Journal of Information Systems Engineering and Management
2024, 9(2)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

Techno-Economic Analysis of a Standalone Solar PV/DG/Battery Hybrid System for Rural Electrification

Urvashi Praful Chudasama[1], Yogini R Pandya[2], Praful P Chudasama[3*]
[1,2]*Assistant Professor, Electrical Engineering Department, Government Engineering College, Bharuch, Gujarat, India, Email: upchudasama@gmail.com, yoginirpandya@gmail.com*
[3*]*Assistant Professor, UPL University of Sustainable Technology, Ankleshwar, Gujarat, Email: chudasama.praful@gmail.com*
****Corresponding Author:*** *Praful P Chudasama*
**Email: chudasama.praful@gmail.com*

ARTICLE INFO

Received: 15 Apr 2024

Accepted: 26 Jun 2024

ABSTRACT

The increasing demand for reliable, sustainable, and cost-effective electricity has accelerated the adoption of hybrid energy systems powered by renewable energy sources (RES). This paper presents the design and techno-economic analysis of a standalone hybrid renewable power system intended to meet the day-to-day energy demands of a household in Bharuch, Gujarat. The proposed system integrates solar photovoltaic (PV), diesel generator (DG), and battery storage technologies. Using HOMER software, the hybrid system is optimized to minimize the total net present cost (NPC) while ensuring efficient and reliable energy supply. The simulation and optimization process determined the optimal configuration to include 3 kW of solar PV arrays, a 2.6 kW DG, 12 battery units each rated at 25.9 kWh, and a 1 kW power converter. The analysis revealed that the hybrid PV/DG/battery system offers a 47% reduction in NPC compared to a standalone diesel generator system. The optimized hybrid system achieved a total NPC of $16,875 and a levelized cost of energy (COE) of $0.471/kWh, demonstrating its cost-effectiveness. Additionally, the system offers enhanced technical performance and a significantly lower environmental impact due to reduced fuel consumption and emissions. These findings underscore the viability of hybrid renewable systems in rural and off-grid areas, offering a sustainable alternative to conventional fossil-fuel-based power generation. This study contributes to the growing body of research advocating for renewable-integrated MGs as a solution for energy access, environmental sustainability, and long-term economic benefits in remote regions.

Keywords: Hybrid System, Solar PV, Battery, HOMER, Cost of Energy

Introduction:

India's energy security continues to pose a significant challenge due to its heavy reliance on imported fossil fuels, with approximately 40% of its primary energy needs being met through imports [1]. The energy self-sufficiency rate, which represents the share of domestically produced energy in total consumption, remains low, leaving the nation vulnerable to supply disruptions and global price volatility [2]. Despite considerable growth in the electricity sector, the country's dependency on coal and imported energy raises long-term sustainability and environmental concerns [3].

To mitigate these challenges, India is undergoing a transition from centralized, fossil fuel-dominated systems to decentralized energy solutions utilizing renewable sources. Distributed Energy Resources (DER) including solar photovoltaic (PV), wind turbines, biomass, hydro, and battery storage are at the forefront of this transformation. DER systems are especially advantageous in rural and remote areas, where grid access is limited or entirely unavailable [4].

Microgrid (MG) localized grids that can operate independently or in conjunction with the main grid are emerging as promising solutions to support this energy transition. In the Indian context, stand-alone microgrids are particularly effective in rural electrification, offering resilient and cost-effective alternatives to traditional grid extension [5]. MGs offer several technical and economic advantages like Scalable and modular investment approaches that reduce financial risk, lower energy losses due to proximity to the load, reduced transmission infrastructure needs, higher overall efficiency, particularly in Combined Heat and Power (CHP) applications [6]. In the deregulated energy landscape, various Distributed Generation (DG) systems such as diesel generators, PV systems, wind turbines, fuel cells, and micro turbines are being deployed closer to the point of consumption. These DG systems can function autonomously or be

Journal of Information Systems Engineering and Management
2024, 9(2)
e-ISSN: 2468-4376
https://jisem-journal.com/
Research Article

integrated into hybrid MG configurations [7]. Many research efforts have focused on optimizing such systems with respect to cost, reliability, and renewable integration.

