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Research Article

Techno-Economic and Viability Analysis of Incorporating Rooftop Solar Photovoltaic and Natural Gas Generators in Educational Institution

Anuj Kumar Choudhary[1], Aditya Kumar Jha[2] and K. Manjunath[3,*]

[1,2,3] Assistant Professor, Department of Mechanical Engineering, Delhi Technological University, Bawana Road, Delhi 110042, India

[*]Corresponding Author: K. Manjunath. Email: manjunath.k@dtu.ac.in

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Abstract: This research paper investigates the viability and advantages of putting in place a modified hybrid microgrid system at an academic campus to mitigate adverse environmental impacts and enhance energy sustainability. Utilizing HOMER Pro software, we conducted a comprehensive comparative analysis between a base case, relying chiefly on generation of fossil - based energy, and our proposed hybrid model incorporating Energy storage and geothermal energy. The analysis reveals a powerful reduction in harmful emissions with the hybrid system, achieving approximately a 50% decrease in pollutants such as CO_2, SO_2, and NO_x compared to the base case, directly contributing to improved air quality and a reduced in carbon footprint. Economically, the hybrid system demonstrates superior performance across varying Nominal Discount Rates (NDR). At an NDR of 8%, the hybrid model exhibits a Net Present Cost (NPC) of $5,845,200.51, significantly lower than the base case's $10,181,815.25. Similarly, at an NDR of 12%, the hybrid model's NPC stands at $4,283,849.55, a reduction of approximately 40% compared to the base case's $7,297,728.42. Furthermore, a sensitivity analysis of fuel prices indicates that the hybrid system is less susceptible to market fluctuations, consistently showcasing lower NPC, Cost of Energy (COE), and operating expenses as fuel prices for both diesel and natural gas increase by increments of $0.2/$m^3$. The study underscores the practicality and ease of deployment of the hybrid system at our specific project location, highlighting its adaptability to existing infrastructure and geographical conditions. In summary, the results strongly advocate for the adoption of our modified hybrid model, demonstrating its potential to achieve a cleaner, more economically viable, and sustainable energy system for academic campus by significantly reducing emissions and costs while being easy to integrate into the current infrastructure. This project showcases the ability to reduce both environmental impact and financial burdens.

Keywords: Natural Gas Generator, Rooftop Solar PV Panel, Grid Outage, Environmental Impact, Economic Analysis

1.Introduction

The National Capital Region (NCR) of India, characterized by its rapid urbanization and industrial growth, faces a myriad of environmental challenges, with pollution from Diesel generators emerging as a significant concern. As power supply remains inconsistent in many areas, particularly during peak demand seasons, the reliance on Diesel generators has surged. This reliance not only contributes to deteriorating air quality but also has profound implications for public health and mental well-being. The noxious emissions from these generators release particulate matter, NO_x, CO_2, $SO_{x,}$, etc. into the atmosphere, exacerbating respiratory conditions and cardiovascular diseases among the populace.

Furthermore, the psychological ramifications of living in an environment plagued by pollution cannot be overlooked. Studies have shown that air pollution is linked to arosed levels of anxiety, depression, and stress-related disorders, creating a cycle that adversely affects both mental physical well-being and living standards. The Global Burden of Disease Study (GBD) highlights that environmental factors, including air pollution, are among the leading causes of morbidity and mortality worldwide, emphasizing the urgent need for effective interventions [1].

In this context, the Green Rating for Integrated Habitat Assessment (GRIHA) framework serves as a vital instrument for judging and mitigating the environmental impact of urban infrastructure, including energy generation practices [2]. By promoting sustainable alternatives and encouraging the adoption of cleaner technologies, GRIHA aims to reduce the ecological footprint of urban centres like the NCR. This research paper seeks to explore the multifaceted effects of generator-induced pollution in the NCR, examining its environmental consequences and implications for public health and mental well-being while advocating for sustainable solutions aligned with the principles of GRIHA. Through this investigation, we aim to contribute to a deeper understanding of the pressing need for cleaner energy alternatives in urban planning and policy-making to foster healthier communities. The National Capital Region (NCR) experiences Substantial air pollution, especially in winter, with PM2.5 and PM10 levels often extreme safe limits. Major contributors include vehicular emissions, industrial discharges, and diesel generators. Despite measures like odd-even traffic schemes and construction restrictions, success has been limited. Experts caution that long-term exposure to contaminated air might cause mental health problems in addition to cardiovascular and respiratory disorders. There is an urgent need for sustainable energy alternatives and stricter emission regulations to protect public health and the environment [3]. The article highlights the environmental impact of fuel-based generators used in areas with unreliable power supply.

