Beni-Suef University Engineering Journal

Contents lists available at Science Direct

Journal of Engineering Science and Sustainable Industrial Technology

Journal homepage: www.….

Optimal Sizing and Techno-Economic Analysis of an Off-Grid PV/Battery System for Fruit Farm Electrification

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A R T I C L E I N F O

Article history:
Received:
Accepted:
Online:

Keywords:
rural electrification, off-grid systems, PV/Biogas/Lithium Ion Battery, HOMER software, sensitivity analysis.

A B S T R A C T

This research explores the intricate dynamics of rural electrification, presenting a meticulous analysis of a revolutionary PV/Biogas/Lithium Ion Battery Off-Grid System. Utilizing advanced simulation via HOMER software, the optimal system configuration is unveiled, and the system's nuanced sensitivity to variations in photovoltaic (PV) and Lithium-Ion battery costs is examined. The optimal system configuration, derived through rigorous analysis, encompasses a PV capacity of 50 kW, a Biogas capacity of 50 kW, and a Lithium-Ion battery capacity of 12 kWh. These findings serve as crucial benchmarks, providing tangible parameters for the design of sustainable and economically viable energy solutions in remote, off-grid communities. The study delves into economic intricacies, emphasizing the direct relationship between cost multipliers and key metrics such as Total Net Present Cost (TNPC) and Cost of Energy (COE). The research's implications reach far beyond the specific system, resonating profoundly within the broader landscape of rural electrification. Identified sensitivities in cost variations offer actionable considerations for stakeholders, policymakers, and practitioners involved in energy solutions for off-grid communities. Furthermore, the optimal system configuration serves as a tangible blueprint, guiding the implementation of efficient and sustainable energy solutions across diverse off-grid contexts.

1. Introduction

In the realm of El Fayoum, Egypt, where the rhythm of rural existence persists in the face of energy deficiencies, this research undertakes the task of delineating a trajectory toward sustainable progress. Specifically focused on the electrification of a remote village warehouse, our investigation navigates the potentialities inherent in a PV/biogas/Lithium-Ion battery off-grid system. Our approach is methodically underscored by comprehensive techno-economic and sensitivity analyses.

In addressing energy challenges in remote villages, the consideration of competing objectives by stakeholders and the evaluation of outcomes related to energy access, climate benefits, health impacts, economic costs, and quality of life are imperative [1]–[4]. A potential solution involves the implementation of renewable energy (RE) systems, where success hinges on factors such as energy system design and demand profile [5]–[7].

The comprehensive mind map presented in Fig. 1 delineates various aspects of energy challenges and their potential solutions.

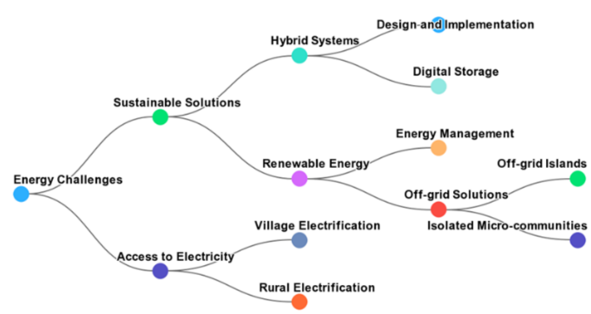

Fig. 1: A comprehensive mind map solutions and strategies of energy challenges.

The implementation of RE solutions has been observed in remote villages to tackle energy challenges. Several approaches exist for the implementation of RE solutions:

Electrification programs: Electrification programs have been established by governments, private institutions, and NGOs to gradually provide electricity to remote locations [8], [9]. The primary goals of these programs are to stimulate community development and enhance access to basic services [8].

Hybrid systems: In both small islands and remote villages, a prevalent configuration for RE systems involves a combination of diesel, wind, and photovoltaic sources [10]. This hybrid approach serves to meet energy demand while addressing challenges such as peak demand and seasonal oscillations.

Biomass-driven combined heat and power (CHP) plants: The implementation of biomass-driven CHP plants as the primary energy source has proven to be economically attractive in both remote and rural community energy systems [11]. These plants present a cost-effective alternative to conventional diesel power generation systems.

