Hydrogen tank

A hydrogen tank (HT) is a container used to store and transport hydrogen gas and is a crucial component in HS systems, as it allows for the safe and efficient storage of hydrogen. The hydrogen gas is stored inside a metal or composite shell and is compressed using a gas compressor or a high-pressure pump. In low-temperature storage, hydrogen gas is cooled below −253 °C, causing it to transform into a liquid state. This liquid form enables the storage of hydrogen in a significantly reduced volume [31,32,40]. The capital cost of the HS tank is $438/kg was considered [33].

3.6. Fuel cell

A fuel cell (FC) is an electrochemical apparatus that transforms hydrogen and oxygen into electricity, producing water and heat as its byproducts [40]. The FC contains two electrodes (anode and cathode) divided by an electrolyte. Hydrogen is fed to the anode, undergoing oxidation to release protons and electrons. The electrons move through an external circuit to the cathode, generating an electric current. Concurrently, protons traverse the electrolyte to the cathode, uniting with oxygen and electrons to produce water [20,33,41]. The output voltage of V_{FC} can be calculated as,

$$V_{FC} = E_{oc} - V_{act} - V_{ohm} E_{oc} - NAln(i_{FC} / i_o) - Ri_{FC} \tag{7}$$

where, E_{oc}(V), i_0(A), i_{FC}(A) and N are the open circuit voltage (OCV), exchange current, the output current of FC and the number of cells respectively. To develop an HS-based HERS system, the capital and the replacement cost of the FC were considered as $600 and $500 per kW capacity respectively. The O&M cost was $0.1 per hour whereas the lifespan was considered 40,000 h [33].

3.7. Diesel generator

Diesel generators (DG) can be used in conjunction with hydrogen fuel cells to provide backup power when the fuel cell is not able to meet the electrical demand. The selected DG fuel has a lower heating value of 43.2 MJ/kg with a density of 820 kg/m^3. The fuel curve equation is as follows where F_0 and F_1 fuel curves intercept coefficient and slope respectively, whereas Y_{gen} and P_{gen} are rated capacity and electrical output of the generator.

$$F = F_0 . Y_{gen} + F_1 . P_{gen} \tag{8}$$

For the Diesel Generator (DG), a Generic 50 kW Fixed Capacity Genset is considered with $5000.00/kW of capital cost, and the fuel price is considered as $1.21/L [42].

3.8. Converter

The converter is a critical component of HRES systems as it enables the efficient and effective conversion of electrical energy into different forms of ESS and vice versa, allowing for the efficient and reliable storage and utilization of RE. For efficient system development, the system converter with capital, replacement and O&M costs are $300/kW, $300/kW, and $1/operation hour respectively. The efficiency and lifetime are 97.45% and 10 years. The power rating of the converter (P_{conv}) is directly proportional to the peak load demand (P_{peak}) and inversely proportional to the efficiency (e_{conv}). The equation is as follows [43];

$$P_{conv} = P_{peak} \big/ e_{conv} \tag{9}$$

3.9. System optimization parameters

This article aims to develop an optimized HRES system that is reliable, cost-effective, and environmentally friendly. Current energy generation from kerosene and wood fire leads to significant amounts of GHG emissions as well as deforestation. The optimization is categorized into two key stages such as economic assessment, and environmental assessment. In Table 2, the details about the objective functions, decision variables and constraints that are considered are presented.

3.10. HRES system energy management

The objective of EMS in an HRES is to maximise the use of RES, reduce the consumption of non-RESs such as DGs, and meet the energy demand of any circumstances. The optimal sizing of HRES system is referred to as the developed system which has a low unmet load and can satisfy the load demand by maintaining a low percentage of excess energy (E_xE) per year at a low overall cost. In Table 3, an EMS strategy is proposed for using the RES and non-RES sources as well as the charging-discharging algorithm for the battery and HT under two different scenarios. In the HRES system, the summation of the output power of an individual component is the total output power which should be greater than the total load demand expressed as follows:

$$P_{PV}(t) + P_{WT}(t) + P_{BATTERY}(t) + P_{DG}(t) + P_{HS} \geq P_{LOAD}(t) \tag{10}$$

3.11. Economical assessment

The proposed systems simulated system is based on RE which can reduce the GHG emission and have scope for future grid extension. The main objective functions are net present cost (*NPC*) and levelized cost of energy (LCOE). The annualized cost of each component separately is calculated to obtain the total annualized cost ($C_{ann.tot}$) which includes capital (C_c), replacement (C_r), maintenance (C_m), fuel (C_f), salvage (C_s), other costs (C_o).

$$C_{ann.tot} = C_c + C_r + C_m + C_f + C_s + C_o \tag{11}$$

The total NPC (C_{NPC}) can be calculated as:

$$C_{NPC} = C_{ann.tot} \big/ CRF\left(i, R_{proj}\right) \tag{12}$$

Where CRF is the capital recovery factor, I is the real interest rate and R_{proj} is the project's lifetime. The LCOE is considered a vital socioeconomic factor in HRES system optimization, and it is defined as the average cost per kilowatt-hour ($/kWh) of useable energy. If E_s is the total energy generation, the *LCOE* can be denoted as:

Table 2
Summary of the optimization parameters.

Objective functions	Minimizing LCOE and NPC	Min (*LCOE*), Min (*NPC*)
Decision variables	Number of PV	N_{PV}
	Number of WT	N_{WT}
	Number of batteries	N_{batt}
	The rated power of the electrolyzer	N_{ELEC}
	Nominal fuel cell output	N_{FC}
Constraints	The SOC of the battery	$SOC_{min} < SOC_{batt} < SOC_{max}$
	SOC of HT	$SOC_{min} < SOC_{HT} < SOC_{max}$
	Minimum renewable fraction	Min (*RF*)
	Minimum CO$_2$ emission	Min (*Total CO$_2$ emmision*)

Table 3
The proposed EMS strategy.