It discusses the pollution caused by emissions of CO2, NOx, and particulate matter, which lead to health and environmental issues. The author stresses the need to shift to sustainable energy alternatives like solar, wind, and hydroelectric power to reduce carbon footprints and improve air quality. The article advocates for more investment in renewable technologies and policies that encourage moving away from fossil fuels. It calls for action from individuals, businesses, and policymakers to prioritize sustainable energy solutions for a healthier planet [4]. As of October 1, 2023, the use of diesel generators in the National Capital Region (NCR) of Delhi has been banned to address air pollution and public health concerns. Diesel generators contribute significantly to high levels of particulate matter and other harmful pollutants. The Delhi government is advocating for cleaner energy options, including solar energy and battery storage, to support those affected by the ban. This move highlights the urgent need for sustainable energy practices to combat pollution and protect public health, marking a significant step towards environmental responsibility in the region [5].

In response to the persistent air pollution emergency in Delhi NCR, authorities have implemented a ban on diesel generators as of October 1, 2023. This measure is aimed at reducing the harmful emissions that significantly contribute to the region's deteriorating air quality. The decision follows extensive studies linking diesel exhaust to significant hazards to one's health, including respiratory issues and cardiovascular diseases. With many residents and businesses relying on diesel generators for power, especially during outages, the ban poses challenges for these stakeholders. However, it also opens avenues for promoting cleaner energy options like solar energy and batteries. The move is part of a broader strategy to combat pollution and enhance public health, reflecting a growing commitment to environmental sustainability in urban planning [6]. This study presents an in-depth technological and economical analysis and design of a combined energy system customized for a ordinary household in a village of Malaysia for supplemental power supply. The research includes a detailed assessment of the specifications combined for of the hybrid system and evaluates alternative scenarios, including standalone PV and diesel generator-only systems. A simulation program was created to represent the functioning of these different configurations, allowing for the identification of the most cost-effective solution that meets the household's energy demands. The study employs a genetic algorithm to identify the best tilt angle for the PV panels, enhancing energy generation. Additionally, a sensitivity analysis was conducted to understand how variations in certain parameters affect the overall cost of energy.

The findings indicate that the most efficient and economical solution is the hybrid system combining PV panels, a storage bank, and a diesel generator. This approach not only reduces operating costs and increases energy efficiency but also significantly lowers pollutant emissions equated to diesel working systems. The analysis of solar data specific to the region further supports the viability of enacting such hybrid systems in remote areas, demonstrating their potential as a sustainable energy solution [7]. This paper addresses the challenge of supplying energy to remote villages, particularly those either disconnected from the grid or experiencing frequent outages. The study focuses on a hybrid energy solution that integrates PV, biomass, and diesel generators to fit the energy demands of a grid-connected village in eastern Iran. Given the volatile economic circumstances in the region, various astronomy and discounted rates were analyzed to identify the optimal scenario for energy production.

A comparative investigation was held to evaluate the benefits of unique photovoltaic installation methods—centralized plants versus rooftop systems. The findings indicate that under the current economic conditions of 10% inflation and an 18% discount rate, the optimal configuration consists of a 63 kW photovoltaic system, a 10 kW biogas generator, and two diesel generators (10 kW and 15 kW). This hybrid setup can produce energy at a cost of approximately $0.193 per kWh. The research also highlights that fluctuations of fuel prices, interest rates, and also the inflation can significantly impact the overall cost of energy throughout the project's lifespan. The analysis suggests that within a reasonable range of expected economic conditions, the energy fee for the optimal system could vary between $0.085 and $0.238 per kWh [8]. This paper explores the development of an optimal hybrid energy system to address the electrical demands for the off-grid village of Gwakwani in South Africa. Recognizing the limitations of traditional single-energy technologies, the study investigates three alternative off-grid systems: (i) a Photovoltaic system paired with a diesel generator, (ii) a PV system with battery storage, and (iii) a PV system that combines both a diesel based generator and battery storage. Various sizes of photovoltaic panels (1 kW, 0.8 kW, 0.6 kW, and 0.4 kW) were tested to determine the optimal configuration for each scenario based on three key objectives: 1. The fulfillment of energy requirements, the expenses associated with the system, and the decrease in pollution levels. The findings indicate that the optimal size for both the PV-battery system and the PV-diesel generator system is 1 kW. However, the third scenario, which includes both a diesel generator and charging storage, did not adequately meet all three objectives. A comparative analysis reveals significant differences between the two optimal systems.