Traditionally, diesel generator sets (DG) have been the most widely used solution for rural electrification. They are relatively simple, can be sized according to local needs, and have a low initial cost. However, they present numerous drawbacks including Low efficiency and poor performance at partial loads, frequent breakdowns due to mechanical wear from start-stop cycles and High fuel and maintenance costs, especially in remote areas where diesel supply logistics are difficult and expensive [8]. These challenges necessitate a shift toward more sustainable solutions.

Solar PV has become a favourable renewable solution due to its falling costs and ease of deployment. However, intermittency in solar generation leads to unreliable power supply in standalone applications. A promising solution lies in hybrid energy systems, which integrate multiple renewable sources such as solar, wind, and biomass, with backup systems using LPG, diesel, or gasoline. Stand-alone hybrid systems combine various renewable energy sources like solar, wind, and biomass with backup generators. This integration reduces fuel consumption, enhances reliability, and ensures a 24/7 electricity supply, even without consistent sunlight or wind, making it an ideal solution for off-grid and remote areas. [9]. these systems are being increasingly recognized as a sustainable, resilient, and economically viable approach for electrifying off-grid and underserved communities in India.

The following table 1 presents a review of various studies on the optimal design of stand-alone hybrid microgrid systems. It includes details on the system components, optimization methods, objective functions, and key observations from each study.

Sr No	System Components	Optimization Method	Objective Function(s)	Observation Remarks	Reference
1	PV, Wind, Battery, Diesel	Particle Swarm Optimization	Minimize Net Present Cost (NPC)	Designed a residential hybrid system in Japan; improved cost efficiency and reliability.	[10]
2	PV, Wind, Biomass, Diesel, Battery	Modified Backtracking Search	Minimize Cost and Loss of Power Supply Probability (LPSP)	Multi-objective sizing optimization increased system reliability and cost effectiveness.	[11]
3	PV, Battery, Diesel	HOMER, SAM, PVsyst	Assess Feasibility and Performance	Used bifacial PV for industrial application in Iraq; achieved substantial CO_2 reduction.	[12]
4	PV, Wind, Battery	Genetic Algorithm	Minimize Life Cycle Cost (LCC) and LPSP	System optimization in Tunisia; battery size was crucial for improving reliability.	[13]
5	PV, Wind, Diesel, Battery, TLC	HOMER	Minimize COE and NPC; Maximize Renewable Fraction	Indian rural microgrid reached 91.6% renewable share at $0.272/kWh COE.	[14]
6	PV, Wind, Diesel, Battery	Benders Decomposition	Minimize Cost and Emissions; Maximize Reliability	MILP model ensures system reliability under supply and demand uncertainties.	[15]

Table 1: Review on Optimal Design of Stand-Alone Hybrid Microgrid Systems

Journal of Information Systems Engineering and Management
2024, 9(2)
e-ISSN: 2468-4376
https://jisem-journal.com/
Research Article

This paper aims to analyse the technical and economic viability of a Solar PV/diesel with battery standalone hybrid system for a remote house located in Bharuch, Gujarat. The analysis is conducted using HOMER software to evaluate system performance. Economic comparisons, including present worth, annual worth, return on investment, and simple payback period, are made between the base case system (a standalone diesel generator) and the optimal hybrid system, which combines PV, diesel generator, and battery storage.

Assessment Criteria:

HOMER software initially assesses the technical feasibility of a system to determine whether it can meet the specified load demand. Subsequently, it estimates the total Net Present Cost (NPC), which reflects the life-cycle cost of the system, comprising the initial capital cost (IC), component replacement cost (RC), operation and maintenance cost (OM), fuel cost (FC), and, where applicable, the cost of electricity purchased from the grid (PC). The NPC is calculated using the equation [16], [17]:

$$NPC = \frac{Ctotal}{CRF\ (i, Tp)} ------(1)$$

Where Ctotal is the total annualized cost of the system ($/year), i is the annual real interest rate (%), Tp is the project lifetime, and CRF(.) is the capital recovery factor, which is calculated in the following formula [16]:

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} ----(2)$$

Where n is the number of years. In HOMER, the salvage costs (SC), which are the residual values of the system components at the end of the project lifetime, are taken into account in the estimation of the NPC. HOMER uses the following formula [16]:

$$SC = C_{RC}\frac{T_{rem}}{T_{com}} ------- (3)$$

Where C_{RC} is the replacement cost of the component ($), Trem is the remaining life of the component (year), and Tcom is the lifetime of the component (year). In HOMER, we use the following formula to calculate the levelized cost of energy (COE) [18]:

$$COE = \frac{C_{total}}{E_{total}} ------- (4)$$

Where Etotal is the total electricity consumption per year (kWh/year).