Charging-discharging algorithm for PV-WT-DG-BESS-based system	Charging-discharging algorithm for PV-WT-DG–HS–BESS-based system
Input: Battery voltage, SOC_{batt}, $SOC_{Battery.min}$, $SOC_{Battery.max}$, P_{PV}, P_{WT}, $P_{battery}$, P_{DG}, and P_{Load} Output: Current **Stage 1**: Identify the essential load (P_{Load}) Identify the battery SOC (SOC_{batt}) **Stage 2**: Initiation of the simulation **Stage 3**: function Battery charging () while true if Availability of RES () Charge Battery (RES()) else if DG Available() Charge Battery (DG()) end; end; end; **Stage 4**: if $SOC_{batt} = SOC_{Battery.min}$ (For controlling the over-discharging) Charging ON = 1 else Go to Stage 2 end **Stage 5**: if $SOC_{Battery.min} < SOC_{batt} < SOC_{Battery.max}$ (To operate within the safety region) Initiate Stage 1 if $P_{PV}(t) + P_{WT}(t) < P_{LOAD}(t)$ (when the load demand exceeds the available power) Discharging ON = 1 else if $P_{PV}(t) + P_{WT}(t) > P_{LOAD}(t)$ (When the available power is greater than the load demand, the excess power to charge the battery) Charging ON = 1 else Go to Stage 2 end; **Stage 6**: if $SOC_{batt} = SOC_{Battery.max}$ (To control the Overcharging) Go to Stage 1 if $P_{PV}(t) + P_{WT}(t) < P_{LOAD}(t)$ (when the load demand exceeds the available power) Discharging ON = 1 else if $P_{PV}(t) + P_{WT}(t) > P_{LOAD}(t)$ (When the available power is greater than the load demand, the excess power to charge the battery) Charging ON = 0 else Go to Stage 2 end; end; end;	Input: Battery voltage, SOC_{batt}, $SOC_{Battery.min}$, $SOC_{Battery.max}$, SOC_{HT}, $SOC_{HT.max}$, $SOC_{HT.min}$, P_{PV}, P_{WT}, $P_{battery}$, P_{DG}, P_{HS} and P_{Load} **Stage 1**: Identify the essential load (P_{Load}) Identify the battery SOC (SOC_{batt}) and SOC (SOC_{HT}) **Stage 2**: Initiation of the simulation **Stage 3**: function System charging () while true if Availability of RES () Charge Battery(RES() and Charge HT (RES)) else if DG Available() Charge Battery (DG()) end; end; end; **Stage 4**: function Availability of RES() if $P_{PV}(t) + P_{WT}(t) > P_{LOAD}(t)$ (When the available power is greater than the load demand, the excess power to charge the battery) Charging ON = 1 end; **Stage 5**: function Battery charging (RES) if $SOC_{batt}() < SOC_{Battery.max}()$ Required energy = $SOC_{Battery.max}()$- $SOC_{batt}()$ Required energy for charging = min (Required energy, RES) Battery.charging(Required energy for charging) end; end; **Stage 6**: function HT charging (RES) if $SOC_{HT}() < SOC_{HT.max}()$ Required energy = $SOC_{HT.max}()$ - $SOC_{HT}()$ Required energy for charging = min (Required energy, Electrolyzer Output ()) HT.charging(Required energy for charging) end; end; **Stage 7**: function Discharging System () if $P_{PV}(t) + P_{WT}(t) < P_{LOAD}(t)$ (when the load demand exceeds the available power) Discharging ON = 1 end; **Stage 8**: function Battery discharging (load) if $SOC_{Battery.min} < SOC_{batt} < SOC_{Battery.max}$ (To operate within the safety region) Required energy = Required energy to meet the load demand() Required energy for discharging = min (Required energy, $SOC_{batt}()$) Battery.discharging(Required energy for discharging) end; end; **Stage 6**: function FC discharging(load) if $SOC_{HT.min}() < SOC_{HT}() < SOC_{HT.max}()$ (To operate within tank capacity) Required energy = Required energy to meet the load demand() Required energy for discharging = min (Required energy, $SOC_{HT}()$) FC.discharging(Required energy for discharging) end; end;

$$LCOE = C_{ann.tot} / E_s \tag{13}$$

3.12. Environmental assessment

The key parameters for environmental assessment are RE fraction, RE penetration, and emission analysis. The renewable fraction refers to the percentage of energy supplied to the load that derives from RE sources. If E_{nonren} is the non-renewable load and E_{served} is the total served load, the RF can be calculated as follows:

$$RF = 1 - E_{nonren} / E_{served} \tag{14}$$

in this article, five distinct combinations of components for a rural community are shown in Fig. 5, which consists of PV, lithium-ion battery, lead-acid battery, hydrogen tank, electrolyzer, fuel cell, diesel generator, wind turbine, and converter.

4. Result and discussion

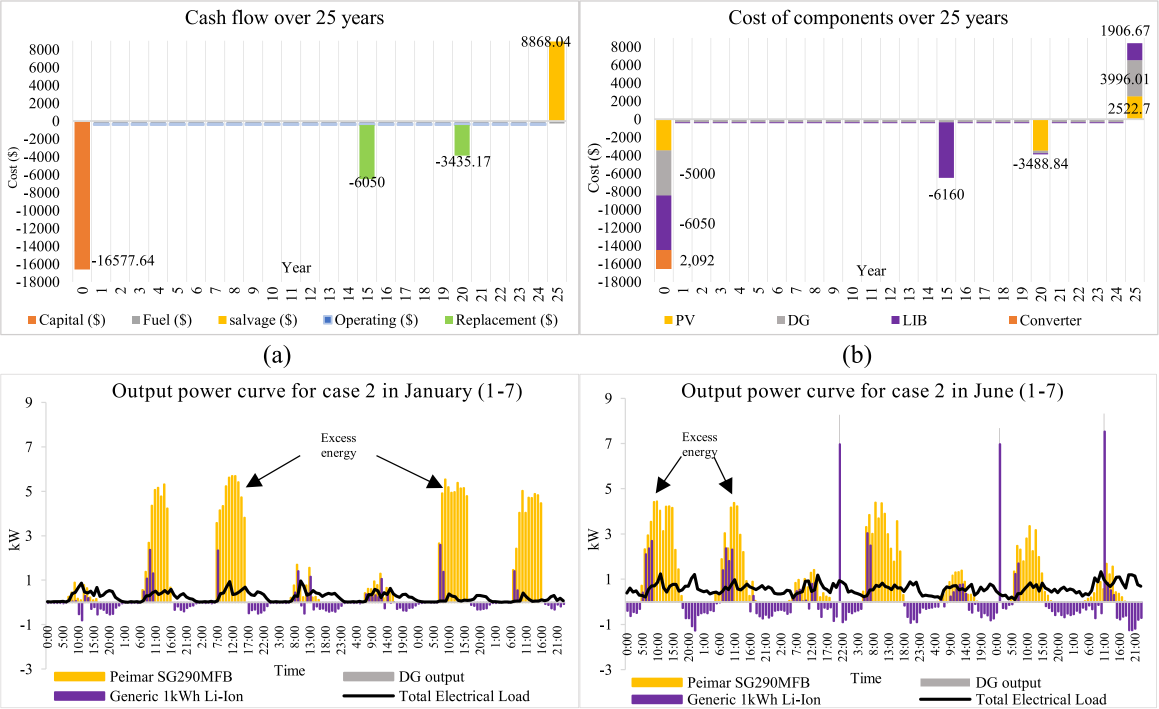
To develop an optimal system with the best possible outcome for the rural community, five different system configurations were developed and a comparative study between the developed systems was also presented. Two different types of batteries (LIB and LAB) are used for two different system configurations with the same RES and load profile to observe the changes in terms of NPC and LCOE. HS is considered instead of BESS along with the battery to observe the changes in the system parameters, system sizing, overall NPC and LCOE. The HS is considered because of its recent popularity as ES as it has some benefits such as higher energy density means more efficiency, longer lifetime and faster refuelling speed making it more convenient for the long-term ESS. The system having DG only is considered as the base case for the analysis as the rural community without grid availability is mostly dependent on fossil fuel-based energy generation. Moreover, the project lifetime is considered 25 years and the inflation rate is considered as 5%. The system configurations are defined as the case study and a detailed description is provided below.

4.1. Case 1: DG-only system

Case 1 involves modelling and simulating a system solely relying on DG to illustrate the present state of energy generation based on fossil fuels. The DG-based system has an NPC of $294,668 and an LCOE of $4.05 with a CO_2 emission of 27,348 kg/yr. The project lifetime is 25 years and the total CO_2 emissions are 683,700 kg/yr. To achieve the goal of zero-emission, the use of HRES is needed which can significantly reduce the CO_2 emission and reduce the overall NPC and LCOE.

