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3E analyses of battery-assisted photovoltaic-fuel cell energy system: Step towards green community

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Abstract

Diesel generator-based energy systems (DGES) are often utilized for rural electrification, which is neither economical nor an eco-friendly choice. Also, fuel logistics in rural areas and uncertain varying prices of diesel are obstacles that make the DGES technically and economically unfeasible. Thus, a battery-assisted photovoltaic-fuel cell (PV-FC) green energy system (GES) is proposed to meet the energy demand of the rural community in Pakistan. 3E (energy, economic, and environmental) analyses are conducted to access the feasibility of GES in all three domains. The sensitivity analyses are performed to evaluate the effect of the most uncertain parameters on the economy of GES. In addition, the proposed GES is contrasted with DGES. It is investigated that the TNPC and COE of the proposed GES are 15% and 38.4% less expensive than DGES. The proposed GES contributes no emissions to the environment saving 384.47 tons/yr of greenhouse gas emissions as compared to DGES. Furthermore, no significant difference in the technical performance of both DGES and GES is observed. Hence, it is concluded that the proposed GES is financially, technically, and environmentally a feasible solution for rural electrification. Finally, future work is recommended to further explore this research direction.
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1. Introduction

For the past decade, Pakistan is dealing with a serious energy crisis caused by a huge gap between energy demand and generation, which has resulted in frequent power outages for many hours all over the country. The overall power demand in Pakistan is around 25,077 MW [1], however, 18,000 to 20,000 MW of power demand is satisfied with a

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power shortfall between 5000 MW to 7000 MW in peak hours [2]. In Pakistan, 61% of total energy generation is dependent on thermal power plants, with fuel oil accounting for 36%, causing the high price of energy generation and being heavily reliant on oil price fluctuations. Therefore, greenhouse gas (GHG) emissions in Pakistan are estimated to rise by 277.9 Mt in the next 15 years [3]. To combat GHG emissions, Pakistan has planned to introduce 60% of electricity in the national grid from renewable energy (RE) sources by 2030. Presently, RE (except massive hydropower) such as solar, wind, and biomass make up less than 3% of the total energy generation [4]. Economical, environmentally friendly, and robust RE sources are a potential substitute for conventional fuel-based power plants, particularly in rural areas.

Pakistan's topographical location, being among the countries close to the equator, is ideal for solar energy projects due to its high solar radiation. Pakistan's overall solar radiation is around 5.5 × 1014 kWh in a year, with an average of 9.5 h of sunshine each day [5]. However, the intermittent nature of solar energy owing to regional weather and geography causes an impact on solar power output. As a result, an energy storage system is needed [6]. Batteries are commonly used to store energy, however, power leakage and inadequate energy density are associated with batteries [7]. Hydrogen, on the other side, is seen as a feasible energy source for an endurable future of green energy utilization. Howbeit, hydrogen's ordinary roundtrip efficiency, and deteriorated productivity of a RE-powered electrolyzer emphasize using batteries to improve the electrolyzer's efficiency [8]. Energy can be stored for short as well as extended periods using a battery-coupled electrolyzer energy system [9] and [10]. Whenever the excess power from PV is less than the electrolyzer's rated power, the battery bank saves surplus RE output to assist the electrolyzer. This method minimizes the number of electrolyzer start due to the varying RE output and thus increasing electrolyzer lifetime and performance of the whole system.

Keeping in view the advantages of this system, the present study proposed the battery-assisted PV/FC green energy system (GES) to electrify the grid isolated community in Pakistan. Sensitivity analyses are investigated to observe the effect of variation in inflation and discount rates, solar radiation, and load demand on the proposed GES. To examine the 3E (energy, economic, and environmental) benefits of the GES, the results are compared with a case study of a diesel generator-based energy system (DGES) serving the community's energy demand.

