Optimizing Renewable Energy Integration: a Hybrid Energy System Approach for Residential Applications

Asjad Ali, Asma Bibi, Noor Izzri Bin Abdul Wahab, Muhammad Nadeem Akram, Hafiz Abdul Muqeet and Rizwan A. Farade

January 20, 2025

Optimizing Renewable Energy Integration: A Hybrid Energy System Approach for Residential Applications

Asjad Ali[1]*, Asma Bibi[2], Noor Izzri Bin Abdul Wahab[3], Muhammad Nadeem Akram[4], Hafiz Abdul Muqeet[5], Rizwan A. Farade[6]

[1,3,6] *Advanced Lightning, Power and Energy Research (ALPER), Department of Electrical and Electronics Engineering, Faculty of Engineering, University of Putra Malaysia ,43400, Serdang, Malaysia*
[2] *Ericsson Pakistan Private Limited Islamabad, Pakistan*
[4]*Department of Mechanical, Automotive and Materials Engineering, University of Windsor,* Windsor, ON N9B 3P4, Canada;
[5]*Department of Electrical Engineering Technology, Punjab Tianjin University of Technology, Lahore 54770, Pakistan*

**gs71809@student.upm.edu.my*

Keywords: Hybrid Energy Systems, Distributed Energy Sources, Renewable Energy, Techno-Economic analysis

Abstract

Climate change, soaring inflation and energy shortages are driving interest in Distributed Energy Sources (DES), especially in developing countries like Pakistan, where power outages disrupt daily life. Residential communities are increasingly adopting renewable energy sources (RES) and battery storage systems (BESS) to reduce reliance on utility grid and produce cheap energy compared to grid. The authors propose a hybrid energy system (HES) combining solar PV, a diesel generator, and BESS to reduce levelised cost of energy (LCOE) and emissions while addressing energy outages for a residential building in Lahore, Pakistan. The average daily utilization of selected building is around 463 kWh/day with a peak demand of 33 kW. Different configurations are designed and their techno-economic and environmental analysis is conducted using HOMER Software. In one scenario combining PV-DG-BESS-Grid, the lowest LCOE of $0.0120 was achieved, but it resulted in higher emissions due to DG dependence. A PV-BESS-Grid configuration had a slightly higher LCOE of $0.0124 but significantly lower emissions. Sensitivity analysis also revealed that PV-BESS-Grid system to be most robust among all the designed systems.

1. Introduction

Pakistan has abundance of renewable energy sources. Among renewable energy sources, solar energy has a tremendous potential in different regions of Pakistan. Regions in Punjab, Sindh and Baluchistan receive around 2 MWh/m^2 of solar irradiation and 3000 h of sunshine per year which is ideal for utilizing solar energy. Recent surges in inflation have increased the prices of fossil fuels and electricity prices have also exacerbated. Apart from this, due to poor infrastructure of transmission and distribution, scheduled load shedding is also common which severely disturbs the daily activities [1], [2]. In ref. [3], the authors showed the potential of solar energy and wind energy produced from 1kWh solar panel and 1 kWh of wind turbine in different cities in Pakistan. The results indicate that solar energy was cheapest among both sources. Solar energy in the form of rooftop installed PV systems presents the practical solution to cater with the problem of frequent grid outages and high electricity prices. HES consisting of PV system and BESS can assure reliable and uninterrupted energy supply, reduce the dependence on the grid and cut electricity costs and can also contribute to environmental sustainability [4], [5]. The articles have shown that incorporating PV systems with BESS can considerably augment the energy security by providing backup during outages [6], [7]. A review of the literature on designing HES reveals that researchers tailor these systems based on the specific energy resources available in a given region and the unique challenges faced by those areas. These challenges can include power shortages, high fuel costs, environmental concerns, or grid instability, driving the development of HES configurations that address both local needs and resource potential effectively [8], [9]. The potential of HESs goes beyond individual financial benefits, as they play a key role in modernizing energy systems, promoting decentralized power generation, and improving grid reliability. By optimizing energy production, storage, and utilization, these systems reduce reliance on conventional fossil fuels and help address global concerns about carbon emissions. In addition, their ability to mitigate grid congestion and improve energy efficiency makes HESs an attractive solution for both urban and rural applications [10], [11]. Therefore, the authors in this article have strived to propose a HES for a residential colony to reduce energy costs and emissions, addressing frequent grid outages and high inflation.

The rest of the article is arranged as; Section 2 provides literature review. Section 3 discusses the methodology adopted in this study. Section 4 provides simulations and results while section 5 concludes the article.