4.2. Case 2: PV-WT-DG-LIB-converter-based system

A PV-WT-DG-Battery-Converter-based system is modelled and simulated. The optimal system configuration includes a 5.37 kW of PV, 10 kW DG, 11 pieces of LIB, and a 6.97 kW converter. The total energy generation with the system configuration is 4113 kWh/year and the total RF is 83.1%. The total NPC of the system is $25,946, and the LCOE is $0.357/kWh. In Fig. 6, the details of the system simulation output are shown. In Fig. 6 (a) and 6 (b), the cash flow and cost of the components over the project lifetime of 25 years are shown. In Fig. 6 (b), it can be noticed that, after 15 years the LIB and in the 20th year of the project the PV panel has to be replaced as the lifetime of the LIB and PV is considered as 15 years and 25 years respectively. From Fig. 6 (c) and 6 (d) it can be observed that, most of the time the load demand was served by the PV unit and when the PV was not available, the LIB and DG served the load. The DG only has to operate in the summer when the load is at the peak and the LIB charges in the morning when PV has available excess electricity and discharges during the night when it is necessary. The system has an internal rate of return (IRR) and a return on investment (ROI) of 127% and 133% respectively. Moreover. The sensitivity analysis shows that if the fuel price increased from $1.05 to $1.15, 1.65% of the overall NPC increase is observed.



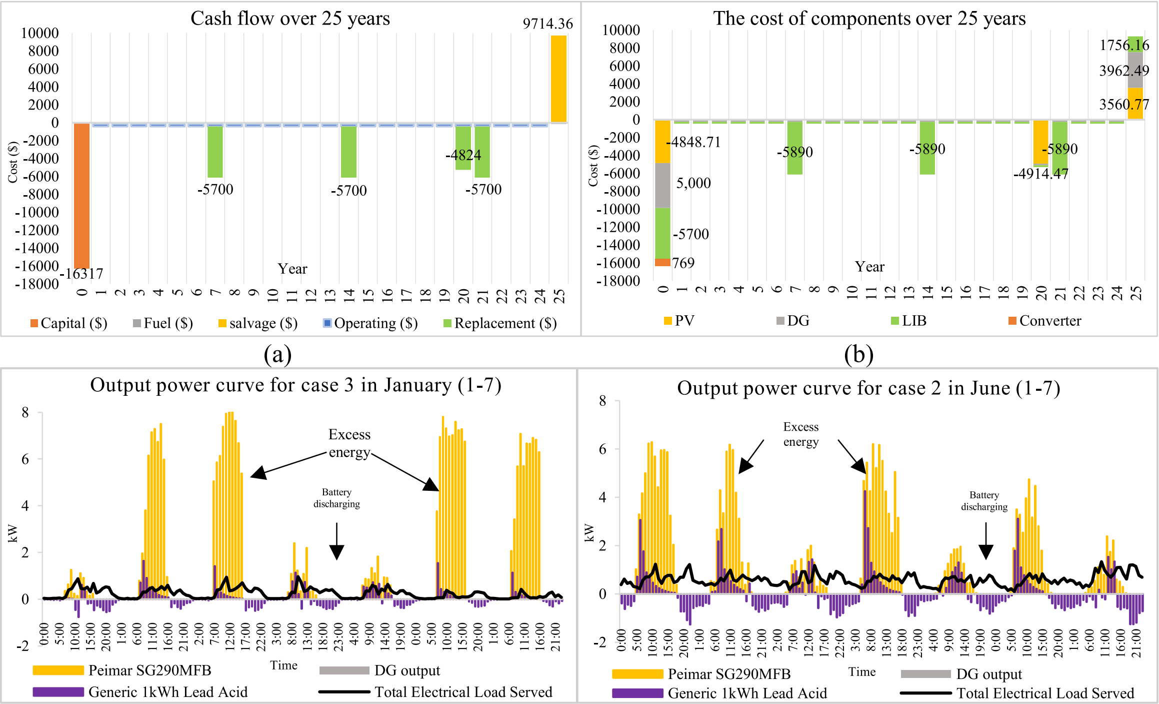
(a) (b)

(c) (d)

Fig. 6. The generation output by each component in Case 2 (a) cash flow (b) cost of components over lifetime (c) output power curve of the components (January) (d) output power curve of the components (June).

4.3. Case 3: PV-WT-DG-LAB-converter-based system

A system with PV-WT-DG-LAB-Conv. Was modelled and simulated in case 3. The total energy generation of the developed system configuration is 4113 kWh/year and has no unmet load. The optimal system sizing includes 7.58 kW of PV, 10 kW of DG, 19 LAB and 2.56 kW of the converter. As the system RF is 92.2%, the CO_2 emissions are 369 kg/year and a total of 9225 kg of CO_2 is emitted during the overall project lifetime. The simulation outcomes are presented in Fig. 7 where the cash flow and cost of components are shown in Fig. 7 (a) and (b) respectively.



(a) (b)

(c) (d)

Fig. 7. The generation output by each component in Case 3 (a) cash flow of the system (b) cost of components over the lifetime of the project (c) output power curve of the components (January) (d) output power curve of the components (June).

In Fig. 7 (b) in every 7th year the LAB has to be replaced as the expected lifetime of the LAB is 6.83 years which caused the overall NPC increase compared to the LIB-based system. The salvage cost of the system is $9724.36 which is shown in the 25th year in Fig. 7 (a). The load demand is mainly served by the PV followed by LAB and DG. The total NPC and LCOE of the system are $33,922 and $0.466/kWh respectively as shown in Fig. 7 (c) and (d). The sensitivity analysis shows that, with the increase in diesel fuel price from $1.05 to $1.15, the COE also increased from $0.466/kWh to $0.470/kWh.

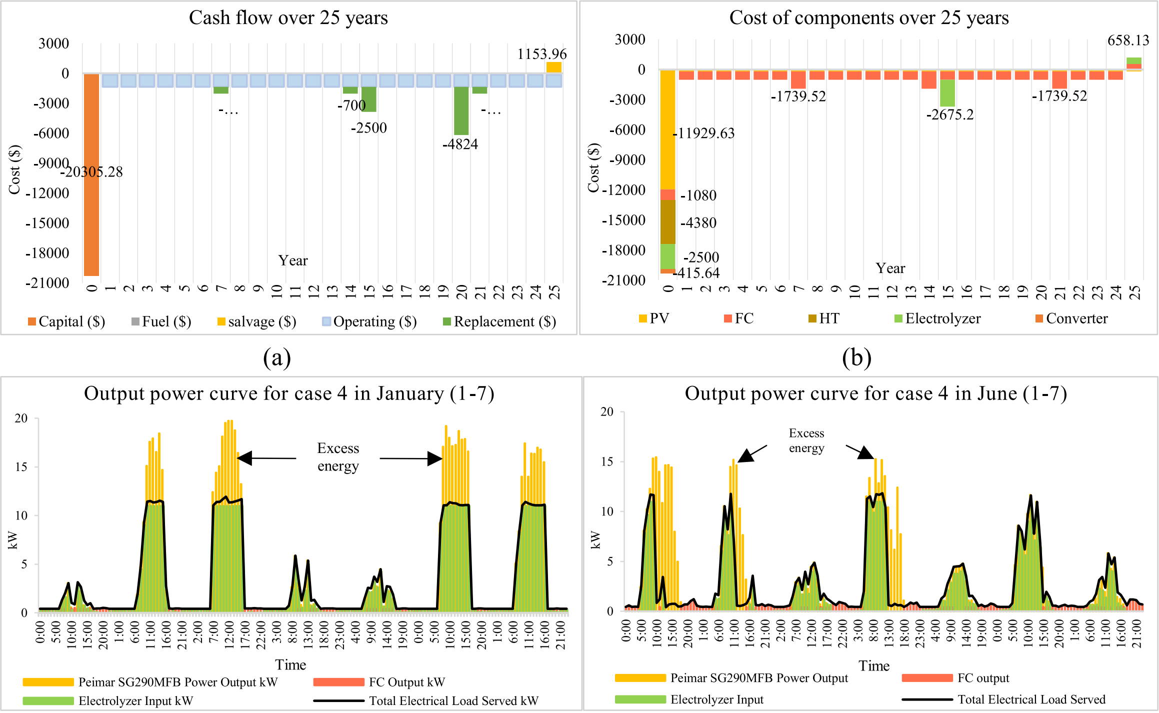
4.4. Case 4: PV-WT-DG–HS–converter-based system