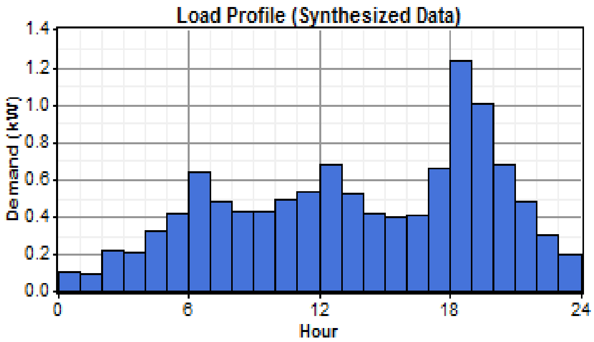
Data Inputs:

Load Profile of Site:

The nominal consumption profile for a household in Bharuch, Gujarat, is a crucial component of the study's methodology. In this analysis, HOMER software is employed to artificially generate the hour-by-hour electrical load of the Bharuch household. To initiate this process, a single day's hourly load profile from a typical year is used as the base input. HOMER then synthesizes the full-year profile comprising 8,760 hourly values by incorporating random variability approximately 2% for both day-to-day and time-step-to-time-step fluctuations. The average daily energy consumption of the household is 10 kWh, with a peak demand of 1.6 kW. The household's energy use is primarily driven by appliances such as lighting, a color television, an air conditioner, a washing machine, a water heater, an electric cooker, and various small electronic devices. Seasonal variations are evident, with consumption peaking during summer and winter months due to increased demand for cooling, heating, and lighting, as illustrated in Figures 1 and 2.

Journal of Information Systems Engineering and Management
2024, 9(2)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article



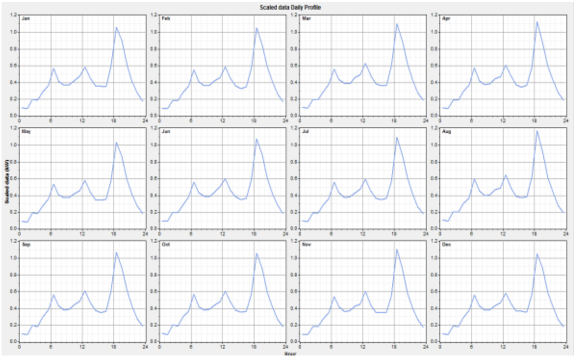


Fig. 1 Load profile (24 hrs) for the site

Fig. 2 Variation of load during different months of a year

Solar radiation:

The main electricity generator in the proposed system is a solar photovoltaic (PV) panel, which directly converts solar irradiation into electrical energy. Given that solar radiation fluctuates on a daily, hourly, and seasonal basis, the electricity output from the PV array also varies accordingly. In the case of Bharuch, Gujarat, solar radiation ranges from 3.616 kWh/m²/day to 6.815 kWh/m²/day, with an estimated annual average of 5.21 kWh/m²/day. This variability highlights the importance of incorporating storage and backup systems to ensure a stable energy supply.