2. Literature Review

This section discusses the literature related to design of HES for different regions. In ref. [12], the authors designed an Energy Management System (EMS) consisting Solar PV, Wind Turbines, EVs and Grid. Bidirectional flow of energy is also considered and excess of energy is imported back to grid. In the best-case scenario LCOE was reduced by 18.28% with Lithium-Ion batteries and by 14.88% with Lead Acid batteries. The designed system also saved carbon emission up to 36 kg/day for the given load. However, in the analysis, the authors did not conduct any sensitivity analysis to determine the behaviour of system with varying inflation rates. In ref. [13] Zahra et al. designed an HES for Mediterranean island campus consisting of wind turbines, solar PV and BESS. The wind PV system with BESS was identified as the best configuration, achieving the lowest energy cost at €0.1838/kWh. This system successfully met 44% of the energy demand while maintaining a 60% renewable energy fraction. Like previous study in sensitivity analysis impact of outages or changes in inflations are not considered. The article in ref. [14] evaluated a novel hybrid solar power system for electricity generation and reducing thermal load in heating and cooling systems. A residential building in Tehran was taken as a case study and simulations were conducted on MATLAB, TRNSYS, and Carrier HAP software. The results showed an increase in energy generation by 50% compared to stand alone system, and a considerable reduction in heating loads was also observed. In sensitivity analysis, the authors varied inflation rates which significantly influenced the payback time of project. However, grid outages are not taken into consideration in this study. Sanjay et al. in ref. [15] accessed the techno economic and environmental performance of building integrated photovoltaic system in Australia. Various load scenarios were analysed to optimize the size of the PV system for a residential building. The proposed system demonstrated an LCOE of 0.074 AUD/kWh and is projected to reduce GHG emissions by approximately 160,198 kg over its lifetime. The study did not incorporate a sensitivity analysis to assess the effects of inflation on the LCOE, nor did it take into account the potential impacts of grid outages, which could significantly influence the reliability and economic viability of the system. In ref. [16], Zhihan et al. optimized an off grid PV-BESS and DG-PV-BESS for smart buildings. They found out that PV-BESS setup with total annual cost of $0.78 million achieved zero emission. Integrating the diesel generator into the system reduced costs to $46,478 but resulted in an annual increase of 50,000 kg in CO_2 emissions. However, in this study, the authors neglected to study the impacts of sensitivity parameters like inflation rates or grid outages on the system performance. In ref. [17], Muskan et al. proposed a consisting of PV-DG based HES for a Akhnoor village in India. The most feasible system achieved LCOE of $0.428, and Operational cost (OC) of $493.72, and an NPC of $16,157. In ref. [18], the authors introduced a reliability based EMS for residential buildings consisting of DES. The designed model included Demand Response (DR) with multiple participation rates, optimization flows, PV power utilization, and grid interaction to minimize the LCOE. The numerical analysis revealed that 30% DR participation reduced the LCOE by 33% during off-peak hours and 76% during peak hours. However, in numerical analysis grid outages or inflation rates are not considered. The authors in ref. [19] proposed a grid connected HES consisting of PV, wind and BESS to supply energy to supermarkets in Casablanca. The designed system incorporated 71% renewable energy achieving COE of $0.0841/kWh and an operating cost of $0.124 M/year. In the sensitivity analysis, renewable energy fraction, energy intensity, and renewable energy resources availability was varied which significantly impacted the reliability of HES. However, the analysis did not account for grid outages or incorporate inflation rates as sensitivity parameters. The authors in ref. [20] designed a standalone HES for a residential area in Manoka Island where fishing is very common activity. The HES is designed to meet an average daily energy demand of 9.28 kWh with a peak load of 0.88 kW, while supporting oxygen production for fish farming. The system achieved an impressive 92.5% renewable energy fraction and generated minimal carbon emissions of just 1.69kg, demonstrating its efficiency and environmental sustainability. The analysis did not include sensitivity analysis for determining robustness of designed system. In ref. [21] the authors optimized a micro grid (MG) using real-time and climate change. Hybrid Grey wolf and Cuckoo Search Algorithm (GWSCO) is used to conduct the analysis. The results showed for optimal design the COE achieved is $0.1992 with annual cost of $2.69 billion. Like previous study, in this article authors did not entail any sensitivity analysis to determine the reliability of the designed system. The main contributions of this article are given as:

- A HES is designed for a residential building to cope with frequent power outages and inflation rate variations, while reducing the COE compared to a grid system.
- The viability of the system is assessed by analysing capacity shortages and inflation rate variations, while its environmental impact is assessed by comparing reductions in hazardous gas emissions with those of a DG-Grid system.

3. Methodology of Study

The system integrates a DG, PV panels, BESS and the grid connection, as shown in the figure 1. PV panels generate electricity during the day, with excess energy stored in BESS or exported to the grid. Stored power provides reliable power during peak or grid outages.

Figure 1: Hybrid Energy System Design

The research aims to propose a HES for the load profile of the residential building. The methodology of the study consists of various stages. The first step is to determine the profile of the location which consists of determination of load demand and available natural resources. In the first stage load data is collected from the selected location and is converted into observable daily load profile. In the second step mathematical modelling of components involved in HES is performed. In this step problem is formulated. In the third step simulation are performed to determine the feasible energy system configuration. HOMER considers techno economic and environmental perspectives in its simulation. HOMER follows load following, cycle charging or hybrid optimizing algorithm to achieve the most optimal solution.