For case 4, instead of LIB or LAB, HS is considered to evaluate the potentiality of the HS for a developing country. The HS system consists of HT, FC and electrolyzer. The simulation outcome of Case 4 is shown in Fig. 8. The optimal system sizing includes 18.6 kW of PV, 1.8 kW of FC, 11 kW of electrolyzer, 10 kg of HT and 1.39 kW of the converter. The primary load is 4,113 kWh/year and the electrolyzer consumption is 17,907 kWh/year which is 81.3% of the total electricity consumption. However, the developed system has no unmet load. The PV generated 91.8% of the total served load and the FC generated the rest 8.2%. The system is 100% renewable and the NPC and LCOE of the system are $44,483 and $0.611/kWh respectively. The FC has a lifetime of 40,000 h, in the developed system the FC have to be replaced every 6.86 years which is shown in Fig. 8 (a) and 8(b). It is anticipated that the project lifetime will be 25 years; thus, there have been three FC replacements. Moreover, hydrogen consumption is high from April to August compared to the other times of the year because of the high demand in the summer. The total electrolyzer output is 386 kg of hydrogen per year. The operating characteristics of each component during the summer and winter season is shown in Fig. 8(c) and (d). The RF of the system is 100% and as there is no DG used the change in diesel price does not affect the system's NPC and COE.

4.5. Case 5: PV-WT-DG–HS–LIB-converter-based system

Case 5 is considered the most optimal system among the five case studies as it has the lowest NPC and LCOE. The system NPC is $25,099 whereas the LCOE is $0.34/kWh. A combination of PV-WT-DG–HS–LIB-Converter is modelled. The capacity of each component of the optimal system is 8.67 kW of PV, 7 LIB, 6 kW of electrolyzer, 1.8 kW of FC, 5 kg of HT and 1.67 kW of the converter. The system is 100% renewable so there are no CO_2 emissions. The overall consumption of the developed system is 8,849 kWh/year where the AC primary load is 4,113 kWh/year and electrolyzer consumption is 4,738 kWh/year. The excess energy of the system is 7,362 kWh/year and the unmet load is 2.31 kW/year, which is only 0.056% of the overall. The system has an IRR and ROI of 177% and 187% respectively whereas the simple payback year is 0.62 years. The simulation result of the overall system is presented in Fig. 9.

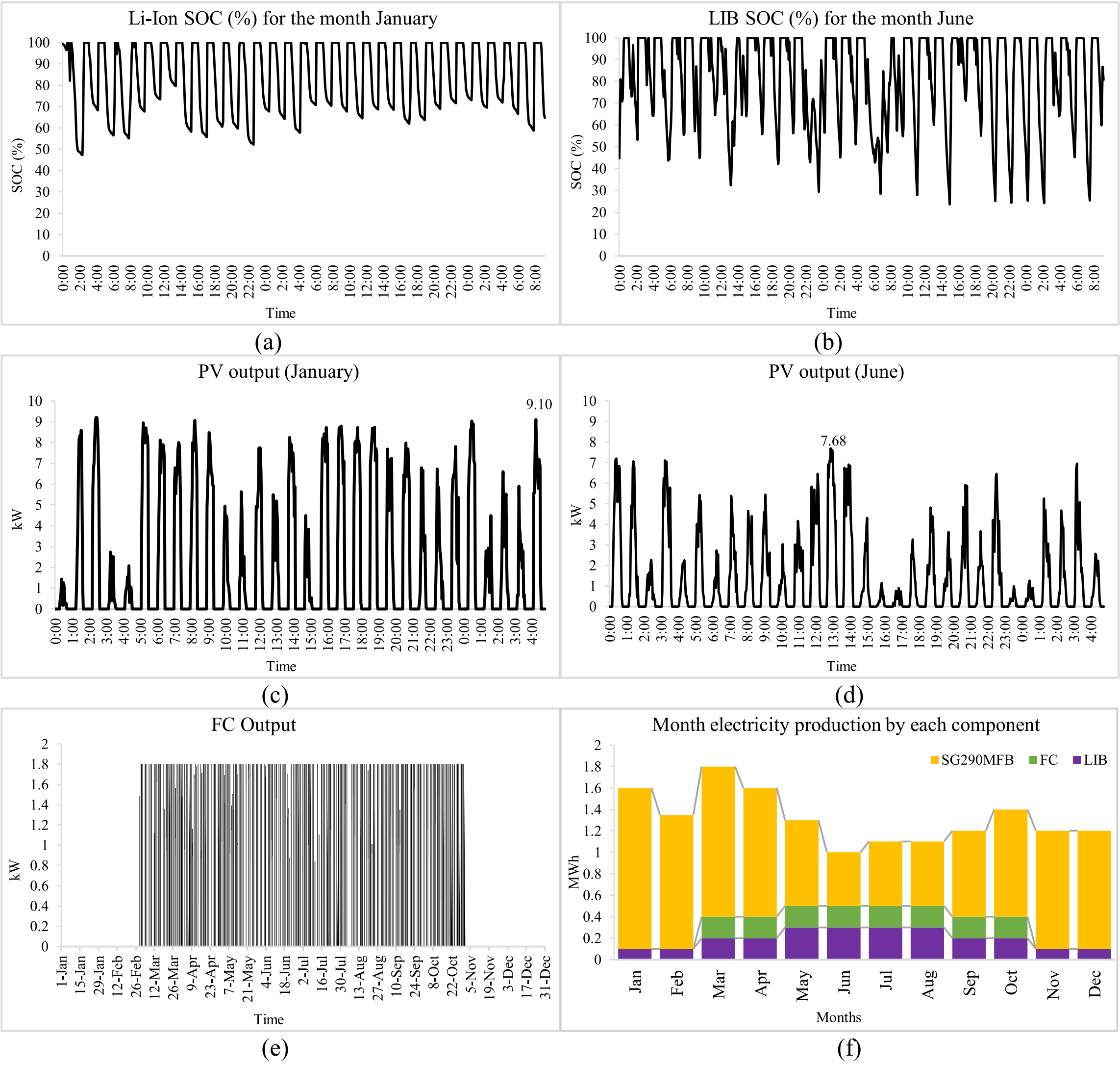
It can be observed that the PV is supplying most of the required energy and the rest is supplied using the LIB and FC. The PV supplied 93.2% of the total generation whereas the rest 6.8% was served by LIB and FC. The PV system is operated for 4371 h/year with a mean output of 42.4 kW/d and a capacity factor of 20.4%. The FC is operated for 686 h/yr with a capacity factor of 7.21%. The total output of the FC is 1137 kWh/year with an efficiency of 34.3 and total hydrogen consumption of 99.6 kg. The 1 kWh LIB has a nominal capacity is 7 kWh with an energy output of 1633 kWh/yr. The battery operating region is considered as $S_{battery,min} = 20\%$ and $S_{battery.\ max} = 100\%$. The battery SOC (%) for the months of January and June are shown in Fig. 9 (a) and 9 (b) respectively whereas the hourly output of PV (kW) for the months of January and June are shown in Fig. 9 (c) and 9 (d). The output of FC is shown in Fig. 9 (e) where it can be observed that the FC only delivered power from March to October when the daily average load was comparatively higher than from November to February. The monthly electricity production by each component is shown in Fig. 9 (f). The energy generation output of each component during days 1–7 of the coldest month (Jan) and warmest month (June) is presented in Fig. 9 (i) and (j). It can be observed that, during the winter, the load can be served only with PV and LIB. In the summer (June) the load demand during the morning



(a) (b)

(c) (d)

Fig. 8. The generation output by each component in Case 4 (a) output power curve of the components (January) (b) output power curve of the components (June).