2. Load profile and solar resource assessment

The studied region is a small rural village known as Chukhi, situated (geographically 25°18′N 68°36′S) in Hyderabad, a city in Sindh province, Pakistan. The energy demand of the studied region is calculated as per the information obtained from a local household load assessment. This study employs a load of 200 households, where each house contains various typical electrical equipment, having average daily electrical energy consumption is 1320 kWh/day with a peak load of 121 kW/day Fig. 1. Due to the unavailability of ground-based solar radiation data, the monthly average solar radiation data and ambient air temperature of the studied region are taken from [11] renewable access library for the simulation of the proposed GES. The clearness index remains above 0.55 in the studied region throughout the year showing the potential of solar-powered energy projects.

3. Methodology

3.1. Proposed green energy system (GES) description

The proposed GES, including PV, FC, electrolyzer, hydrogen tank, converter, and battery, is optimized to serve 1320 kWh daily load as shown in Fig. 2. The primary source of electricity is the solar panel. The excess electricity is utilized by the electrolyzer to provide hydrogen to FC, which is further converted into electricity to serve the load at peak hours or nighttime. The battery energy system (BESS) stores the electricity whenever the excess power from PV is less than the electrolyzer input power, which is also used to serve the load when needed. BESS not only improves the performance of the GES, electrolyzer lifetime, and hydrogen roundtrip efficiency but is also cost-effective. The cost and considered size details of each component are enlightened in Table 1. The detailed mathematical modelling and specification of each component can be found in references against each component in Table 1. For economic analysis, the nominal discount rate and inflation rate are obtained as 13.75% and 13.80%, respectively from the State Bank of Pakistan [12].

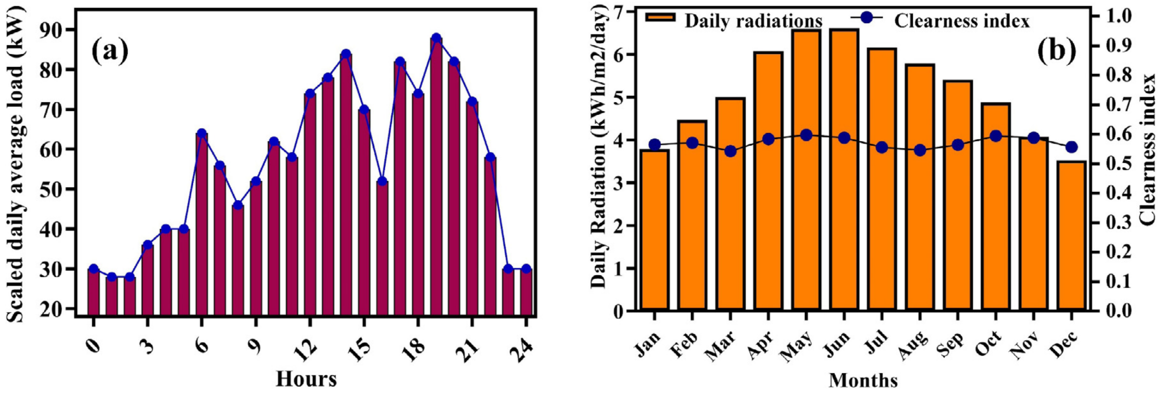

Fig. 1. Input data for proposed energy system (a) Scaled daily average load, (b) Monthly average solar GHI.