The deployment of these RE solutions aims to enhance energy access, mitigate carbon emissions, and foster sustainable development in remote villages.

The daily lives of residents in remote villages are significantly affected by energy challenges, encompassing limited access to modern energy services, hindrances to social and economic development, and a notable impact on overall quality of life and well-being. In numerous remote villages worldwide, electricity remains elusive, compelling reliance on basic, cost-effective local energy sources like biomass and kerosene lamps. This constrained access to energy has far-reaching effects on essential aspects of daily life. Furthermore, the absence of reliable energy sources acts as a barrier to social and economic progress, impeding community development, access to crucial health services, and the provision of clean water. Energy poverty in these settings detrimentally influences the residents' quality of life, affecting routine activities such as cooking, lighting, and access to communication and information technologies. Additionally, the lack of electricity bears consequences for health outcomes and educational opportunities. Thus, the energy challenges in remote villages permeate various dimensions of residents' lives, impacting their access to vital services, economic prospects, and overall well-being.

Increasingly employed for rural electrification in areas with restricted access to a reliable power supply, off-grid RE systems necessitate optimization to ensure efficient and sustainable electricity generation [12]–[14]. Past research has extensively examined the utilization of HOMER software for the simulation and economic analysis of off-grid systems. Key findings derived from these investigations include:

1. **Optimized system configuration:** The optimized configuration for off-grid systems, catering to warehouse electrification in a remote village, encompasses a combination of photovoltaic (PV) panels, biogas generators, and battery storage [15].
2. **Feasibility of renewable-based systems:** The amalgamation of PV, biogas generators, and battery storage has proven to be a feasible solution for energy provisioning in rural communities and institutions within off-grid systems [16].
3. **Techno-economic analysis:** The application of techno-economic analysis via HOMER software aids in ascertaining the most cost-effective configuration of RE systems for remote rural electrification, taking into consideration factors such as energy demand, supply patterns, and system reliability [17], [18].

In the endeavor to craft an optimized PV/Biogas/Battery Off-Grid System for warehouse electrification in a remote village, meticulous consideration of several key factors is imperative. Foremost among these considerations is the need for optimal sizing of hybrid system components, including solar photovoltaic (PV), biomass, and battery units, to effectively meet the village's electrical demand [19]–[21]. A crucial aspect involves conducting a techno-economic analysis to systematically evaluate the cost-effectiveness of diverse system configurations and storage options [18]. Additionally, the paramount objective is to ensure a dependable power supply capable of accommodating electrical load peaks and variations. By methodically weighing and integrating these factors, the prospect emerges to architect an optimized PV/Biogas/Battery Off-Grid System tailored precisely to fulfill the unique requirements of warehouse electrification in a remote village.

The facilitation of performance and cost-effectiveness optimization in the Off-Grid System for electrification in remote villages can be achieved through the utilization of the HOMER software. Designed as a hybrid optimization model for electric renewables, it is purposed to simulate various power plant configurations, thereby allowing the identification of the most optimized configuration concerning operating cost, NPC, and economic comparison. Particularly adept at the analysis and optimization of hybrid RE systems (HRES) for off-grid and stand-alone applications, the HOMER software can simulate and optimize the most suitable solution for a hybrid system. This encompasses considerations such as power generation, pollutant gas emissions, and system reliability. Through the application of the HOMER software, the simulation and optimization of a PV-Biomass hybrid power system can be executed, facilitating the determination of the most effective combination of power generation while minimizing system costs.

The objectives of this paper are twofold: firstly, to explore and assess the optimization potential for performance and cost-effectiveness in an Off-Grid System designed for rural electrification in remote villages, with a particular focus on the integration of photovoltaic (PV), biogas, and battery technologies. The study aims to employ the HOMER software, a hybrid optimization model for electric renewables, to simulate and evaluate various configurations, emphasizing factors such as operating cost, NPC, and economic comparisons. Secondly, the paper seeks to provide a detailed examination of the multifaceted components involved in the design and operation of a hybrid power system, offering a comprehensive understanding of the intricacies associated with power generation, pollutant gas emissions, and system reliability. Through these objectives, the paper endeavors to contribute valuable insights into the effective design and implementation of optimized off-grid systems tailored for the electrification needs of remote villages.