(a) (b) (c) (d) (e) (f)

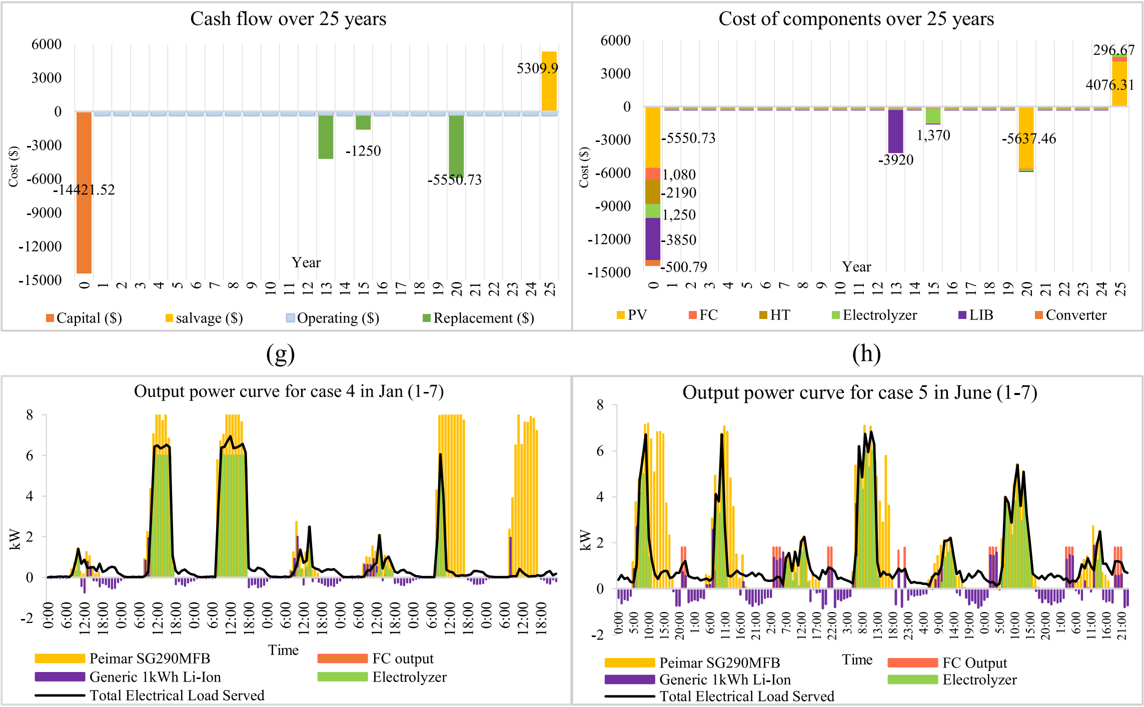
Fig. 9. The generation output and the cost analysis of Case 5 (a) battery SOC for January (b) battery SOC for June (c) PV system output for January (d) PV system output for June (e) FC output over 8760 h (f) monthly electricity generation by each component (g) cash flow (h) cost of components over the lifetime (i) output power curve of the components (January) (j) output power curve of the components (June).

hours is served by PV but during the evening and night, the required load demand is served by LIB and FC. Moreover, as the system has no DG component the diesel price change has no impact as well. The cash flow and the cost of each component over the project lifetime are shown in Fig. 9(g)–(h). It can be noticed that the initial cost (IC) of the system installation is $14,421 and the replacement cost of the LIB and electrolyzer was added in the 12th and 15th year of the project with a cost of $3850 and $1250 respectively.

4.6. *Comparative techno-economic and environmental analysis of the HRES system*

This article has demonstrated a techno-economic analysis of five different HRES models for a rural community. A comparative study between the models is presented in this section in terms of cost type, NPC, LCOE, CO_2 emissions, and RF. The PV-WT-DG–HS–LIB-Converter-based system is considered the most cost-effective and optimal system as it has the lowest NPC and LCOE. The proposed optimal system is also 100% renewable with an unmet load of only 0.056% of the overall load. The LCOE of the proposed optimal system is 91.48%, 3.36%, 25.97%, and 43.54% less than cases 1, 2, 3 and 4. The capital, replacement, operation and maintenance, fuel and salvage cost (SC) of each HRES system configuration is presented in Fig. 10(a)–10(d). Moreover, a cumulative cost analysis over 25 years of the project lifetime for all the case studies is also presented in Fig. 10 (e). It can be observed that, although the base system has a lower initial cost due to a single energy generation component (DG), the proposed optimal system has the lowest overall cost.

Moreover, for case 2 and case 3, with the same load profile and components, two different battery technology such as a 1 kWh lithium-ion battery and a 1 kWh lead acid battery is used and a techno-economic comparative analysis is presented. Battery selection is influenced by its price, expected lifespan, size, how it performs in different temperatures, sustainability, and availability. According to Ref. [44], the LIB has higher energy density (250WhL), specific energy (150 W h/kg) and cycle life (1900 at 80% depth of discharge) compared to the LAB. Moreover, LIB has higher temperature tolerance as the cycle life of LAB can significantly be degraded above 25 °C and the average temperature of Sutabaria is 26 °C. The battery sizing of the LIB-based HRES includes 11 units with one string size, 11 strings in parallel and the bus voltage is 6 V whereas the LAB-based HRES system sizing includes 19 units with one string size, 19 strings in parallel and the bus voltage is 12 V. The LIB



(g) (h) (i) (j)

Fig. 9. (*continued*).

tends to have a higher lifetime throughput of 32,800 kWh compared to the LAB batteries (15,200 kWh). Moreover, the simulation shows a 45.33% higher lifespan of the LIB batteries (15 years) compared to the LAB batteries (6.83 years). During the project lifetime of 25 years, the LAB pack needs to be replaced 3 times which causes a 30% increase in LCOE compared to the LIB-based system. Moreover, due to the various dispatch strategies, the techno-economic outcomes are also varied as shown in Table 4. Two different dispatch strategy is applied for the simulation for case study 2 and case study 3 such as; cycle charging (CC) and combined dispatch (CD). Using the CC strategy, BESS is periodically charged and discharged for best performance, with an emphasis on system operation. The CD strategy, in comparison, combines various energy sources for an efficient supply while considering issues like costs and limitations. While CD optimises the entire energy mix, CC optimizes the utilization of storage [5]. From Table 4 it can be observed that, for both LIB-based and LAB-based system, CD provide the lowest NPC and LCOE while lowering the RF. In addition, as the CC strategy focuses on best performance and lifespan, using the CC strategy in the PV-DG-LAB system, the battery lifetime throughput is improved by 41.4% whereas the expected life also improved by 46.41%.