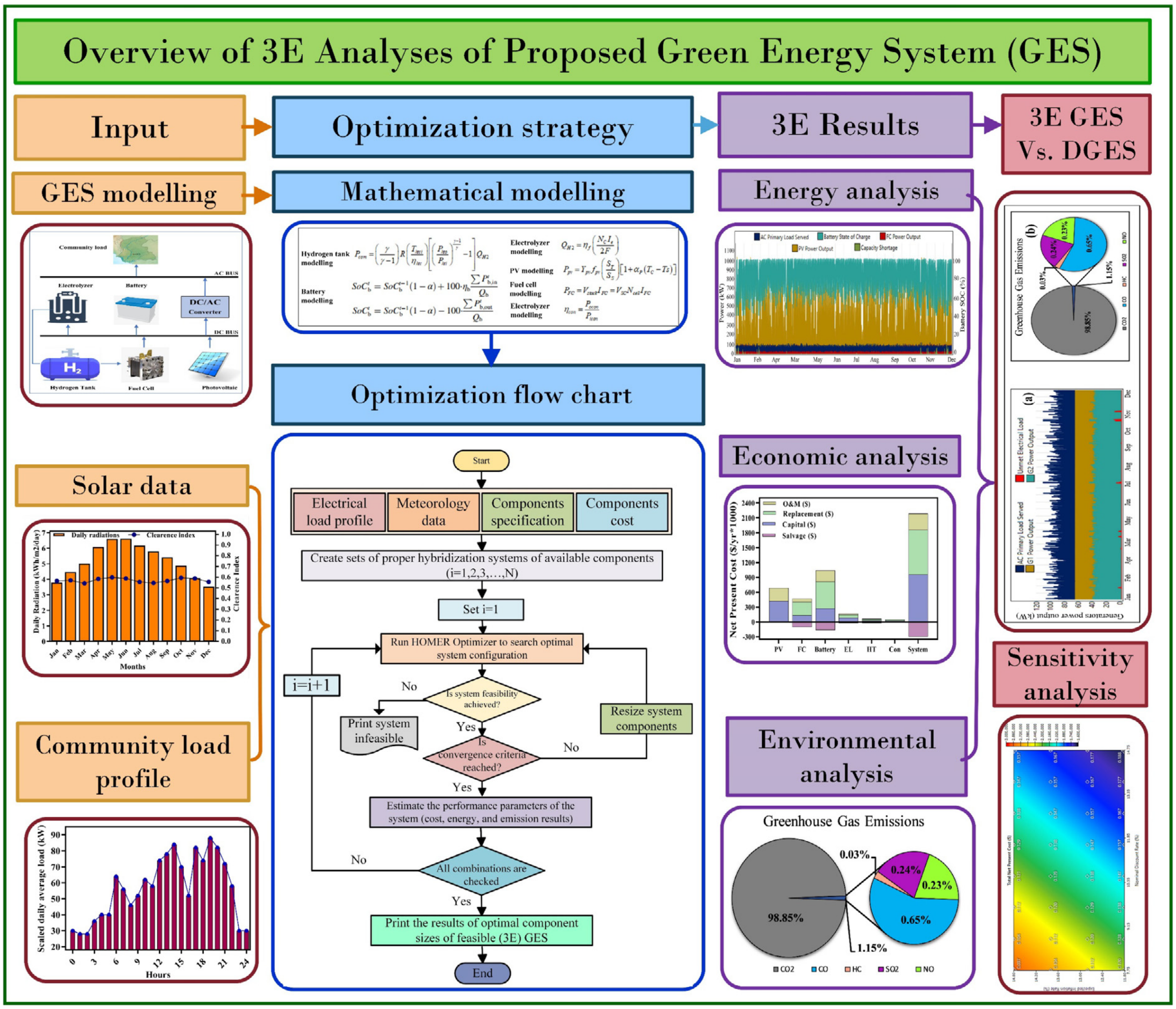

Fig. 2. Overview of 3E analysis of proposed green energy system.

Table 1. Proposed GES components cost and considered size details.

Components	Initial cost ($/kW)	Replacement cost ($/kW)	O&M cost ($/yr)	Efficiency (%)	Useful life (Yrs)	Considered sizes
PV (CS3U-360P)	400	400	10	18.2	25	0 to 1200 kW, step size 100 kW
Fuel cell [13]	2,000	2,000	0.03 ($/h)	58.3	15000 (h)	0 to 120 kW, step size 10 kW
Battery [14]	300	300	10	80	20	0 to 1000 kWh, step size 100 kWh
Electrolyzer [15]	1,100	850	10	85	15	0 to 80 kW, step size 100 kW
H_2 tank [16]	600	600	10	–	20	0 to 50 kW, step size 100 kW
Converter [17]	200	200	0	90	15	0 to 140 kW, step size 10 kW