2. Methodology

2.1. Site Selection

The initiation of site selection for the implementation of an optimized PV/Biogas/Battery Off-Grid System involves the identification of specific criteria that guide the selection of the warehouse and the corresponding remote village. Parameters encompassing geographical location, solar irradiance levels, energy demand profiles, and accessibility will be meticulously considered to ensure the meticulous selection aligns with the overarching objective of electrification in remote areas. These criteria will function as the foundational basis for the subsequent stages of system design and optimization, establishing a robust framework for the comprehensive evaluation of the chosen site's suitability for the proposed hybrid energy solution.

The chosen case study site is situated in El Fayoum, Egypt, precisely located at coordinates 29° 19.1' N and 30° 50.0' E. This geographical location serves as the focal point for the comprehensive examination of the proposed PV/Biogas/Battery Off-Grid System for electrification. In the context of load profile data, the daily energy consumption characteristics are as follows: an average load of 262 kWh per day, a peak load of 34 kWh, and a load factor of 0.32. These key parameters provide essential insights into the energy demand patterns, facilitating the subsequent stages of system design and optimization tailored to the specific requirements of the identified site in El Fayoum.

Figure 2 illustrates the selected case study site in El Fayoum, Egypt (29° 19.1' N, 30° 50.0' E), providing a spatial reference for the subsequent analysis. Meanwhile, Figure 3 presents the hourly load profile, offering a concise graphical overview of the daily energy consumption patterns.

Fig. 2: A map of the selected case study site.

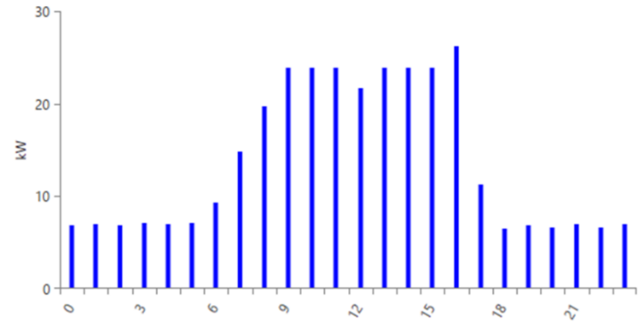

Fig. 3: The hourly load profile of the selected case study site.

Meteorological data crucial to the analysis of the chosen site is presented in Figure 4. This figure details the monthly average solar irradiance of the case study site, with an annual average irradiance of 5.79 kWh/m^2/day. Complementing this, Figure 5 provides a representation of the monthly average biomass data for the chosen site, indicating a consistent supply of 20 tons per day. This biomass data serves as a foundational parameter for the integration of biomass as an energy source within the proposed hybrid system. Together, these figures offer critical insights into the meteorological conditions influencing the RE potential of the designated location.

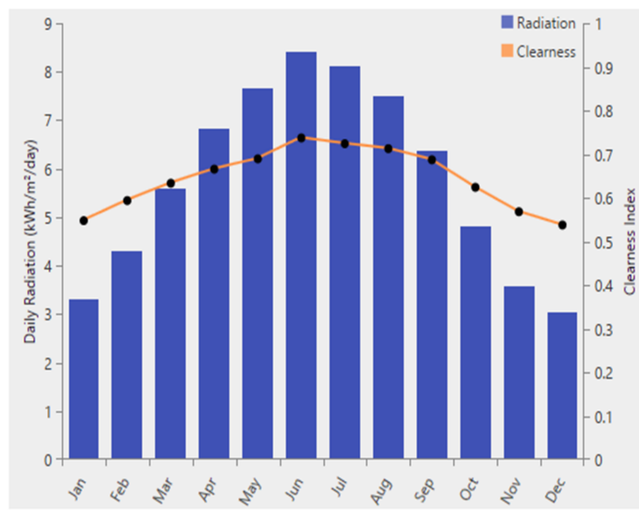

Fig. 4: The monthly average solar irradiance of the selected case study site.