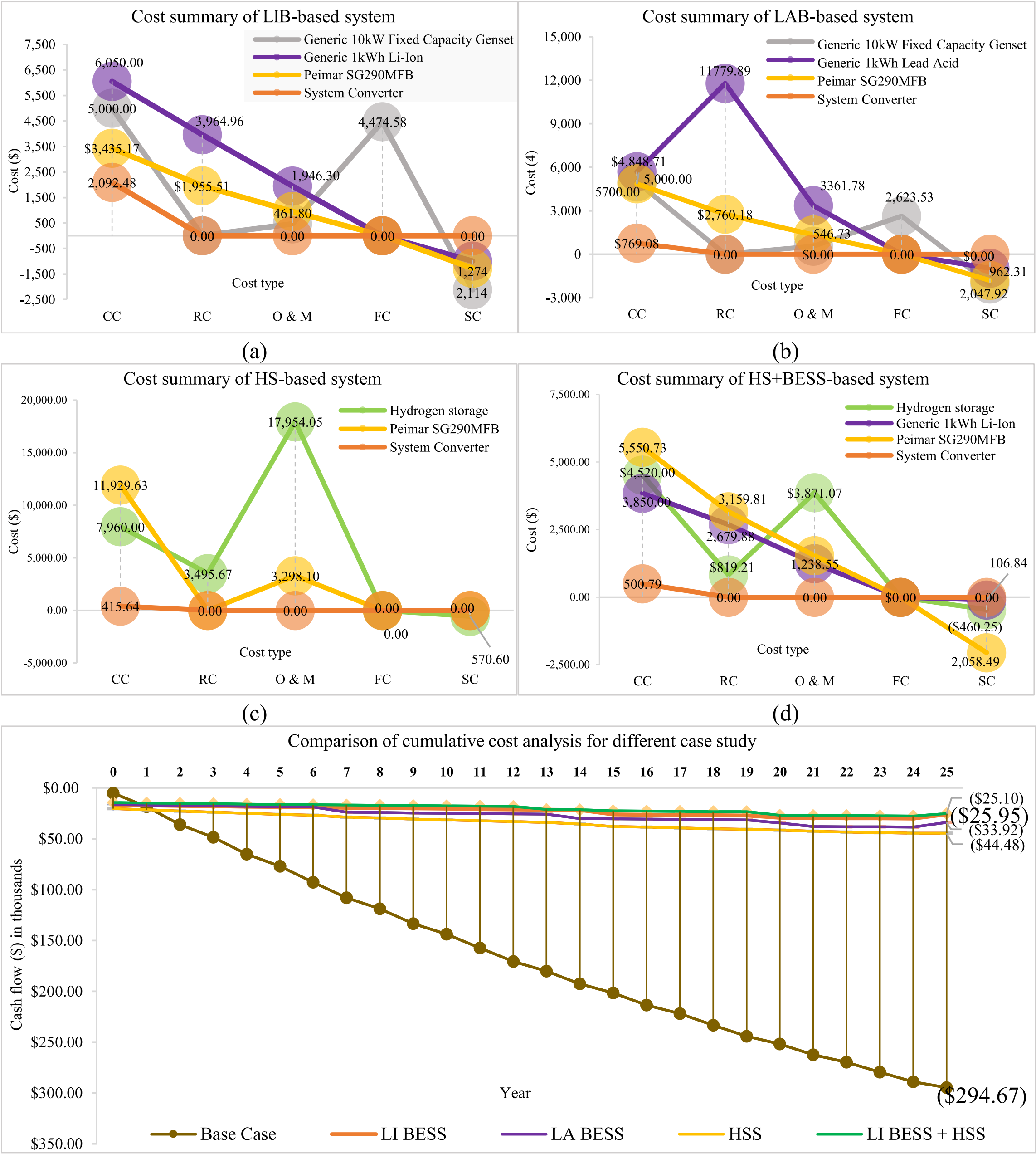
Furthermore, two different combinations of HS-based systems are developed. In case 4, the HS is connected with PV whereas in case 5, the HS is connected with both PV and LIB. The PV-HS-based system has the highest LCOE due to the replacement cost of the HT, FC and electrolyzer. The operation hour of the electrolyzer is 5997 h/year and a large amount of input energy (17,907 kWh/year) is needed to meet the electrolyzer demand. The operational hour of the FC is 5830 h/year and uses 381 kg of hydrogen as an input with an efficiency of 23.5%. High replacement costs and technical complexities affected the overall system performance and cost-effectiveness. On the other hand, using HS along with LIB and PV can improve the system LCOE significantly. The results indicate that the incorporation of LIB in conjunction with HS leads to a substantial reduction of 43.58% in the overall NPC and a corresponding decrease of 44.35% in the LCOE. The implemented EMS control strategy prioritizes LIB utilization for power supply, with HS serving as a backup. When battery SOC is minimal, the FC is activated to deliver the required power. The surplus PV energy is utilized for charging the battery and electrolyzer. The annual throughput of the LIB and FC is 1,633 kW/year and 1,137 kWh/year.

The environmental assessment of the proposed HRES system has two key factors: CO_2 emission and a renewable fraction (RF). One of the key goals of the proposed system is to reduce CO_2 and other GHG gas emissions by replacing the current kerosene and wood-burning-based energy production. Case 1 or the base system (27,348 kg/year) has the highest CO_2 emission followed by case 2 (629 kg/year) and case 3 (369 kg/year). The proposed optimal system has no CO_2 emission and the RF is 100%.

4.7. Comparative analysis of the proposed HRES system with the existing systems

For the validation of the proposed system, a comparative study between the existing HRES systems for Bangladesh developed by various researchers over the years and the proposed system is presented in Table 5. It can be observed that only the proposed system has considered HT–FC–electrolyzer for the HRES development and using HS with the BESS reduces CO_2 emission and increases the renewable fraction to make the system more sustainable. Moreover, in all the developed systems, DG is used as a backup power and PV is considered as the main source of energy generation. When PV cannot able to meet the high demand during the night-time DG and other sources supply the necessary power to meet the demand. High use of fossil fuel is required to operate the DG thus increasing the overall CO_2 emission. The proposed system uses HS and LIB instead of DG to supply the necessary power.

The NPC and LCOE are two key features to evaluate the economic feasibility of HRES systems. Various factors that are affecting the NPC and LCOE are; geographic locations, resource availability, project lifetime, experts for maintenance, and policy incentives. A comprehensive analysis of the existing studies with the proposed system based on NPC and LCOE is presented in Fig. 11. It can be observed that the proposed system has a competitive LCOE and a very low NPC compared to the existing system configurations. In Ref. [48], an off-grid



(a) (b) (c) (d) (e)

Fig. 10. A comparative techno-economic analysis of the developed HRES system (a) cost summary for case 2 (b) cost summary of case 3 (c) cost summary of case 4 (d) cost summary of case 5 (e) cumulative cost analysis for the five different case study.

Table 4
Comparative analysis between PV-DG-LIB and PV-DG-LAB system based on dispatch strategy.