3.2. Optimization tool and control strategy

In this work, HOMER is utilized for energy-economic-environmental analysis. A pre-HOMER analysis is conducted-crucial for the effective design and implementation of renewable projects-taken into account solar energy assessment and the daily energy needs of the studied rural community. Numerous scientists have used HOMER in their investigations [18]. To successfully produce optimum results in HOMER, three primary steps are outlined: develop system design, carry out optimization, and perform sensitivity analysis [19]. The objective function of the optimization is to reduce TNPC, COE, and GHG emissions while ensuring reliability. The constraints include the number of PV and electrolyzer, the capacity of the battery, and the volume of the hydrogen tank. The input parameters have been discussed in Section 2.

The control strategy adopted is based on the load-following concept, which attempts to optimally utilize the self-consumption of RE sources. Using this technique, FC would only be powered on to meet the current load shortfall and is not allowed to produce power to recharge batteries, resulting in fewer duty hours and lower fuel consumption. Additionally, avoiding unneeded charge/discharge of the battery extends its life and saves replacement expenses, resulting in a load-flowing strategy that can ensure reduced system cost.

4. Results and discussion

Table 2 shows the optimized GES configuration and system cost, while Table 3 presents the electrical profile of the optimized energy system.

Table 2. Optimized GES configuration and system cost.

PV (kW)	FC (kW)	Battery (kWh)	Electrolyzer (kW)	Hydrogen Tank (kg)	Converter (kW)	TNPC ($)	COE ($/kWh)	Operating Cost ($/yr)	Initial cost ($)
1050	100	900	75	45	135	2,152,231	0.179	47,547	956,721

PV: Based on the rated output of photovoltaic, the yearly mean power output and daily mean energy output of a PV panel are obtained to be 196 kW and 4712 kWh/day, with a capacity factor of 18.7%. PV penetration is the proportion of installed PV panel capacity to the peak energy demand, which is 357% in this study. The daily mean energy output is found to be proportionate to the PV penetration. PV operating hour is defined as the total hours per year in which PV generates electricity, which is found to be 4380 h.

Fuel Cell: The FC efficiency is determined by dividing the electrical energy output by the hydrogen energy input, which is 58.3% in this work. The average quantity of hydrogen utilized by FC to generate 1 kWh of energy is referred to as specific fuel consumption. The yearly hydrogen utilization is 4424 kg/yr, whereas the specific hydrogen consumption is noted as 0.0481 kg/kWh. The fuel energy input is examined as 147,457 kWh/yr. FC has a total of 1341 h of operation per year. The total number of FC starts over the years is 631. The functional life of

Table 3. Electrical profile of optimized GES.

PV panel output power (kWh/yr)	(%)	Fuel cell output power (kWh/yr)	(%)	AC primary load (kWh/yr)	(%)	Electrolyzer load (kWh/yr)	(%)
1720043	94.9	91,909	5.07	477,937	70	205,074	30
Battery throughput (kWh/yr)		Unmet electrical load (kWh/yr)	(%)	Capacity shortage (kWh/yr)	(%)	Renewable fraction	
137,543		1841	0.401	2641	0.55	1	

FC is observed to be 11.2 years, which must be replaced after this time. The maximum, minimum and mean power output from FC is measured as 100 kW, 30 kW, and 68.5 kW, respectively.

Battery: Energy in and out over the year is found to be 153,587 kWh/yr and 123,022 kWh/yr, respectively. The reduction in the SOC of a battery at the end of the year with respect to the start of the year is known as battery storage depletion. It is examined to be 171 kWh/yr. In addition, storage wear cost turned out to be 0.210 $/kWh. The usable nominal capacity and annual throughput of the battery were found to be 540 kWh and 137,543 kWh/yr, respectively. The SOC of the battery remains above 40% throughout the year Fig. 3(a).