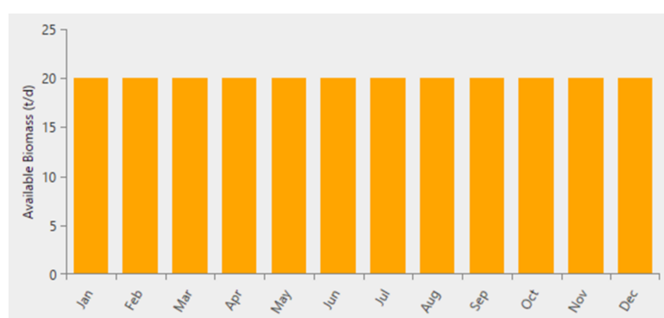

Fig. 5: The monthly average biomass data of the selected case study site.

2.2. System Design

In the design process of the PV/Biogas/Lithium Ion Battery Off-Grid System, several critical parameters must be carefully considered to ensure optimal performance and efficiency. These parameters encompass the specifications and characteristics of each system component, including the photovoltaic (PV) panels, biogas generators, and Lithium-Ion batteries. Factors such as the capacity, efficiency, and lifespan of each component play a pivotal role in determining the overall effectiveness and sustainability of the hybrid system. Attention to these parameters is deemed paramount in achieving a harmonious integration of RE sources and storage technologies for a reliable and continuous power supply in the targeted remote village in El Fayoum, Egypt. The technical and economic specifications of the selected system components are detailed in Table 1.

Table 1

Technical and Economic Specifications of the proposed System Components

Parameter	Unit	Value
PV panels		
Rated power	kW	1
Lifetime	years	25
Initial cost	$	2,500
Replacement cost	$	2,500
O&M cost	$	10
Lithium-Ion Battery (Blue Ion 2.0)		
Capacity	kWh	4.16
Lifetime	years	25
Initial cost	$	15,000
Replacement cost	$	13,800
O&M cost	$	1
Generic Biogas Genset		
Rated power	kW	50
Lifetime	Hours	10,000
Initial cost	$	10,500
Replacement cost	$	8,000
O&M cost	$/op. hr.	0.10
Economic parameters		
Discount rate	%	19.75
Inflation rate	%	32
Project lifetime	Years	25

Incorporation of the HOMER software into the research methodology is regarded as a pivotal step for the simulation and optimization of the proposed PV/Biogas/Lithium Ion Battery Off-Grid System. Through this integration, various system configurations can be comprehensively analyzed, considering factors such as operating costs, NPC, and economic comparisons. The capabilities of HOMER are leveraged to establish a robust simulation environment, enabling the fine-tuning and optimization of the hybrid system components. The outcomes of this integration will yield valuable insights into the feasibility, efficiency, and economic viability of the proposed off-grid system. These insights contribute to the informed design and implementation of sustainable energy solutions for remote electrification in El Fayoum, Egypt. A detailed illustration of the multifaceted components involved in the design and operation of a hybrid power system using HOMER is presented in Fig. 6.

In Figure 6, a detailed illustration is presented, showcasing the multifaceted components involved in the design and operation of a hybrid power system utilizing HOMER. Additionally, Figure 7 depicts a schematic diagram of the proposed system.

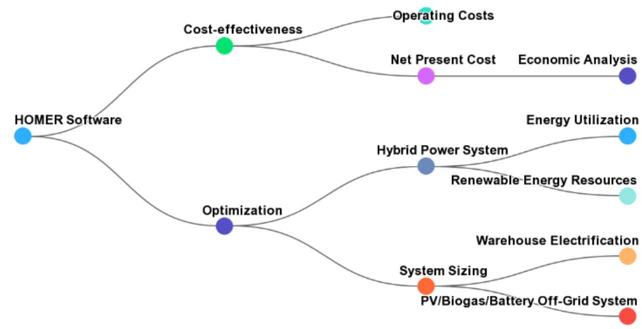

Fig. 6: Design and Operation of Hybrid Power Systems.