3.1. Location Profile

A commercial block is selected in Model Town Lahore for analysis to determine the feasibility of the different configurations. The coordinates of the selected location are given as 31° 28.8 N and 74 18.9 E. Model Town is located in the southern part of Lahore, Pakistan. It is about 5-6 kilo meters from the city centre of Lahore. The figure 2 below shows aerial view of the selected location.

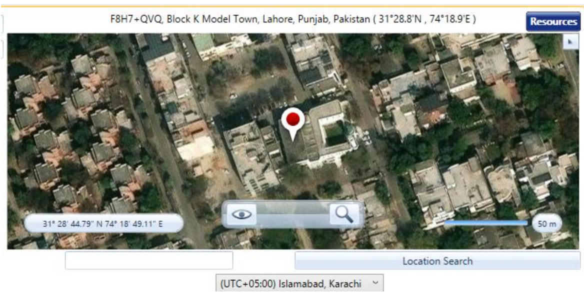


Figure 2: Selected Location for Analysis

The average solar irradiance is 5.12 kWh/m^2/day with an annual average temperature of 26.07 °C. Solar irradiance, clearness index and temperature are presented in the figure 3 below.

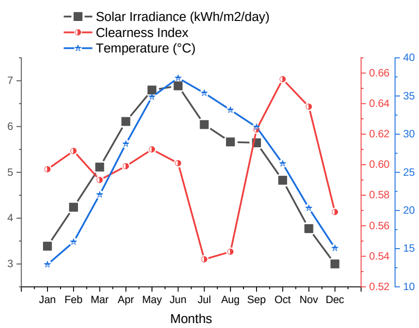


Figure 3: Solar irradiance, Temperature and Clearness Index

The load for the selected location is monitored on hourly basis. The average baseline consumption is found to be 516.9 kWh/day while the peak load consumption is around 33 kW. Scaled annual consumption is calculated to be 463.5 kWh/day. The daily load pattern is depicted in figure 4 below.

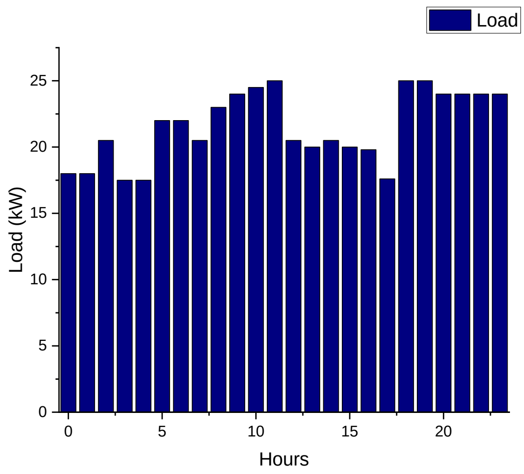


Figure 4: Average Daily Load profile

3.2. Mathematical Modelling

In this section, mathematical modelling of different components of the designed system is presented. The problem formulation is given below in the section of objective function formulation

3.2.1. Objective Function Formulation: The main aim in the objective function is to reduce the LCOE and overall emissions of the system. Equation below presents the formula for calculating LCOE [15].

$$LCOE = \frac{Cost_{\ Total}}{\sum_{t=1}^{8760} Energy_{\ Total}} \tag{1}$$

The total annual energy of the system can be calculated from the equation below.

$$Cost_{\ Total} = Capital_{Recover\ Factor}\left(int_{\ r}, Time_{y}\right) \times NPC \tag{2}$$

In equation 2, $Capital_{Recover\ Factor}$ is capital recovery factor which depends upon the interest rate, and, $Time_y$ is the time period in years.

$$Capital_{Recover\ Factor}\left(int_{\ r}, Time_{y}\right) = \frac{int_{\ r}(1+int_{\ r})^{Time\ y}}{(1+int_{\ r})^{Time\ y}{}_{-1}} \tag{3}$$

NPC represents the net present cost of the project which can be calculated using equation below.

$$NPC = Inv\ Cost + Fu\ Cost + O\&M\ Cost + Rep\ Cost \tag{4}$$

In equation 4, $Inv\,Cost$ is the investment cost, $Fu\,Cost$ represents fuel cost, $O\&M\,Cost$ is the operation and maintenance cost of the designed configuration, and $Rep\,Cost$ is the replacement cost of the designed configuration. Each configuration has some emissions which can be calculated using equation 5 [15].

$$Em = Fu \times EmF \quad (5)$$

Em is the emission of gases from the either the gird or DG unit. Fu is the fuel consumption and EmF is the emission factor of gases released (kg of gas /per liter fuel).