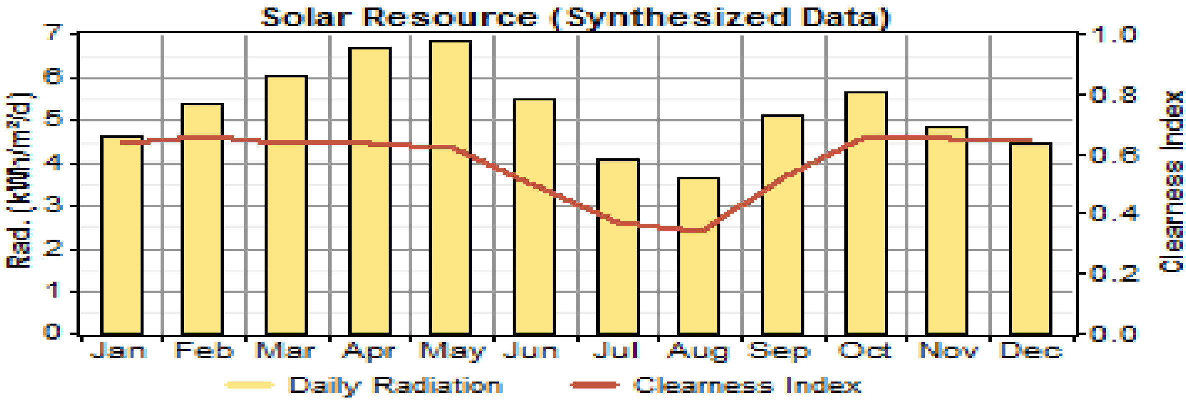


Figure 3 illustrates the average monthly solar radiation data

As shown, higher solar radiation is observed from March to June, while relatively lower levels occur from July to September due to monsoon conditions.

Solar PV Panel:

The photovoltaic (PV) capacity in the proposed hybrid system is varied from 0 to 3 kW using polycrystalline panels. The PV array is oriented with a slope angle of 21.9° and an azimuth of 0°, facing true south, and employs a two-axis tracking system to optimize solar energy capture throughout the year. Designed for a 20-year lifespan, the system includes a de-rating factor of 90% to account for performance losses due to environmental and operational factors. Additionally, a ground reflectance of 20% is considered, contributing to the overall efficiency and long-term reliability of the system's energy output.

Battery (Energy Storage):

The storage component of the proposed hybrid system consists of the Trojan L16P battery, rated at 6V and 380Ah, with a lifetime energy throughput of approximately 1075 kWh. This battery is selected for its deep-cycle capabilities suitable for renewable applications. The cost of a single unit is estimated at $305, which also applies to its replacement cost, reflecting the long-term investment considerations in system design and sustainability.

Journal of Information Systems Engineering and Management
2024, 9(2)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

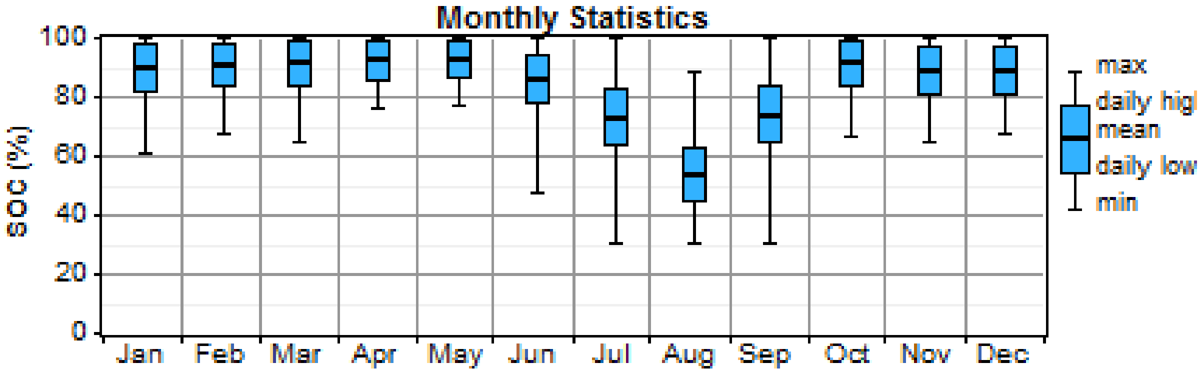


Figure 4 Battery State of Charge of optimal PV/DG/battery Standalone hybrid system

As shown in Fig. 4, the state of charge (SOC) of the battery remains high throughout most months, except from June to August, which correspond to the rainy season at the site with lower solar radiation. During these months, the battery's charge decreases as the PV output is insufficient to meet the load, causing the system to rely more on stored energy. On the other hand, during daytime hours, the battery remains nearly full as the power generated by the PV system directly covers the load, minimizing the need for battery discharge.

Power Converter:

In the proposed system, a converter is required to ensure the efficient transfer of energy between the DC and AC components. The converter, assumed to have an efficiency of 95%, plays a crucial role in regulating the flow of power from the PV array, diesel generator, and battery storage to meet the household's energy demand. The optimal size of the converter is set to 2 kW, which ensures that it is capable of handling the maximum expected load. The converter is designed to have a lifespan of 15 years, ensuring long-term reliability and performance in the system.