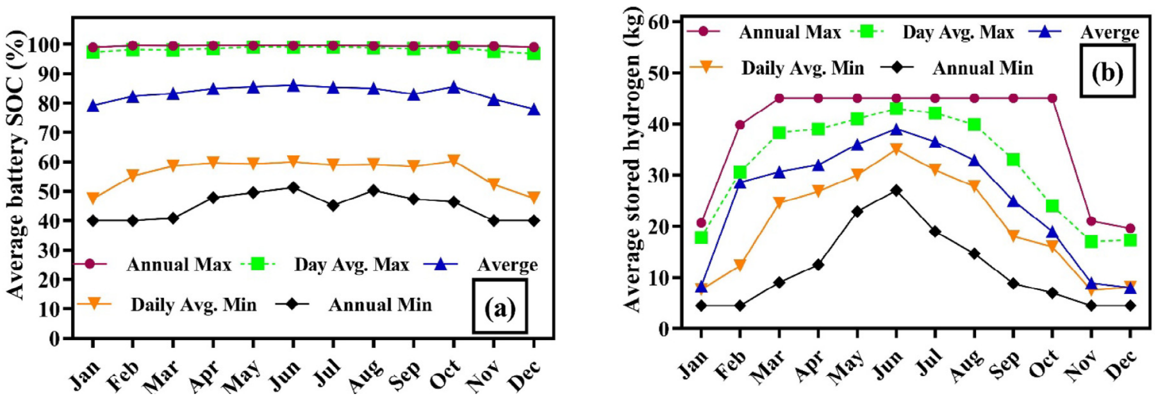

Fig. 3. Performance of battery and hydrogen tank (a) Average SOC of battery, (b) Average stored hydrogen in the hydrogen tank.

Hydrogen Tank: The energy storage capacity of the hydrogen tank is 1500 kWh because the initial tank level with respect to tank storage is set at 10%, thus the hydrogen at the beginning of the year is 4.5 kg, while it is 5.1 kg at the end of the year Fig. 3(b). The autonomy of the hydrogen tank is examined to be 27.3 h.

Tables 4 and 5 exhibit the performance of electrolyzer and inverter. Fig. 4. represents the electrical performance and cash flow summary of the proposed GES.

Table 4. Performance of electrolyzer.

Maximum input power (kW)	Maximum output hydrogen (kg/h)	Mean input power (kW)	Mean output hydrogen (kg/h)	Specific fuel consumption (kWh/kg)	Capacity factor (%)	Functional hours
75	1.62	23.4	0.504	46.4	31	6,698

Cost analysis: The battery is contributing a higher NPC of $ 872,937.29 followed by PV of $ 684,005.29 among other components. The higher NPC of the battery is due to the replacement cost of $ 543,741.10, which is almost double the capital cost. On the other hand, H_2 tanks and batteries share a minimum NPC ($ 45,079.16 and $39,882.52) in the energy system. The salvage value and replacement cost of PV are zero because the life of PV and GES is the same e.g., 25 years. The TNPC and COE are estimated to be $ 2,152,231 and 0.179 $/kWh.

Table 5. Performance of inverter.

Monthly average input power (kW)	Monthly average output power (kW)	Inverter's capacity (%)	Monthly Mean output power (kW)	Monthly Maximum output power (kW)	Annual input energy (kWh/yr)	Annual output energy (kWh/yr)
58.09	52.28	45.7	61.83	135	503,092	452,782

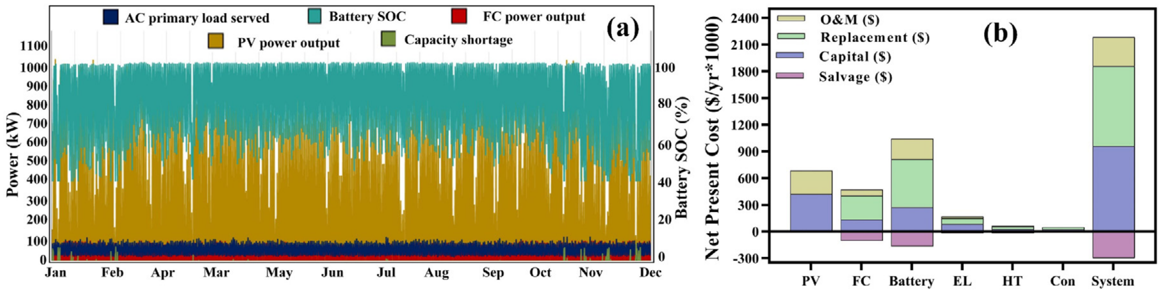

Fig. 4. Overall performance of proposed GES (a) electrical ouput, (b) cash flow summary of individual components.