3.2.2. Mathematical Modelling of Grid Energy: The equation below represents the mathematical modelling of energy transaction with the grid [19].

$$\mathrm{T_{AEnC}} = \sum_{rates} \sum_{mn=1}^{12} (E_{purchased,rt,mn} \times Cost_{purchased,rt}) - \sum_{rates} \sum_{mn=1}^{12} (E_{sold,rt,mn} \times Cost_{sold,rt}) \quad (6)$$

In equation 6, $\mathrm{T_{AEnC}}$ is the total energy annual energy cost, $E_{purchased,rt,mn}$ is the total energy purchased in ($/kWh) at rate rt in the month mn at cost $Cost_{purchased,rt}$ ($). Similarly, $E_{sold,rt,mn}$ is the energy sold in ($/kWh) at rate rt in the month mn with cost $Cost_{sold,rt}$($). Peak and non-peak hour rates are calculated explicitly from the equation 7 below.

$$\mathrm{T_{Cost}} = \sum_{rates} \sum_{mn=1}^{12} (E_{purchased,rt,mn} \times Cost_{purchased,rt} + E_{purchased,non-peak,rt,mn} \times C_{purchased,non-peak,rt}) - \sum_{rates} \sum_{mn=1}^{12} (E_{sold,peak,rt,mn} \times C_{sold,peak,rt} + E_{sold,non-peak,rt,mn} \times C_{sold,non-peak,rt,mn}) \quad (7)$$

In equation 7, $\mathrm{T_{Cost}}$ is the total cost of energy including both peak and non-peak hours.

3.2.3. Mathematical Modelling of PV System: The energy engendered from solar panels entirely depends upon the availability of solar irradiance. The power obtained from solar cells is calculated using equation below [20].

$$PV_{out}(t) = P_{rated} \times \psi_{der} \times \left(\frac{irrd_h(t)}{irrd_{STC}}\right) \times [1 + £_T(T_{panel} - T_{STC})] \quad (8)$$

In the equation 8 above, P_{rated} is the rated power of solar arrays (kW), ψ_{der} is the derating factor of solar panel, $irrd_h(t)$ is the average hourly solar irradiation of solar panels. $irrd_{STC}$ is the solar irradiation under standard test conditions. $£_T$ is the temperature coefficient of PV panels which is measured in (%/°C). T_{panel} is the represents the temperature of module and T_{STC} is the temperature of module under standard test conditions. The variations in temperature also impacts performance of solar panels which is calculated using equation 9 below.

$$T_{panel}(\mathrm{t}) = \mathrm{T_{ab(t)}} + (\mathrm{T_{panel,ref}} - \mathrm{T_{ab,ref}}) \times \left(\frac{irrd_h(t)}{irrd_{ref}}\right) \times \left(1 - \frac{\mho_{\mathrm{mp}}}{Þ \times ø}\right) \quad (9)$$

In equation above, $\mathrm{T_{ab(t)}}$ is the ambient air temperature of panel at time t in (°C). $\mathrm{T_{ab,ref}}$ is the ambient temperature under normal conditions. $\mho_{\mathrm{mp}}$ is the efficiency of solar panels at maximum point in (%).Þ is solar transmittance factor and ø is the solar absorptance factor. The product of Þ and ø is usually 0.9 which is used in equation 9.

3.2.4. Mathematical Modelling of BESS: Batteries store excess energy generated from sources which is utilized in peak hours and during outages and after utilization the excess energy is exported to grid. The state of charge and discharge of batteries can be found using equations 10 and 11 below [13].

$$SOC_{batt}(t) = SOC_{batt}(t-1) \times (1-\tau) + \left(PV_{out}(t) - P_{dem}(t) - \frac{P_l(t)}{\eta_{\mathrm{eff}}}\right) \times \eta_{\mathrm{ch}} \quad (10)$$

$$SOC_{batt}(t) = SOC_{batt}(t-1) \times (1-\tau) - \frac{\left(\frac{P_l(t)}{\eta_{\mathrm{eff}}} - P_{\mathrm{aux}}(t) - PV_{out}(t)\right)}{\eta_{\mathrm{dch}}} \quad (11)$$

In the above equations, η_{ch} , η_{dch} are charging and discharging efficiencies of BESS, and $SOC_{batt}(t)$ is the state of charge of batteries at time while $SOC_{batt}(t-1)$ is the previous state of charge. $P_{dem}(t)$ is the power demand and $P_l(t)$ is the power consumed by load. The depth of discharge of battery can be found using equation 12 below.

$$\mathrm{SOC}_{batt}^{\mathrm{min}} = (1 - \mathrm{DOD_{batt}}) \times \mathrm{C_{batt}} \quad (12)$$

The $SOC_{batt}^{\mathrm{min}}$ is represents the minimum amount of state of charge that battery can have which depends upon the depth of discharge and capacity of battery $\mathrm{C_{batt}}$. The maximum amount of power that battery can provide is given in equation 13 below.

$$\mathrm{P_{max}} = \eta_{\mathrm{disc}} \times \mathrm{P_{max,disc}} \quad (13)$$

In equation 13, η_{disc} is the discharging efficiency and $\mathrm{P_{max,disc}}$ is the maximum discharging power of battery.