The PV-battery system (Scenario 1) demonstrates a total cost that is only 26% of that of the PV-diesel system (Scenario 2), while also producing zero harmful emissions compared to nearly 6 tons of CO_2 per year from the diesel generator. Although Scenario 3 shows potential for energy production, it incurs higher costs and is suggested to be more advantageous when considered through an economies of scale lens [9]. Off-grid communities often rely on fossil fuel generators, but this study explores the potential of integrating PV-BES systems to improve system reliability, autonomy, and environmental impact. This paper presents a bi-objective optimization model for designing hybrid PV BES diesel based generator systems, targeting simultaneous reductions in LCOE and carbon footprint. The model considers hourly energy demand, solar irradiation, and battery charge/discharge dynamics. Application to a isolated hamlet in Yakutsk, Russia, demonstrates the benefits of this approach, revealing potential for significant emission reductions with manageable cost increases. Specifically, optimized hybrid system configurations achieve around 48% emission reduction and slight increase in LCOE [10]. This research offers an examination of a hybrid solar-biomass power system developed for an educational facility as a pathway toward decarbonization. The study employs HOMER software to enhance the system's efficiency, evaluating its technical, economic, and environmental dimensions. A case study for the Mechanical Engineering Department at DTU reveals that the designed HRES generates 376,780 kWh of power annually, reducing CO2 emissions by 161 metric tons per year, while achieving the cost energy of ₹16.96/kWh, thereby demonstrating the system's potential to facilitate a sustainable energy transition [11].

The best battery storage technology for SPV/DG hybrid systems on remote Indian islands is examined in this study. The study uses HOMER software to assess four BES alternatives, such as lead-acid, Zinc-bromine flow (ZBF), vanadium redox, and lithium-ion batteries at the islands of Baratang and Minicoy. The best techno-economic performance, with the lowest energy cost, highest return on investment, and largest penetration of renewable energy, is provided by an SPV/DG/ZBF system, according to the results. The study also used a Scenario analys is methodology to evaluate the system's behaviour [12]. A two-step approach to improve and analyze a remastered edition of hybrid renewable energy system (HRES) for rural electrification in sub-Saharan Africa is detailed in this study. This methodology utilizes a genetic algorithm and MATLAB to optimize a system encompasses of PV, wind, storage, and diesel components for a remote Nigerian village. The study compares this optimized system to grid extension, using break-even distance, and to diesel generators, using net present value and simple payback period. Results show the optimized model achieves significant carbon emission savings and can be economically viable, This analysis reveals that the proposed system offers significant economic advantages. With a optimal distance of 16.2 km, the system exemplifies its potential to be cost-effective over long distances. Furthermore, the system boasts a rapid payback period of just 2.8 years when compared to traditional diesel-based solutions. This quick return on investment, coupled with the relatively short break-even distance, underscores the financial viability and long-term economic benefits of adopting this alternative approach. This contrasts starkly with diesel, which lacks these favorable economic characteristics, making our system a superior choice from a financial perspective [13].