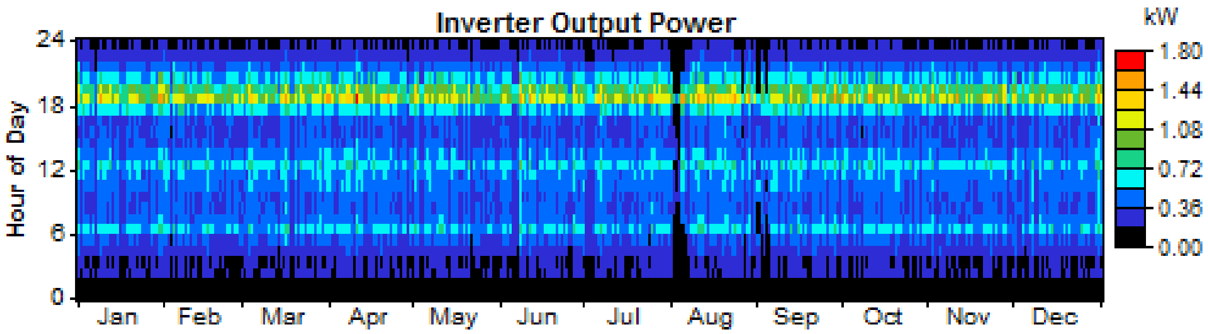


Figure 5 Inverter output

Figure 5 illustrates that the inverter operates intensively during the daytime, converting the DC power generated by the PV system into AC power to meet the load demand. This conversion process is crucial for supplying the required electricity to the household, as the load operates on AC power. The inverter plays a key role in ensuring continuous and reliable power availability during daylight hours when the PV system

Diesel generator (DG):

Diesel generators are widely used for off-grid power generation due to their advantages such as low installed capacity, high shaft efficiency, suitability for start-stop operation, and the ability to utilize high exhaust heat. These engines convert the heat generated by combustion into mechanical work, which is then used to rotate the shaft of the generator to produce electricity. In this optimal configuration, a 2.6 kW diesel generator is used. The current approximate price of diesel in Gujarat is approximately $1 per liter, with a lower heating value of 43.2 MJ/kg and a density of 820 kg/m³. This information is crucial for estimating fuel consumption and operational costs of the diesel generator within the hybrid system.

Journal of Information Systems Engineering and Management
2024, 9(2)
e-ISSN: 2468-4376
https://jisem-journal.com/

Research Article

Proposed Standalone Hybrid System description:

HOMER simulates all feasible system configurations that meet the load requirements for the selected site under specified conditions of renewable resources. The software performs energy balance calculations for each viable system configuration and ranks them according to the Net Present Cost (NPC) in increasing order. Figure 6 illustrates the configuration of the Standalone hybrid PV/DG/battery system used in the HOMER software. This configuration was analysed to assess the most cost-effective solution for meeting the electrical demands of the Bharuch household while integrating renewable energy sources and ensuring system reliability.

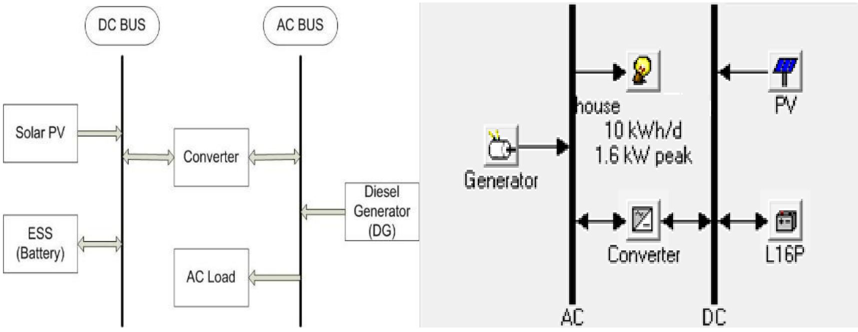


Figure .6 Proposed Solar PV/DG/Battery Standalone Hybrid system

Results & discussion

Based on the collected data and load from site, a total of 840 simulation runs were conducted. The simulations were performed with a project lifetime of 20 years. During the analysis, the PV capacity was varied from 0 to 3 kW, while the battery storage capacity was adjusted from 0 to 18 units to explore different system configurations for comparison purposes. These variations allowed for an in-depth evaluation of the optimal configuration for the hybrid PV/diesel/battery system, considering factors such as cost, reliability, and energy output efficiency. The results of the simulations provided valuable insights into the performance of the system under various conditions.