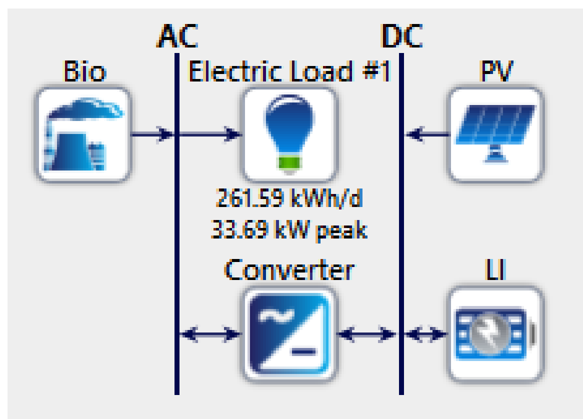

Fig. 7: The schematic diagram of the proposed system.

3. Results and Discussion

In the exploration of system performance within the context of the proposed PV/Biogas/Lithium Ion Battery Off-Grid System, this section delves into the intricate analysis of energy output and reliability.

3.1. System Performance

In evaluating the efficacy of the implemented PV/Biogas/Lithium Ion Battery Off-Grid System, this section delves into a comprehensive examination of its overall performance.

The proposed optimal system architecture demonstrates a carefully balanced integration of photovoltaic (PV), biogas (Bio), and Lithium-Ion (LI) battery components. Key performance indicators showcase the system's efficiency and economic viability:

1. **Power Generation Distribution:**
    - PV Capacity: 50 kW
    - Bio Capacity: 50 kW
    - LI Capacity: 12
2. **Economic Metrics:**
    - TNPC: $664,841.7
    - COE: $0.062
3. **Cost Breakdown:**
    - Initial Capital: $842,514.2
    - Operating Cost: -$1583.217 (indicating a potential revenue)
    - Biogas Genset/Fuel Cost: $732 per year
    - Biogas Genset/O&M Cost: $2550 per year
    - PV Capital Cost: $125,000
4. **Fuel and Energy Production:**
    - Total Biogas Genset Fuel: 73.2 tons per year
    - Biogas Genset Production: 24,341 kWh
    - PV Production: 90,567.81 kWh per year
5. **Lithium-Ion (LI) Battery Performance:**
    - Autonomy: 18.3hours
    - Annual Throughput: 39,566.13 kWh
    - Nominal Capacity: 201.6 kWh
    - Usable Nominal Capacity: 199.6 kWh
6. **Converter Output:**
    - Rectifier Mean Output: 1.76 kW
    - Inverter Mean Output: 9.97 kW

This system configuration demonstrates a holistic approach, maximizing RE sources while considering economic factors. The negative operating cost suggests potential revenue generation, emphasizing the economic sustainability of the proposed off-grid system. Additionally, the Lithium-Ion battery's autonomy and energy throughput contribute to system reliability, ensuring uninterrupted power supply. Further detailed simulations and sensitivity analyses will provide a comprehensive understanding of the system's robustness and effectiveness in the specific context of electrification in El Fayoum, Egypt.

The primary energy producer in the proposed system is the PV system, constituting a share of 78.8%, whereas the Biogas Genset holds a share of 21.2%. Monthly electric production and system dynamics are visually represented in Figure 8, illustrating the system's output trends. Additionally, Figure 9 presents the State of Charge (SOC) curve for the LI battery bank, and Figure 10 depicts the PV power output over time.

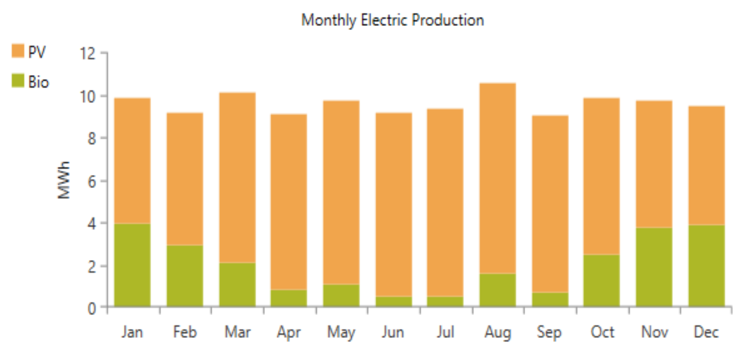

Fig. 8: The Monthly electric production of the proposed system.