This research presents a cost-optimized craft of a grid-connected hybrid energy system, incorporating solar power and a diesel generator, to address unreliable electricity supply in developing countries. Through an electrical audit and HOMER software simulations for a building at Accra Technical University, the paper proposes a system that primarily relies on solar power while the grid serves for backup. An electricity cost of $0.472/kWh was achieved when the grid is operational, and $1.496/kWh if there are outages. The paper also analyzed the carbon footprint, showing a reduction of carbon, sulphur and nitrogen emissions compared to grid electricity, along with a 10.43-year payback period [14]. Addressing the challenges of inadequate and unreliable electricity supply in Nigeria, this study explores the potential of off-grid hybrid solar PV and diesel generator systems for private industries. Using load profiles developed from surveys across six sectors, the research demonstrates that transitioning to these hybrid systems can significantly reduce operating costs for businesses currently relying on expensive diesel generation. The analysis shows lower levelized costs of electricity, enhanced reliability, and the positive implications of reducing dependence on imported petroleum [15]. This research investigates a hybrid energy system incorporating solar PV, diesel, and biogas as a solution to untrustworthy grid electricity, using a case study at a central abattoir in Nigeria. The analysis, conducted with HOMER® software, identified two viable configurations: a Grid/PV/Biogas and a Grid/PV/Diesel system. The Grid/PV/Biogas system, utilizing biogas produced from animal waste, was found to be more economically favorable with a COE of $0.164/kWh compared to the $0.280/kWh COE of the Grid/PV/Diesel system, and also reduced emissions by 61% [16].

An extensive review of hybrid solar energy storage systems for building power supply is provided in this study. It analyzes the global adoption of these systems, focusing on PV-battery installations, and categorizes various energy storage technologies. The review then assesses these technologies based on technological, economical, and environmental factors. The inspection concludes with a discussion of optimization methods and highlights the potential of lithium-ion batteries, supercapacitors, and flywheels for building applications, while also outlining key areas for future research [17]. This study addresses the need for reducing emissions and promoting renewable energy by installing a power system at the Aswan Campus of AASTMT in Egypt. The study assesses several photovoltaic panel types and tracking systems using a combo of observational data, HOMER Pro applications, and pollution analysis. The results show that PV integration can decrease grid dependence by 50%, lowering emissions and LOCE from $0.0647 to $0.0535. The study reveals that dual-axis tracking enhances energy production, but cost-benefit analyses may favor fixed panels [18]. This study explores the possibility of retrofitting Canadian home stock with solar technologies to lower energy use and greenhouse gas emissions. Hybrid End-Use Energy in Canada use Energy and Emission Model was used in the investigation. Assesses the technological and financial performance of modelling infused photovoltaic/ thermal (BIPV/T) and photovoltaic (PV) systems in residences with south-facing roofs. The results demonstrate that BIPV/T systems significantly reduce the use of fossil fuels while offering higher energy savings (18%) and GHG emission reductions (17%) when compared to PV systems (3% and 5%, respectively) [19]. We have conducted research that addresses the issue of power generator emissions by analyzing the talent of natural gas generators as a replacement for diesel generators in institutional settings during grid disruptions. The study demonstrates that natural gas generators offer significant advantages, including greater fuel efficiency, reduced emissions of harmful pollutants, and substantial cost savings of nearly 50%. The paper highlights the environmental and financial benefits, emphasizing lower NPC, COE, and executional expenses, while positioning natural gas as a sustainable and cost-effective option for a vision with cleaner energy sources [20].

This research paper delves into the practical application of a modified hybrid microgrid system tailored for our specific campus environment, a departure from the theoretical focus often found in literature reviews. While previous studies, such as the one referenced, have explored the enhancement of hybrid renewable energy systems in different contexts, often using generalized models, our work is distinguished by its site-specific approach. Unlike these generalized analyses, our project is centered on the unique demands and constraints of our campus, integrating factors like specific energy consumption patterns, available renewable resources, and existing infrastructure. Furthermore, while existing literature often focuses on optimizing system components for performance, our project places a strong emphasis on both economic and environmental sustainability. We go beyond merely achieving efficient energy generation; we strive to minimize emissions, reduce reliance on fossil fuels, and demonstrate long-term financial viability, all within the context of our campus. This tailored approach, combined with the explicit environmental impact analysis, differentiates our work from broader, less localized studies found in the existing literature. The scope of our paper is therefore not just to model a system, but to provide a blueprint for the practical implementation of a sustainable energy solution within our specific environment, focusing on reducing costs, emissions, and enhancing campus energy independence.

2.Modelling

For the technological economical modelling, simulation, and enhancement of hybrid renewable systems, HOMER Pro is a well-known program. It employs a detailed hourly simulation approach to model system performance, incorporating data on renewable energy resources, load profiles, component costs, and operational constraints. The software's optimization algorithms enable users to identify the least-cost system configurations that meet specific energy demands, while providing insights into performance metrics, like the levelled cost of energy, net present cost, and the dissemination of renewable energy [21].