HOMER performs simulations for a range of prospective system configurations, each designed to meet the load requirements while adhering to system constraints. After evaluating all potential designs, it selects the one that satisfies the load with the lowest life cycle cost. The optimization process in HOMER involves assessing various components, including renewable energy resources, technical specifications, cost parameters, and system constraints. Sensitivity analysis is also conducted across a wide range of exogenous variables to understand how changes in these factors affect the overall performance and economics of the system. This comprehensive approach ensures that the selected configuration offers the most cost-effective and reliable solution for the given location and conditions.

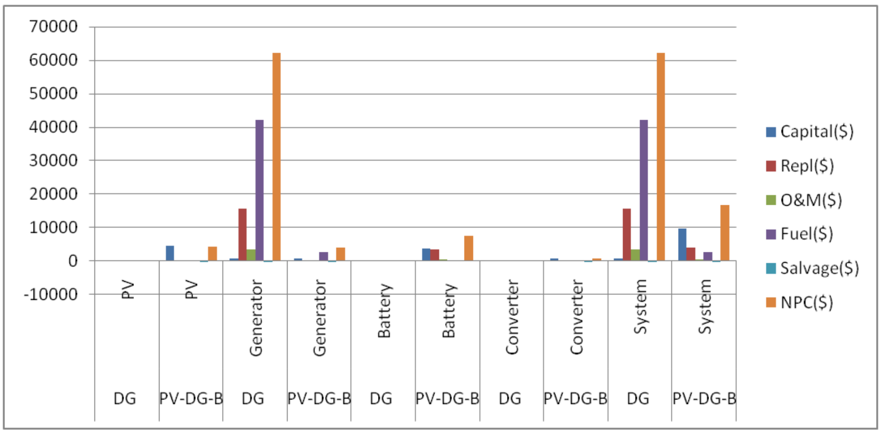


Figure 7 presents a summary of the economic comparison between two standalone hybrid systems: the only DG system and the optimized PV/DG/Battery hybrid system

Journal of Information Systems Engineering and Management
2024, 9(2)
e-ISSN: 2468-4376
https://jisem-journal.com/
Research Article

The analysis clearly shows that between the two power system options PV/DG/Battery hybrid and only DG system hybrid system provides a more optimized and cost-effective solution. The optimal configuration consists of a 3 kW PV array, a 2.6 kW diesel generator, twelve batteries (each with 25.9 kWh capacity), and a 1 kW power converter. This configuration reduces the Net Present Cost (NPC) by approximately 47% compared to the Diesel-only system, with a corresponding reduction in the Levelized Cost of Energy (COE). The hybrid system has an initial cost of $19,560, an annual operating cost of $723, a total NPC of $16,875, and a COE of $0.471/kWh, making it a more economically viable option for selected site.

Configuration	Only DG	PV-DG-Battery
COE($)/KWh	1.731	0.471
NPC($)	62049	29447
O&M($)/Yr	6228	723

Figure 8 Cost Summary of Only DG and PV/DG/Battery Standalone Hybrid System

Figure 8 illustrates the Net Present Cost (NPC), Operation and Maintenance (O&M) cost, and Levelized Cost of Energy (COE) for both the diesel-only and hybrid PV/DG/Battery systems. It is evident that the hybrid system significantly reduces the NPC and COE compared to the Only DG system. Figure 9 presents the emissions comparison, showing that the hybrid configuration generates notably lower pollutants than the standalone Only DG system, making it both economically and environmentally superior.