3.2.5. Mathematical Modelling of Diesel Generator (DG): The output power of the generator can be calculated from the equation 14 below [14].

$$\mathrm{P}_{Diesel}(\mathrm{t}) = \mathrm{P}_l(\mathrm{t}) + \mathrm{P}_{Loss}(t) \quad (14)$$

Here, $P_{Diesel}(t)$ is the power of the diesel and $P_l(t)$ is the load demand which is met by generator and $P_{Loss}(t)$ are the losses that occur during operation. The equation below shows the fuel consumption of diesel generator.

$$F_{Diesel}(t) = P_{Diesel}(t) \times \left((c + d) \times \frac{P_{Diesel}(t)}{P_{rated}}\right) \qquad (15)$$

In equation 15, $F_{Diesel}(t)$ is the consumption of fuel at time t, c is the fuel curve intercept coefficient in L/kWh, and d is the curve slope coefficient. P_{rated} is the power rated capacity of the generator in kW. The overall efficiency of the generator can be calculated from equation 16 below.

$$\eta_{DG} = \frac{P_{Diesel}}{P_{fuel}} \qquad (16)$$

4. Simulations and Results

In simulations overall, 13284 solutions are generated out of which only 5062 are feasible. When categorized option from HOMER is used only three most suitable scenarios are left. The techno economic and environmental performance of the three best configurations as case study is discussed in the section 4.1. It is also assumed that there is bidirectional flow of energy and consumer can sell its excess energy back to the grid.

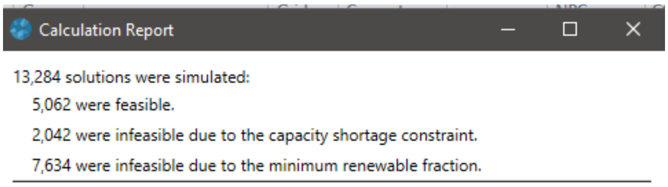


Figure 5: Calculation Report of Simulations

The best optimized systems are

a) Scenario 1: PV-DG-Grid, b) Scenario 2: PV-BESS-Grid

c) Scenario 3: PV-DG-BESS-Grid

However, there are some assumptions that have also been considered for optimization as presented in the table 1 below.

Table 1: Optimization Settings for Simulation

System Settings	Values	Source of Information
Design Precision	0.01	HOMER Settings
Simulation time step	1h	HOMER Settings
Inflation rate	10%	State Bank of Pakistan
Life time of System	20 years	General Settings
Capacity Shortage	0%	General settings
Nominal Discount Rates	8%	State Bank of Pakistan

4.1. Results

In this section performance analysis of three best scenarios are discussed in detail.

4.1.1. a) PV-DG-Grid: The first scenario features a HES composed of PV panels, a 33 kW DG and energy imports from the grid. PV panels dominate energy production, contributing 90.4%, while DG supplies 2.42%, and the remaining 7.14% is imported from the grid. This configuration meets 100% of the load demand and ensures an excess of 20.3% of energy, which can be used during contingencies. The system achieves a COE of $0.0256 and a total NPC of $429,384, with a renewable energy penetration of 86.8%. The DG consumes 7,987 litres of fuel per year and operates for 1,395 hours per year. The technical-economic and environmental performance details of this configuration are summarized in the table 2 below.

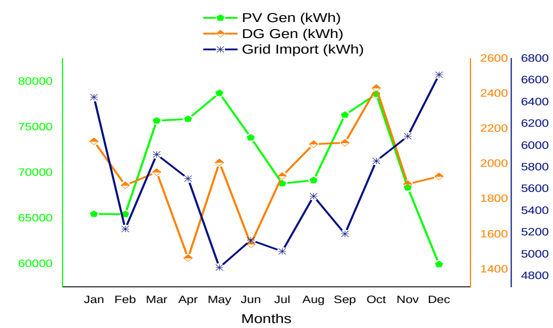


Figure 6: Scenario 1: Power Output from Generation Sources

4.1.2. b) PV-BESS-Grid: Like previous study in this scenario most of the energy share is produced from PV panels with a contribution of 93.4% while rest of energy is imported from the gird which is 6.56%. This system also has an excess energy of 20.9% for contingency situation. However, there is a slight unmet load of 0.007% due to intermittent nature of RES in system. This system achieves over 90.9% renewable energy penetration with a COE of $0.0154, which is around 39.8% lower than Scenario 1. It has an NPC of $273,871 and a payback period of 10.4 years. Total of 13 battery strings are used for storing excess available energy. The techno economic aspects of case study are presented below in table 2.