2.1 Location of Project

This research project is focused on hybrid energy system and renewable energy study at the Delhi Technological University (DTU). DTU is a prominent public engineering university situated in Delhi, India, and serves as the primary site for this study. Understanding the specific characteristics of DTU's location is crucial for contextualizing the findings and ensuring the relevance of the proposed solutions. DTU is situated at 28°44' North latitude and 77°06' East longitude, placing it in the northern part of India, within the National Capital Territory of Delhi. This area is characterized by a subtropical climate that features well-defined seasons, comprising hot summers from April to June, a monsoon period from July to September, and mild winters occurring from December to February. These climatic variations have significant implications for the project, particularly regarding renewable energy resource availability (especially solar irradiation) and energy consumption patterns.

The university's main campus is a sprawling urban campus, encompassing a large area that houses academic buildings, research laboratories, administrative facilities, student hostels, sports complexes, and support infrastructure as shown in Fig.1. The specific area of focus within the DTU campus will depend on the nature of this project "the Department of Mechanical Engineering building,". The energy utilized profile of the specified location is a critical factor in the design and implementation of this study.

Figure 1: Satellite picture of DTU campus

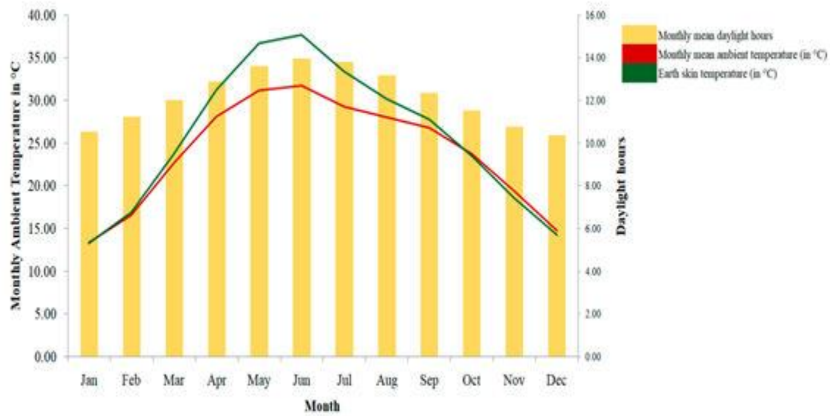

Figure 2: Ground temperature, sunshine hours, and ambient temperature averages for each month of the chosen area.

Monthly variations in key climate factors are displayed in Figure 2. The graph shows the monthly average daylight hours with yellow bars, monthly ambient air temperature (in °C) using a red line, and monthly ground surface temperature (in °C) using a green curve.

3.Methodology

This research employs a technological and economical analysis to evaluate the practicability of a hybrid energy system, combining natural gas generators and photovoltaic solar panels, as a replacement for diesel generators during grid outages. HOMER Pro software is used in the study to assess and optimize the system performance based on a defined load profile and local resource data. HOMER's procedure to improve system is illustrated in figure 3. The software simulates different hybrid system configurations as well as a diesel only baseline, considering component specifications and cost specifications, to help minimize the COE, NPC, and environmental impact by reducing emissions.

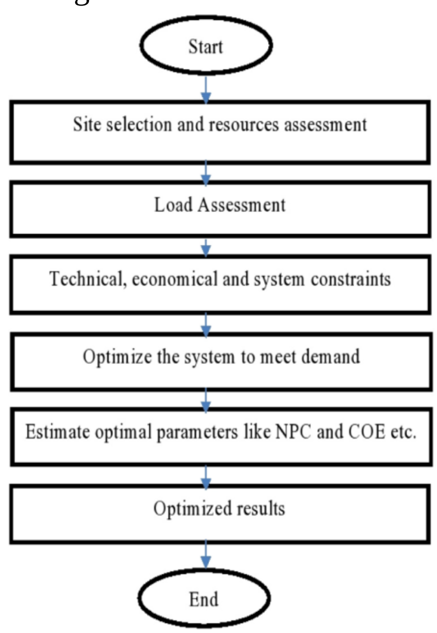

Figure 3: HOMER's procedure to improve system.