Pollutant (Emission Kg/yr)	Only DG	PV/DG/Battery
Carbon dioxide	12,030	751
Carbon monoxide	29.7	1.85
Unburned hydocarbons	3.29	0.205
Particulate matter	2.24	0.14
Sulfur dioxide	24.2	1.51
Nitrogen oxides	265	16.5

Figure 8 Pollutant Summary of Only DG and PV/DG/Battery Standalone Hybrid System

Conclusion:

In conclusion, the analysis clearly demonstrates that a Standalone Solar PV/DG/Battery hybrid system is significantly more cost-effective and efficient than an only DG system for meeting the energy needs of a household in Bharuch, Gujarat. The optimized hybrid system, comprising 3 kW of Solar PV arrays, a 2.6 kW diesel generator (DG) , 12 battery units each with a capacity of 25.9 kWh, and a 1 kW power converter, reduces the total net present cost (NPC) by approximately 47% compared to a conventional diesel generator system. The proposed system achieves a total NPC of $16,875 and a levelised cost of energy (COE) of $0.471/kWh. Beyond economic benefits, the hybrid system also offers improved technical performance and reduced environmental impact, making it a more sustainable and viable energy solution.

References:

[1] Ministry of Power, Government of India, *Energy Statistics India 2023*, [Online]. Available: https://powermin.gov.in
[2] International Energy Agency (IEA), *India Energy Outlook 2021*, [Online]. Available: https://www.iea.org/reports/india-energy-outlook-2021
[3] NITI Aayog, *India's Energy Transition – 2030 Pathways*, 2021.
[4] S. Bhattacharyya, *Rural Electrification Through Decentralised Off-grid Systems in Developing Countries*, Springer, 2013.
[5] S. K. Singh, R. K. Tripathi, and R. Prakash, "Optimal design of a stand-alone hybrid energy system using HOMER Pro: A case study from rural India," *Sustainable Energy Technologies and Assessments*, vol. 43, 2021.
[6] T. Logenthiran, D. Srinivasan, and D. Wong, "Multi-agent coordination for DER in MicroGrid," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1462–1470, Dec. 2012.

Journal of Information Systems Engineering and Management
2024, 9(2)
e-ISSN: 2468-4376
https://jisem-journal.com/
Research Article

[7] A. J. Conejo, M. Carrión, and J. M. Morales, *Decision Making Under Uncertainty in Electricity Markets*. Springer, 2010.
[8] D. Palchak and G. Maclaurin, “Diesel Off-Grid Microgrids in India: Overview and Recommendations,” *National Renewable Energy Laboratory (NREL)*, 2015. [Online]. Available:https://www.nrel.gov
[9] B. Singh, N. R. Chauhan, and A. Joshi, “Design and Optimization of Stand-Alone Hybrid Energy Systems: A Review,” *Renewable and Sustainable Energy Reviews*, vol. 151, 2021.
[10] Y. Yoshida and H. Farzaneh, "Optimal Design of a Stand-Alone Residential Hybrid Microgrid System for Enhancing Renewable Energy Deployment in Japan," Energies, vol. 13, no. 7, p. 1737, 2020.
[11] A. Patibandla, V. K. Patel, P. P. Rajput, and M. K. Tiwari, "A Multi-Objective Approach for the Optimal Design of a Standalone Hybrid Renewable Energy System," Int. J. Energy Res., vol. 45, no. 3, pp. 4005–4022, 2021.
[12] M. Z. A. Bhatti et al., "Design and Analysis of a Hybrid Stand-Alone Microgrid Using Bifacial PV Modules," Energies, vol. 17, no. 1, p. 200, 2024.
[13] S. Fezai, M. Tlili, F. Omri, and M. Bouallègue, "Hybridization Utility and Size Optimization of a Stand-Alone Renewable Energy Micro-Grid," Environ. Prog. Sustain. Energy, vol. 40, no. 4, 2021.
[14] S. Ray, A. J. Shah, and M. N. Shukla, "Optimal Design, Prefeasibility Techno-Economic and Sensitivity Analysis of Off-Grid Hybrid Renewable Energy System," Philos. Mag., vol. 102, no. 10, pp. 1–18, 2022.
[15] W. Wei, Y. Liu, and C. Jiang, "Multi-Objective Optimal Configuration of Stand-Alone Microgrids Based on Benders Decomposition Considering Power Supply Reliability," IET Energy Syst. Integr., vol. 4, no. 2, pp. 130–140, 2022.
[16] Dalton GJ, Lockington DA, Baldock TE. Feasibility analysis of renewable energy supply options for a grid-connected large hotel. Renewable Energy 2009.
[17] Askari B, Ameri M. Techno-economic feasibility analysis of stand-alone renewable energy systems (PV/bat, wind/bat and hybrid PV/wind/bat) in Kerman, Iran. Energy Sources, Part B 2012