System parameters	PV- DG-LIB		PV- DG-LAB	
	CC	CD	CC	CD
NPC ($)	36,471	25,946	36,837	33,922
LCOE ($/kWh)	0.501	0.357	0.506	0.466
RF (%)	100	83.1	100	92.2
CO_2 emission (kg/year)	0	629	0	369

PV-BESS-Biogas-DG-based system is developed which has the lowest LCOE (0.28$/kWh) among the presented systems whereas the off-grid PV-WT-BESS system developed in Ref. [45] the highest LCOE (0.47 $/kWh). However, the NPC and CO_2 emission of [48] is $612,280 and 34,234 kg/year respectively which is high compared to the proposed system due to high DG use, low battery expected lifetime (3.89 years) and low RF (60%). The proposed PV-LIB–HS–based system has an NPC, LCOE, and RF of $25,099, 0.34$/kWh, and 100% respectively with no CO_2 emission. The system also has an excess energy of 7,362 kWh/year and the unmet load is 2.31 kW/year, which is only 0.056% of the overall system. The proposed optimal system is cost-effective, sustainable and environment friendly.

5. HRES impact in achieving SDGs goals

Sustainable development has been identified as the cornerstone of good governance and democratic development. Nowadays, the SDGs have sparked necessary debate and study, and the significance of the energy sector appears to be critical in attaining these SDGs. The HRES

Table 5
Comparison of the proposed system with the existing research.

Ref.	Year	Optimal System	Location	CO_2 emission (kg/year)	RF (%)	Key aspects
[29]	2010	PV-DG-BESS	Cox's Bazar, Sylhet, Dinajpur	24,681	43	Optimal HRES system for 50 households using HOMER
[45]	2010	PV-WT-BESS	Chittagong	25,000	–	Optimal off-grid HRES system for a hypothetical community and evaluate the possibility of grid extension
[46]	2016	PV-DG	Kutubdia	54,300	–	Optimal off-grid HRES configuration using PV-DG for rural people using HOMER and RETScreen
[47]	2016	PV-DG-BESS	Irrigation load	1,78,500	40	PV-DG-based optimal system for irrigation pumps for agricultural countries like Bangladesh
[48]	2017	PV-BESS-Biogas-DG	Katakhali, Khulna	34,234	60	Optimal off-grid HRES system for the rural community using HOMER
[36]	2018	PV-DG-BESS	Rajshahi	13,720	89	Optimal HRES system for 220 households using HOMER
[5]	2019	PV-DG-LAB	Rajshahi	24,649	80	HRES system modelling for evaluating various dispatch strategies and two different battery technologies such as; LIB and LAB.
[30]	2020	PV-WT-DG-BESS	Ukhia, Cox's Bazar	14,041	83	Optimal HRES system for Rohingya refugee community using HOMER
[49]	2021	PV-PHS	Sitakunda	48,314	80	A comprehensive analysis of various system configurations is presented for a rural community
Proposed system	2023	PV-LIB-HS	Sutabaria	0	100	HRES system for a rural community of 2838 people without having grid access using HOMER

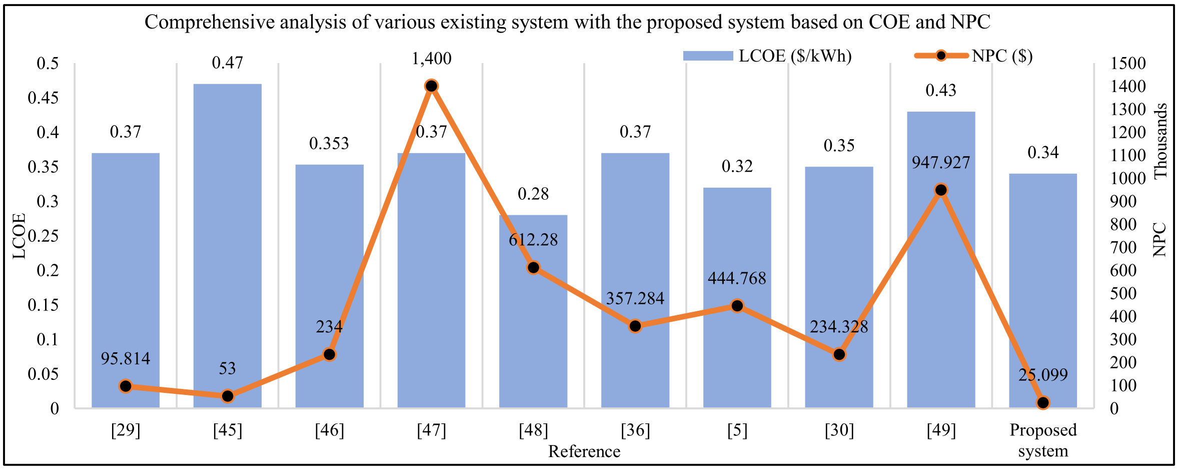


Fig. 11. Comprehensive analysis of various existing systems with the proposed system based on COE and NPC.

systems are playing an increasingly important role in achieving the United Nations' SDGs. Efficient HRES systems combine with diverse ES technologies, such as LIB, HS systems, and flywheels, to provide dependable and efficient energy solutions that facilitate the integration of RES into the grid [50]. The main 17 SDGs goals are divided into three categories; environment, society, and economy [11]. Among the SDG 17 goals, the HRES system development and energy optimization problem has a direct or indirect impact on the ten SDG goals. SDG 7 and SDG 9 have a direct impact on energy resources management, modelling, optimization, and decarbonization whereas SDG 1, 3, 8, 11, 12, 13, 15 and 17 have an indirect impact in achieving the SDGs goals [22]. For a developing country, energy access is a critical concern for improving the socioeconomic situation of rural areas. The proposed PV-HS-LIB-converter-based optimal system configuration has numerous socio-economic as well as environmental benefits. The proposed system has a low LCOE ($0.34/kWh) compared to the other potential system configurations. In Table 6, the positive impacts of the proposed system in accomplishing various SDGs are presented.

The installation of the HRES system also has some negative impacts on achieving the SDGs. The proposed system consists of PV, HS, BESS, and a converter. One of the most renowned BESS is the lithium-ion energy storage system (LIB ESS), known for its manifold benefits including curbing GHG emissions and mitigating energy wastage through surplus energy storage. However, it is imperative to acknowledge that certain drawbacks are also associated with this technology. Negative effects can be categorized into three stages: mining, manufacturing, and recycling [13]. Notably, 500,000 gallons of water are necessary for producing one ton of lithium [52], potentially harming surrounding ecosystems and water bodies. Moreover, only 2% of the total waste generated in Australia from LIB ESS are recycled and the rest is dumped [53] can cause serious damage to the environment as the LIB components consist of toxic materials and chemical that are dangerous to the environment and natural habitats and leads to a direct negative impact on SDG 13, SDG 14 and SDG 15. Due to high flammability, HS systems are potentially dangerous, especially in densely populated areas, which can impact SDG 15.

6. Conclusion and recommendation

The energy sector as a whole is experiencing a structural shift. The energy sectors are shifting towards RES, which is a more dependable, cost-effective, and practical solution. Bangladesh is committed to achieving the 2030 SDGs, which will provide the foundation for sustainable development and progress throughout the country. The current study explores the HRES system's possible application for electrifying an isolated area by developing an efficient HRES system containing optimal cost assessment and regulation of GHG emissions. Five separate HRES system configurations are examined in this analysis, and an optimum

Table 6
Positive impacts of the proposed hydrogen-based HRES system in achieving various SDGs.