Through HOMER Pro's optimization algorithm, the optimal sizing and deploy strategy of the system components will be determined. This will be followed by a performance evaluation and comparative analysis of the technological and economical parameters in addition to the environmental implications through analyzing factors such as emission of CO_2 and other pollutants, with sensitivity analysis used to assess system robustness under varying conditions, ultimately providing insights into the viability of the suggested system and guiding decisions for premiering research.

4.System Description

The effectiveness of a hybrid energy system as an choice to a traditional diesel power plant backup system is investigated in this study. The analysis considers two distinct configurations: a base case and a modified hybrid model. The base case represents a conventional setup where the electrical load is primarily met by the utility grid, with a diesel generator providing backup power during grid outages. In contrast, the modified system replaces the diesel generator with a combination of natural gas and solar power, integrated with battery storage for enhanced reliability and optimal use. This hybrid model includes the utility grid, a natural gas generator for backup power during grid outages, photovoltaic (PV) solar panels as a renewable energy source, a battery storage system to store excess electricity and improve system reliability, and a transmitter to control power flow between the system facets [22-23]. This hybrid system is designed to primarily rely on the PV panels, supplemented by the natural gas generator when needed, with battery storage optimizing energy use and reducing reliance on the natural gas generator, thus promoting a more efficient and sustainable system as compared to the traditional Diesel based system.

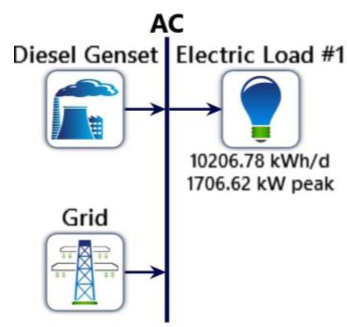

Figure 4: Model for Diesel generator.

Figure 4 shows the HOMER PRO model that is used as a base case in this research project which includes a Diesel generator, a grid and a load. Figure 5 shows the HOMER PRO model that is used as a modified and hybrid case in this research project which includes two natural gas generators, grid, electric load, photo voltaic solar panel followed by its battery storage and a convertor.

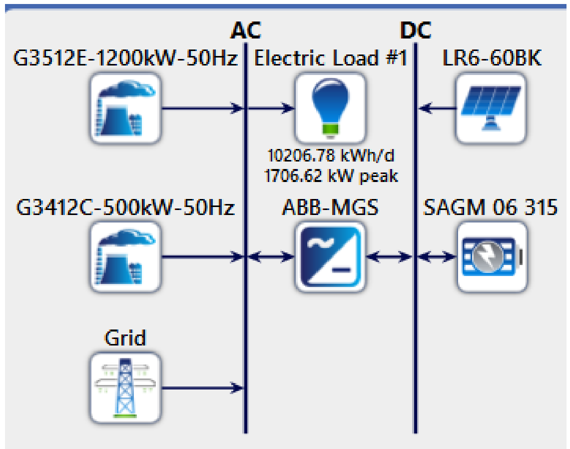

Figure 5: Modified hybrid model on HOMER PRO software.

- **Load Profile**

The load profile of this educational institution exhibits unique characteristics distinct from residential, industrial, or commercial loads, with monthly demand fluctuating due to semester schedules and vacation periods, as shown in Table 1. Peak demand, reaching approximately 407.71 kW, occurs during June, July, August, and September, as depicted in Figure 6, corresponding to the region's peak summer season and humidity which drives the use of air conditioning and water coolers. Conversely, In general, load demand is reduced in the winter, as seen in Figure 7, when heating systems are generally less needed [24-25]. Specifically, July experiences increased demand because of newly admitted students and multiple orientation programs in auditoriums that rely on significant electrical consumption. The scaled average load of the year is 10206.78 kWh/day. This research models two scenarios for backup power, using either a diesel generator or a natural gas generator. The initial outlay for the diesel generator is $120,000, an exchange cost of $96,000, and O&M costs of $0.100 per operational hour, while the natural gas generator has a higher capital cost of $180,000, a replacement cost of $144,000, and lower O&M costs of $0.050 per executional hour. To simulate grid disruptions, an electricity outage from 1100 hrs to 1300 hrs is also implemented in the system.