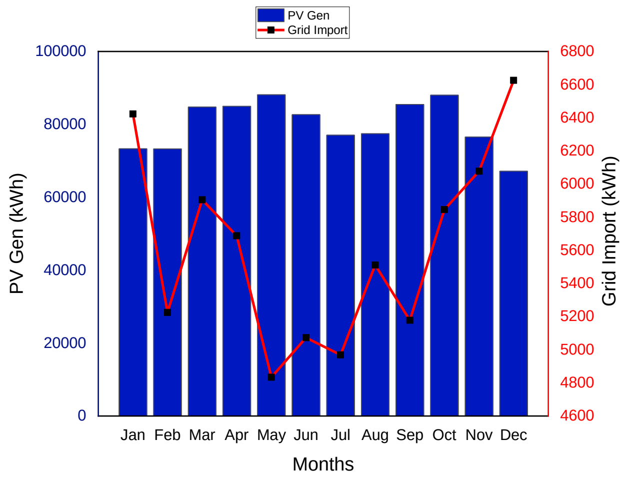


Figure 7: Scenario 2: Power Output from Generation Sources

4.1.3. c) PV-DG-BESS-Grid: This case study mirrors Scenario 2, but includes a DG unit in the system. PV panels provide 93.4% of the total energy, 6.6% is imported from the grid and the DG contributes only 0.00242%. With the inclusion of DG, all loads are met, resulting in no unmet energy demand. The system achieves a renewable energy penetration of 90.8% and generates 20.8% excess energy, similar to the previous cases. Thirteen batteries are used for energy storage. The COE of this system is the lowest, at $0.0149/kWh, 3.24% less than in Scenario 2 and 41.8% less than in Scenario 1. In addition, the payback period is 10.36 years, slightly shorter than Scenario 2.

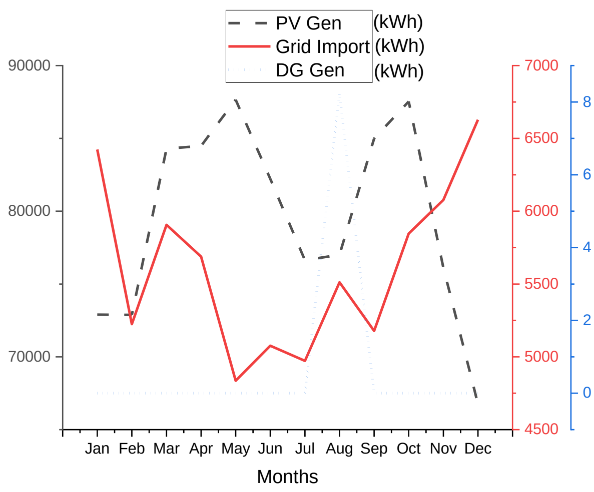


Figure 8: Scenario 3: Power Output from Generation Sources

The techno economic and environmental aspects of this case study are presented below in table 2.

Table 2: Techno Economic and Environmental Results of All Scenarios

Parameters	Scenario 1: *(PV-DG-Grid)*	Scenario 2: *(PV-BESS-Grid)*	Scenario 3: *(PV-DG-BESS-Grid)*
Electrical Parameters			
Grid Sell Back Energy (kW)	519,366	567,782	564,856
PV System (kW)	464	520	517
Diesel Gen (kW)	33	--	33
Converter Size	405	404	405
Economical Results			
Capital Cost ($)	624,735	759,372	772,529
Replacement Cost ($)	20,098	102,713	102,713
O&M Cost ($)	426,349	513,163	509,763
Fuel Cost ($)	214,233	0	305
Salvage ($)	3,334	75,050	98,775
NPC ($)	429,384	273,872	267,009
Environmental Impacts			
CO_2 Emission (kg/year)	63,648	42,568	42,606
CO Emission (kg/year)	132	0	0.188
Unburned Hydrocarbons (kg/year)	5.75	0	0.00819
Particulate Matter (kg/year)	0.799	0	0.00114
Sulfur Dioxide (kg/year)	236	185	185
	214	90.3	90.4

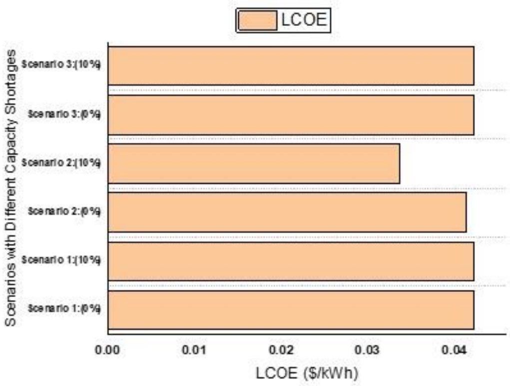
Nitrogen Oxide (kg/year)	

4.2.1. Evaluation of Sensitivity Parameters on Designed Systems: To determine the robustness of the system, variations in both the inflation rate and capacity shortages were analysed. Projections by the State Bank of Pakistan indicate a possible decline in inflation rate which is incorporated into the analysis to ensure a thorough assessment. The table 3 below shows the parameters considered for the evaluation.