5. Sensitivity analyses

Effect of annual discount rate and inflation rate on TNPC and COE: Recently, in Pakistan, the nominal discount rate is significantly increased from 9.75% to 13.75% in the last 4 months [12]. Therefore, it is very necessary to include the nominal discount rate and inflation rate in a sensitivity analysis. Values of both parameters are varied by observing the last 2 years' economic trends. It can be observed from Fig. 5(a) that COE is proportional to the nominal discount rate, whereas it is inversely proportional to the inflation rate. The aforementioned observation is found to be the opposite of the TNPC.

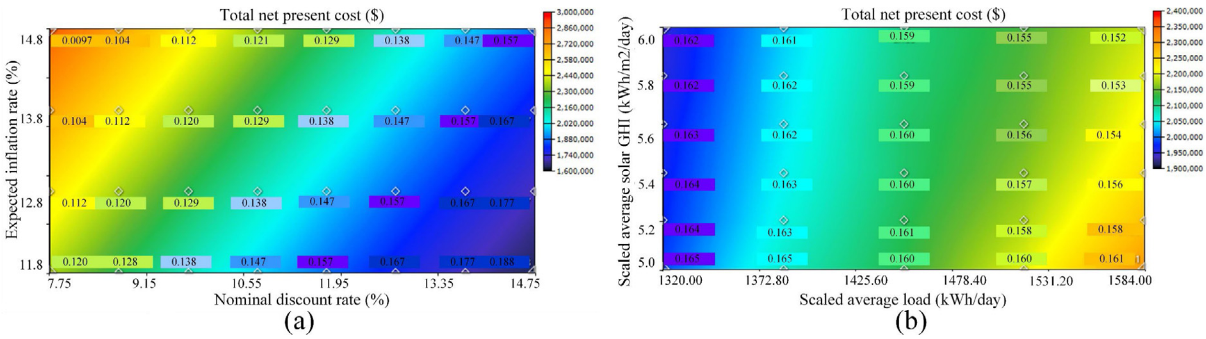

Fig. 5. Effect of variation of (1) Nominal discount and inflation rates, (b) Solar average GHI and load, on TNPC and COE.

Effect of load and solar radiation variation on TNPC and COE: HOMER considers the load profile as constant over the whole lifetime of the project so that it can provide results of only one year's system operation. Nevertheless, in the 25 years lifetime of the project, the load profile may change with the change in the dwellers' lifestyle. In addition, the solar radiation data is satellite-based, which is less reliable as compared to ground-based data. Thus, the sensitivity analysis is done based on the increase in the load demand and variation in solar radiations. It can be observed from Fig. 5(b) that by increasing both load and solar radiations to 20% from their initial values, the COE is reduced by 7.87% and TNPC increased by 9.53%. Increased in load by 20%, while keeping the solar radiation constant, the COE was reduced by 2.5% and TNPC increased by 14.15%. However, no significant effect on TNPC and COE is observed by only varying the solar radiations.

6. Comparison with diesel generator-based energy system (DGES)

To compare the 3E performance of the proposed GES, the energy demand of the studied region is simulated to be met by DGES, which is commonly used for rural electrification. Two diesel generators (G1 and G2), each having a capacity of 70 kW were chosen to meet the energy demand. The capital cost, replacement cost, and O&M cost were taken as $ 460/kW, $ 400/kW, and $ 0.05/hr, respectively [20]. The diesel price was taken to be 0.78 L/$ as of 23rd May 2022 [12]. The annual electricity produced by G1 is 341,471 kWh/yr (58.92%), while G2 produced 140,273 kWh/yr (41.07%) Fig. 6(a). It can be said that G1 met the base demand, whereas G2 serve the load at peak hours. The percentage of different harmful gasses emitted is illustrated in Fig. 6(b). It is deduced that the GES is more economical than the DGES. Also, the GES is emissions less. No significant difference was observed in the technical performance of both systems. Table 6. represents the 3E comparison of both energy systems.