Table 1. Total electricity usage in months (kWh) for the year 2023 and 2024. (DTU campus)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electric Consumption (2023)	182220	216840	191820	91860	191820	91860	191760	270660	236700	198520	220140	149160
Electric Consumption (2024)	250020	210002	239400	418440	582967	565800	579900	604140	696120	694620	465780	364680

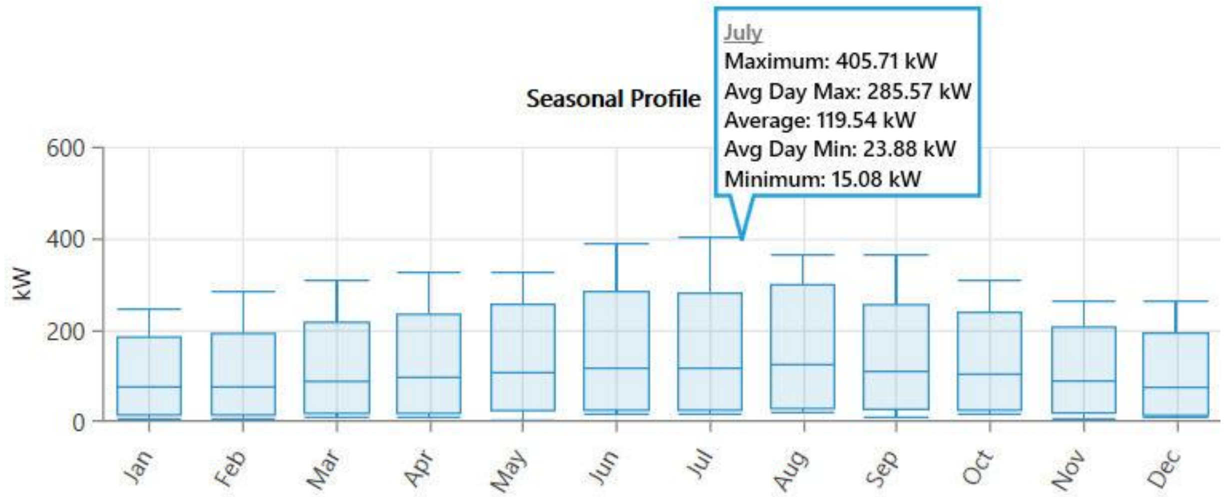

Figure 6: Monthly profile of electric load

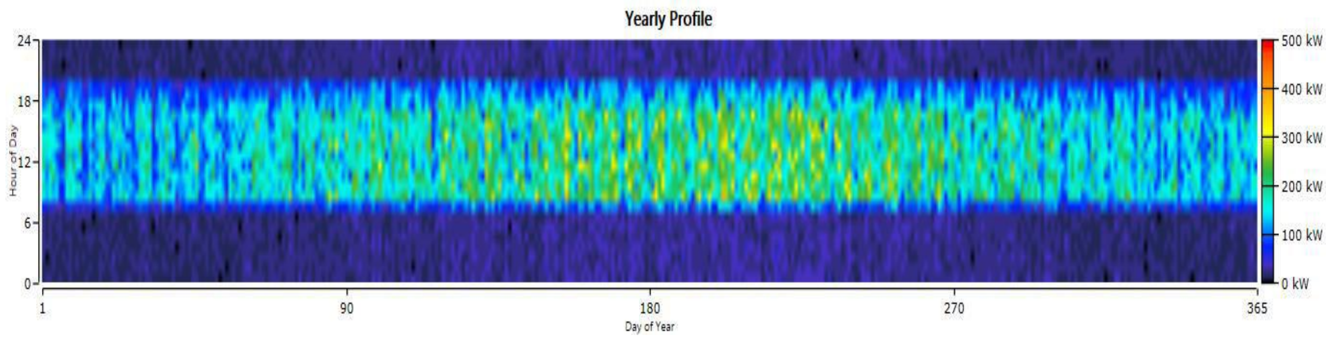

Figure 7: Annual profile of electric load

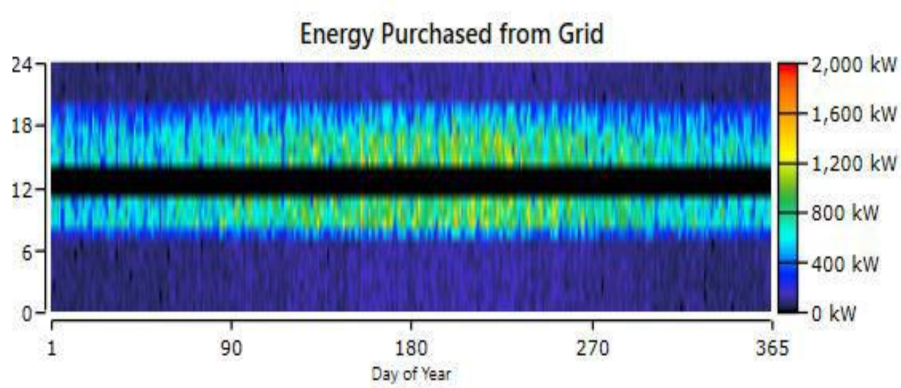

Figure 8: Electricity purchased through grid.

5.Systems

The diesel generator used in this study for the base case scenario is a Caterpillar (CAT) model, specifically the CAT-1825kVA-50Hz-PP, which is a robust and widely used model for backup power applications, rated at 1825 kVA (corresponding to 1500 kW) and operating at 50 Hz. Designed for reliable backup power during grid outages, This generator incurs an initial capital expenditure of $120,000, a replacement expense of $96,000, and operational and maintenance (O&M) costs amounting to $0.100 for each hour of operation. This diesel generator, designed for dependable backup power, serves as a key component in this research, providing a performance baseline for the evaluation and effectiveness of the proposed hybrid system during HOMER Pro simulations and the technological and economical exploration profile of electric load analysis.

This study investigates a hybrid energy system designed to reduce reliance on traditional diesel backup power, including photovoltaic (PV) solar panels, two natural gas generators, a battery accumulating system, and a converter. The system incorporates LONGi Solar LR6-60BK monocrystalline silicon PV panels, which are expected to reduce dependence on the grid and the natural gas generators, with an initial cost of $200, a replacement cost of $130, and an annual O&M cost of $10 per panel. Additionally, two Caterpillar natural gas generators are utilized: the CAT-NG-1000kVA-50Hz-CP, with a rated apparent power of 1000 kVA, which provides the primary source of backup power, and the CAT-NG-500kW generator, also operating at 50Hz, to provide added flexibility and meet varying power demands. A battery storage system and a converter is also used for optimizing energy usage and ensuring proper integration of all the components, respectively. As a baseline comparison, a Caterpillar diesel generator (CAT-1825kVA-50Hz-PP) with a capital cost of $120,000, an exchange cost of $96,000, and O&M costs of $0.100 per executional hour is also considered, against which the performance of this hybrid system will be assessed. The hybrid system is introduced such that the main power source is the PV panels. When sunlight is available, with the natural gas generators supplementing when needed and battery storage optimizing overall energy usage.