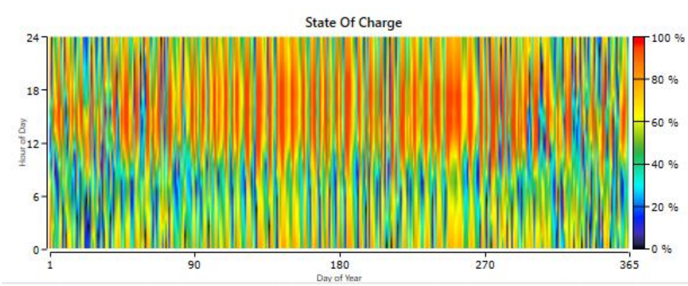

Fig. 9: The State of Charge (SOC) curve for the LI battery bank.

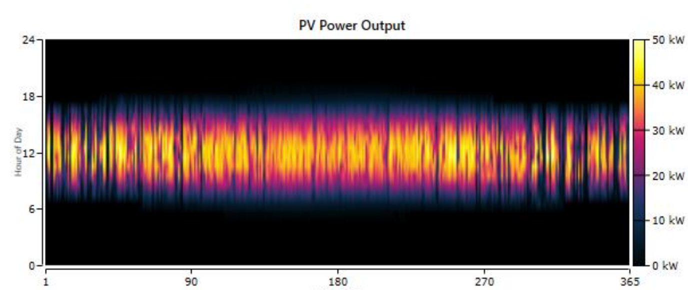

Fig. 10: The PV power output over a year.

The composition of the proposed system includes 12 LI batteries, each with a nominal capacity of 202 kWh, an anticipated lifespan of 25 years, an average energy cost of 0.00925 $/kWh, and losses totaling 1203 kWh per year.

The Biogas Genset operates for 510 hours per year, boasting an operational life of 19.6 years, a fixed generation cost of 45.1 $/hr., and an annual electrical production of 24,341 kWh. The genset's fuel consumption stands at 73.2 tons per year, with a mean electrical efficiency of 31.1%.

The PV system, rated at 50 kW, exhibits a mean output of 10.3 kW, a capacity factor of 20.7%, and operates for 4384 hours annually. The levelized cost is calculated at 0.0178 $/kWh, providing a comprehensive overview of the economic and operational characteristics of the PV system.

3.2. Sensitivity analysis results

In the intricate exploration of system dynamics and economic viability, the unveiling of sensitivity analysis results, particularly in the context of photovoltaic (PV) and battery cost variations, unravels profound implications for the overall performance and resilience of the proposed off-grid system.

3.2.1. Sensitivity analysis for PV cost variations

Figure 11 visually represents the sensitivity analysis concerning variations in PV initial and replacement costs and their consequential impact on the TNPC and the COE within the system.

Observations from the chart reveal a clear correlation: as both the PV Cr multiplier and the PV Ci multiplier experience an increase, there is a corresponding escalation in both the TNPC and the COE. This unmistakably indicates a direct relationship between these variables, shedding light on the crucial interplay between PV costs and the economic metrics of the off-grid system.

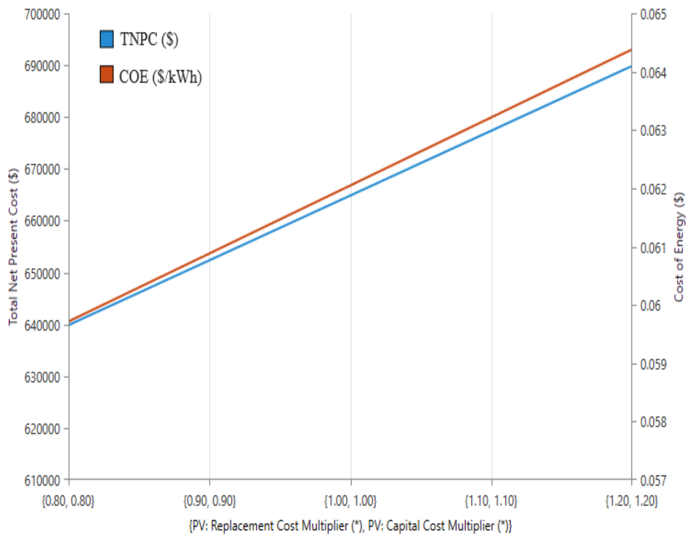

Fig. 11: Sensitivity analysis for PV cost variations on TNPC and COE of the proposed system.