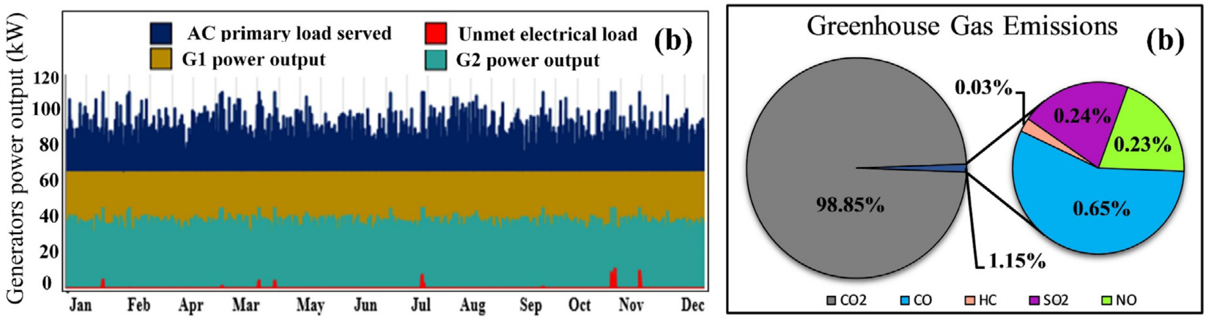

Fig. 6. Performance of diesel generator energy system (a) Electrical profile, (b) Greenhouse gas emissions.

Table 6. 3E comparison of DGES and GES.

System	TNPC ($)	COE ($/kWh)	Initial cost ($)	Operating cost ($/yr)	Capacity shortage (%)	Unmet electric load (%)	GHG (Ton/y)
DGES	3,533,896	0.291	50,600	138,536	0.53	0.39	384.47
GES	2,152,231	0.179	956,721	97,547	0.55	0.401	19.8

7. Conclusion and future recommendation

Motivated by the carbon neutrality goal of Pakistan as the rate of GHG emissions is continuously elevating, the battery-assisted PV/FC GES is proposed to electrify the rural community of Pakistan. The goal of the study was to conduct the 3E (energy, economic, and environmental) analysis of the proposed GES. It was observed that the optimized GES consisting of 1050 kW PV, 100 kW FC, 900 kWh batteries, 75 kW EL, and 45 kg of HT satisfied the required energy demand with a 0.55% capacity shortage. The TNPC and COE were estimated to be $ 2,152,231 and 0.179 $.kWh, respectively which is within an economical range. In addition, no evidence of GHG emission was found. Sensitivity analyses revealed that the proposed GES could be more economical provided that the economy of Pakistan gets stable. Finally, comparison analysis revealed that (1) GES is more economical than DGES except for the initial cost, (2) both DGES and GES are technically feasible and satisfy the energy demand of the community, (3) DGES emitted 384.47 tons/yr of GHG emissions, however, GES proved to be emission less. Therefore, it can be inferred that the proposed GES has the potential in all 3E domains to replace DGES. The study conducted in this investigation is scalable and can be utilized anywhere in the globe provided the input parameters are close to identical to this work.

The researchers can further extend the scope of the present work by comparing the PV/FC energy system with the proposed battery-assisted PV/FC energy system. Other renewable energy sources such as wind, biomass, hydropower, etc., can be used and compared to their 3E results. In addition, renewable/FC-based energy systems can be optimized with other software tools such as TRNSYS, RETScreen, IHOGA, etc., to compare their results.

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

Data will be made available on request.

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