SDG Goal	SDG criteria	Optimal HRES system impact
SDG 1	No Poverty	The proposed HRES system can help to achieve SDG 1 by providing clean, affordable energy to rural communities that do not have access to the grid. HRES systems can drive economic growth and create new job opportunities. This reduction in energy costs can help to improve the financial stability of households, which can help to reduce poverty.
SDG 3	Good health and well-being	The proposed HRES system can provide clean and reliable energy which can improve the healthcare and educational facilities. Furthermore, the HRES system can minimise air pollution by supplying clean energy to replace conventional fossil fuels used for heating and cooking,
SDG 7	Affordability	The proposed HRES system has an NPC is $25,099 and an LCOE is $0.34/kWh. Although, the availability of electricity for 2838 people, the capital cost is comparatively low with a low LCOE which leads to energy affordability.
	Reliability	The total unmet electric load of the proposed system is 2.31kwh/yr which is only 0.056% of the overall system. The developed system is considered a reliable system to meet the demand.
	Sustainability	The proposed HRES system has an RF of 100% with no CO_2 emission which leads to a sustainable system.
	Modernization	The proposed optimized HRES system is a hybrid system and can be operated in both grid-connected and stand-alone modes is a modern technology to ensures electricity access to everyone in an environmentally friendly way.
SDG 8	Decent work and economic growth	By providing affordable and reliable energy, HRES systems can support SDG 8 by offering employment, boosting economic growth, encouraging entrepreneurship and innovation, and fostering sustainable economic development.
SDG 9	Sustainable industrialization	Sustainable industrialization includes a boost in small-scale industries and manufacturing employment proportion. The load profile of the rural village considered for the proposed system does not only consist of residential load but also agricultural and industrial load which is directly related to sustainable development. Thus HRES can positively impact innovation, industry, and infrastructure.
	foster innovation	The stand-alone hydrogen-LIB-based Hybrid system consisting of RES is a modern and innovative way to minimize the negative environmental impact due to fossil fuel-based energy generation.
SDG 11	Safe and inclusive human settlements	According to Ref. [51], energy is a key factor in guaranteeing basic housing and healthcare sustainably and healthily. The availability of electricity with a low LCOE can improve the safety, transportation facility, and lifestyle of the people. People tend to be more involved in industrial activities to improve their financial condition.
	Sustainable cities	Sustainable cities include urban planning and operation to promote social, environmental, and economic impacts. The facilities include sustainable infrastructures, the availability of public transport, and a solid waste management system. An optimized HRES system has an indirect effect on vehicles and transportation facilities. Using a lead-acid battery instead of fossil fuel, 95% of the primary components can be reduced and recycled [14] which leads to lowered amounts of toxic and hazardous wastes. The 100% RF of the HRES system can provide clean and sustainable energy to meet the demands of rural areas.
SDG 12	Responsible consumption and production.	Energy efficiency, reducing reliance on non-RESs, bolstering energy security, and encouraging sustainable consumption are all ways in which the proposed HRES systems can contribute to SDG 12.
SDG 13	Action to combat climate change and its impacts	The proposed optimized system is 100% renewable sources with 0 kg/year CO_2 emission. While comparing with case 6 which is a full diesel generator-based system, it can be seen that the DG-based system has a CO_2 emission of 116,096 kg/year which has a direct negative impact on the environment.
	Effective climate change-related planning and management	The proposed system has a lifetime of 25 years. While considering the whole lifetime, the HRES system can able to reduce 2,902,400 kg of CO_2 emission to the environment. A long-term effective and optimized planning and management to ensure the proper use of energy can drastically improve not only the socio-economic scenario but also the environmental situation.
SDG 15	Life on land	The HRES systems can aid in the achievement of SDG 15 by boosting sustainable energy generation, minimising the environmental impact of energy infrastructure and transportation, giving energy access to remote and rural areas, and promoting sustainable consumption.
SDG 17	Partnerships for the goals	The proposed HRES systems can contribute to the achievement of SDG 17 by increasing alliances and technological collaboration in information exchange, as well as global support and collaboration for sustainable energy generation and storage.

configuration is chosen based on the lowest LCOE and NPC, as well as the relative strengths and weaknesses of a rural community. A combination of 8.67 kW of PV, 6 kW of electrolyzer, 1.8 kW of FC, 5 kg of HT and 1.67 kW of converter capacity is considered the most optimal system due to its lower NPC and LCOE than other system configurations. The primary outcomes of this study are as follows.

- The proposed HRES system configuration has the lowest NPC ($25,099) and LCOE ($0.34) compared to the other configurations.
- The optimal system has an RF of 100% with no CO_2 emission which is significantly less than the full DG-based system (27,348 kg/year), and kerosene-based lighting (36,135 kg/year).
- The proposed system is highly sustainable and environmentally friendly due to its low unmet load (2.31 kWh/year), capacity shortage (4.09 kWh/year), and 100% renewable fraction (RF).

- The comparative analysis between LIB and LAB is presented and the result shows that, due to higher lifetime throughput and higher temperature tolerance, the PV-DG-LIB system has a 30% less LCOE compared to the PV-DG-LAB-based system. Moreover, using the dispatch strategy has also an impact on the overall NPC and LCOE. The result shows that using CD instead of CC will reduce the overall NPC and LCOE by 28.74% and 28.85% respectively for Case 2 whereas 7.9% for Case 3.
- The comparative analysis between the PV-HS system and PV-HS-LIB system is presented and the outcome shows that using LIB along with HS reduces the overall NPC and LCOE by 43.58% and 44.35% respectively.

Although the research shows promising outcomes some factors are needed to be considered before the real-time implementation. Firstly, the research is constrained by the specific geographical and socioeconomic context of a chosen rural community with no grid connection for a developing country, Bangladesh. Secondly, the precision of results could be influenced by the data accuracy regarding load profiling, and modelling assumptions. Thirdly, for developing countries like Bangladesh, the implementation of the project is heavily dependent on government policies, incentives and political influences, which are not considered in the research. These factors can directly affect the overall NPC of the system. For future work, a grid extension design can be proposed, and surplus energy can be sold to the grid, lowering the system's LCOE and NPC significantly. Moreover, load estimation was done according to the number of people and households which can be improved, and real-time primary survey data can be used to develop the load profile as suggested for future investigation. Furthermore, integrating advanced technologies such as artificial intelligence, machine learning, or predictive algorithms could optimize the system's performance by enhancing energy management and decision-making processes. In addition, it is essential to assess the potential negative effects of the HS-based HRES system on the environment, economy, and society to guarantee that they are adequately managed.

The impact of the optimal system in achieving various SDGs in Bangladesh is analyzed. The proposed system with a low LCOE, NPC, capital cost, high RF percentage, and low unmet load leads to an affordable, sustainable and reliable system. The 100% RF indicates zero carbon emission, representing a significant stride towards a cleaner environment. The LCOE is dependent on many factors such as the availability of renewable resources, geographical positioning, income sources, load profile, and grid availability. As access to the grid is still far away, the advantages of modernization in remote areas will increase not just the quality of life but also add to the country's overall economic growth. For HRES systems to effectively contribute to the objective of the developing country for building a sustainable future, additional research and development are required to improve their efficacy and sustainability. Despite the limitations, the study offers valuable insights that contribute to forging a sustainable energy future, particularly as nations seek to transition towards more robust and environmentally friendly energy systems.

Credit author statement

Roles in preparing the manuscript are as follows: Conceptualization by MAH, Data curation by SBW, Formal analysis by SBW, Funding acquisition by MAH and PJK, Investigation by RAB, Methodology by SBW and MAH, Project administration by MAH, Resources by SKT, Software by TMIM, Supervision by MAH and PJK, Validation by MSAR, RAB, Visualization by MSAR, RAB and PJK, Writing - original draft by SBW, Writing - review & editing by MAH, PJK, RAB, SKT and TMIM.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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