Figure 12 delineates the sensitivity analysis regarding variations in Lithium-Ion (Li-Ion) battery bank initial and replacement costs and their consequential impact on the TNPC and the COE within the system.

Analysis of the chart reveals a discernible pattern: as both the initial and replacement costs of the Li-Ion battery bank experience an increase, there is a corresponding elevation in both the TNPC and the COE. This underscores a direct relationship between these variables, highlighting the influential role of Li-Ion battery costs in shaping the economic metrics of the off-grid system.

Furthermore, the chart suggests a higher sensitivity of NPC and COE to changes in the Cr of the battery bank compared to the C_i. This sensitive discrepancy arises due to the repetitive nature of replacement costs incurred multiple times over the system's lifespan, in contrast to the one-time occurrence of initial costs.

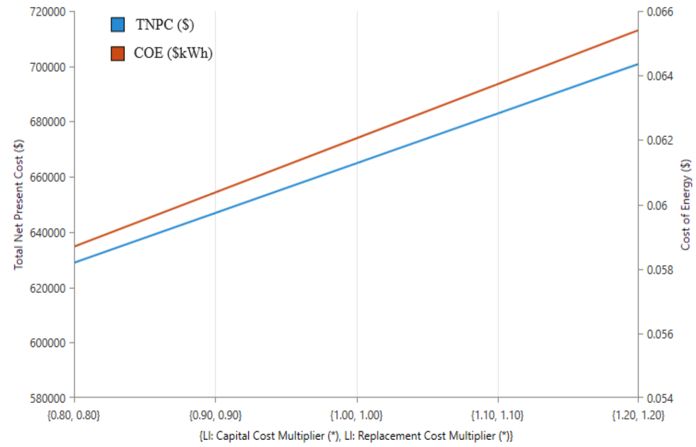

Fig. 12: Sensitivity analysis for Li-Ion Battery Bank cost variations on TNPC and COE of the proposed system.

4. Conclusion

In conclusion, valuable insights have been derived from the thorough investigation of the proposed PV/Biogas/Lithium Ion Battery Off-Grid System, encompassing both its optimal configuration and the system's sensitivity to variations in costs. The optimal system configuration, as ascertained through rigorous analysis, includes a PV capacity of 50 kW, a Biogas capacity of 50 kW, and a Lithium-Ion battery capacity of 12 kWh. These numerical findings establish critical benchmarks, providing tangible parameters for the design of sustainable and economically viable energy solutions in off-grid communities, thereby catering to stakeholders, policymakers, and practitioners.

Additionally, illumination is cast upon the system's responsiveness to alterations in PV and Lithium-Ion battery costs through the sensitivity analysis results. The analysis reveals a direct correlation between cost multipliers and economic metrics, underscoring the significance of meticulous cost considerations in influencing the TNPC and COE. These insights furnish decision-makers with a nuanced comprehension of the economic dynamics, facilitating adept navigation of challenges associated with cost variations during the implementation and maintenance of such off-grid systems.

The ramifications of this study extend well beyond the confines of the specific system under scrutiny, resonating notably within the broader domain of rural electrification in remote villages. The pinpointed sensitivities in cost variations supply actionable considerations for strategy refinement, while the optimal system configuration stands as a tangible blueprint for achieving effective and sustainable energy solutions across diverse off-grid contexts.

Looking forward, recommendations for prospective research endeavors encompass further exploration of techno-economic aspects, delving into advanced storage technologies, and conducting on-ground pilot projects for the validation of simulation outcomes. A sustained emphasis on community engagement strategies and a more profound examination of socio-economic impacts will further enrich the collective understanding of rural electrification initiatives.

In essence, this research, with its optimal system configuration and sensitivity analysis results, not only contributes to informed decision-making but also lays the groundwork for continual exploration and progress in the realm of RE adoption in remote villages.

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