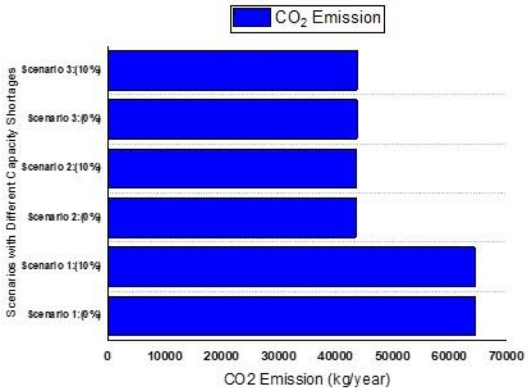
Table 3: Parameters for Sensitivity analysis

Sensitivity Parameters	Values
Inflation rate	7%
Capacity Shortage	0% & 10%

With a reduction in inflation rate from 10% to 7%, scenario 2 achieves the lowest LCOE of $0.0414/kWh with 0% capacity shortfall. Systems 1 and 3, containing a DG display the highest LCOE of $0.0422/kWh. In addition, PV system sizes for scenarios 2 and 3 are reduced to 293 kW and 299 kW respectively. When capacity shortfall increases to 10% for the same inflation rate, scenario 2's LCOE further decreases to $0.0337/kWh. The size of the PV system and LCOE remain unchanged as in case of 0% capacity shortage for both scenario 1 and 3. The chart (b) in figure below shows that scenario 2 and 3 have the least same carbon emission, however, scenario 2 has less LCOE with both capacity shortage of 0 and 10% as evident from chart (a) in figure 9.



(a)



(b)

Figure 9: Impact of Sensitivity Parameters on LCOE and CO_2 Emission

The sensitivity analysis shows the effectiveness of PV-BESS-Grid system both in terms of cheap electricity production and less emission of hazardous gases.

5. Conclusion

High inflation rates have significantly increased electricity costs in developing countries, while frequent grid outages continue to disrupt daily activities. Additionally, growing environmental concerns have driven the adoption of DES, integrating RE and BESS to provide sustainable and reliable solutions. In this article, the authors have proposed a HES consisting DG, PV, BESS and Grid. Following optimization in HOMER, three configurations are designed out of which PV-BESS-Grid configuration emerging as the most suitable due to its balance between cost effectiveness and emissions. The LCOE obtained for this configuration is 0.0124 $/kWh with an NPC of $273,872 and it has least emissions. Sensitivity analysis also indicated this configuration to be most robust against changes in inflation rate and varying capacity shortages. However, integration of RES at distribution level introduces challenges for power system operation and control which are hard for existing SCADA systems to detect because of their latency and delay (2-5 seconds) in measurements, hence it is suggested that advanced monitoring techniques and devices like micro-phasor measuring units should be explored and optimized to place in power system to improve system's reliability. Micro-PMUs are robust devices with data capturing capability in microseconds, however they are very expensive and hence determination of their optimal placement in power system is an interesting area to be explored which authors aim to target in future work.

Acknowledgments

The authors would like to acknowledge university of Putra Malaysia for providing conducive environment for this research.

8. References

[1] M. S. Bakare, A. Abdulkarim, M. Zeeshan, and A. N. Shuaibu, “A comprehensive overview on demand side energy management towards smart grids: challenges, solutions, and future direction,” *Energy Informatics*, vol. 6, no. 1, 2023, doi: 10.1186/s42162-023-00262-7.

[2] M. S. Moeen, F. A. Memon, and N. Hafeez, “Pakistan Energy Outlook Report 2021-2030,” *Pakistan Energy Outlook Rep.*, no. March, 2022.

[3] M. Irfan, Z. Y. Zhao, M. Ahmad, and M. C. Mukeshimana, “Solar energy development in Pakistan: Barriers and policy recommendations,” *Sustain.*, vol. 11, no. 4, 2019, doi: 10.3390/su11041206.

[4] M. Ashraf Fauzi, N. Hanis Zainal Abidin, N. Mohd Suki, and A. Mokhtar Albshir Budiea, “Residential rooftop solar panel adoption behavior: Bibliometric analysis of the past and future trends,” *Renew. Energy Focus* , vol. 45, pp. 1–9, 2023, doi: 10.1016/j.ref.2023.02.002.

[5] M. Irfan, S. Deilami, S. Huang, and B. P. Veettil, “Rooftop Solar and Electric Vehicle Integration for Smart, Sustainable Homes: A Comprehensive Review,” *Energies*, vol. 16, no. 21, 2023, doi: 10.3390/en16217248.

[6] T. M. Y. Khan and E. Jassim, “Solar Thermal Systems , and the Dawn of Energy,” *Energies*, pp. 1–30, 2023.

[7] T. Falope, L. Lao, D. Hanak, and D. Huo, “Hybrid energy system integration and management for solar energy: A review,” *Energy Convers. Manag. X*, vol. 21, no. August 2023, p. 100527, 2024, doi: 10.1016/j.ecmx.2024.100527.

[8] H. A. Muqeet, I. A. Sajjad, A. Ahmad, M. M. Iqbal, S. Ali, and J. M. Guerrero, “Optimal Operation of Energy Storage System for a Prosumer Microgrid Considering Economical and Environmental Effects,” *RAEE 2019 - Int. Symp. Recent Adv. Electr. Eng.*, vol. 4, pp. 1–6, 2019, doi: 10.1109/RAEE.2019.8887002.

[9] H. A. Muqeet, A. Ahmad, I. A. Sajjad, R. Liaqat, A. Raza, and M. M. Iqbal, “Benefits of Distributed Energy and Storage System in Prosumer Based Electricity Market,” *Proc. - 2019 IEEE Int. Conf. Environ. Electr. Eng. 2019 IEEE Ind. Commer. Power Syst. Eur. EEEIC/I CPS Eur. 2019*, 2019, doi: 10.1109/EEEIC.2019.8783636.

[10] S. Ahmad, “A Review of Microgrid Energy Management and Control Strategies,” *IEEE Access*, vol. 11, no. January, pp. 21729–21757, 2023, doi: 10.1109/ACCESS.2023.3248511.

[11] M. Khalid, “Smart grids and renewable energy systems: Perspectives and grid integration challenges,” *Energy Strateg. Rev.*, vol. 51, no. June 2023, p. 101299, 2024, doi: 10.1016/j.esr.2024.101299.

[12] A. Ali, A. Aftab, M. N. Akram, S. Awan, H. A. Muqeet, and Z. A. Arfeen, “Residential Prosumer Energy Management System with Renewable Integration Considering Multi-Energy Storage and Demand Response,” *Sustain.* , vol. 16, no. 5, 2024, doi: 10.3390/su16052156.

[13] Z. Medghalchi and O. Taylan, “A novel hybrid optimization framework for sizing renewable energy systems integrated with energy storage systems with solar photovoltaics, wind, battery and electrolyzer-fuel cell,” *Energy Convers. Manag.*, vol. 294, no. August, p. 117594, 2023, doi: 10.1016/j.enconman.2023.117594.

[14] A. Sohani *et al.*, “Techno-economic evaluation of a hybrid photovoltaic system with hot/cold water storage for poly-generation in a residential building,” *Appl. Energy*, vol. 331, no. September 2022, 2023, doi: 10.1016/j.apenergy.2022.120391.

[15] S. Khan, K. Sudhakar, M. H. Bin Yusof, W. H. Azmi, and H. M. Ali, “Roof integrated photovoltaic for electric vehicle charging towards net zero residential buildings in Australia,” *Energy Sustain. Dev.*, vol. 73, no. December 2022, pp. 340–354, 2023, doi: 10.1016/j.esd.2023.02.005.

[16] Z. Zhang, K. Wen, and W. Sun, “Optimization and sustainability analysis of a hybrid diesel-solar-battery energy storage structure for zero energy buildings at various reliability conditions,” *Sustain. Energy Technol. Assessments*, vol. 55, no. November 2022, p. 102913, 2023, doi: 10.1016/j.seta.2022.102913.

[17] Muskan and H. Kaur Channi, “Optimal designing of PV-diesel generator-based system using HOMER software,” *Mater. Today Proc.*, no. xxxx, 2023, doi: 10.1016/j.matpr.2023.01.053.

[18] M. Nazari-Heris and S. Asadi, “Reliable energy management of residential buildings with hybrid energy systems,” *J. Build. Eng.*, vol. 71, no. September 2022, p. 106531, 2023, doi: 10.1016/j.jobe.2023.106531.

[19] A. Allouhi and S. Rehman, “Grid-connected hybrid renewable energy systems for supermarkets with electric vehicle charging platforms: Optimization and sensitivity analyses,” *Energy Reports*, vol. 9, pp. 3305–3318, 2023, doi: 10.1016/j.egyr.2023.02.005.

[20] W. F. Mbasso, S. R. Dzonde Naoussi, R. J. Jacques Molu, K. T. Saatong, and S. Kamel, “Technical assessment of a stand-alone hybrid renewable system for energy and oxygen optimal production for fishes farming in a residential building using HOMER pro,” *Clean. Eng. Technol.*, vol. 17, no. November, p. 100688, 2023, doi: 10.1016/j.clet.2023.100688.

[21] A. M. Jasim, B. H. Jasim, F. C. Baiceanu, and B. C. Neagu, “Optimized Sizing of Energy Management System for Off-Grid Hybrid Solar/Wind/Battery/Biogasifier/Diesel Microgrid System,” *Mathematics*, vol. 11, no. 5, 2023, doi: 10.3390/math11051248.