6.Cost Analysis

Two important cost criteria will be the focus of our analysis of the suggested hybrid energy system's economic feasibility in this section: Net Present Cost (NPC) and the Cost of Energy (COE). The Net Present Cost (NPC) represents the total lifecycle cost of a system, encompassing typical investments, replacement expenses, and operational costs of the project's tenure, while the Cost of Energy (COE) provides the median price of generating one kilowatt-hour of electricity. These two metrics will be used to assess and compare The financial results of both the intimated hybrid system and the baseline diesel-based system, and will play a vital role in determining the overall feasibility and financial implications of transitioning to the proposed hybrid system.

- **Net Present Cost (NPC)**

It is a fundamental economic indicator used to assess the total capital of a project or investment over its entire lifespan, particularly when comparing different system configurations, The temporal value of money is taken into account. Unlike a simple summation of all costs, NPC recognizes that money has different value at different points in time, and therefore discounts future costs back to their equivalent present value. This discounting process is crucial for accurately comparing projects with varying lifespans and cash flow patterns. NPC is calculated by adding up the present values of all expenses over the course of the project, including the initial upfront capital expenditures for purchasing and installing system components, the costs for replacing components at the end of their useful lives, and the ongoing operational and maintenance (O&M) costs such as fuel, maintenance, and labor. Each future cost is discounted back to its present value using a chosen variation rate, which reflects the opportunity cost of capital and the risk associated with the project. This variation rate has a substantial impact on the NPC; a higher rate places greater weight on present costs and reduces the impact of future ones, while a lower rate gives more emphasis to the long-term costs. As a result, choosing the right discount rate is essential for determining the long-term economic feasibility of a project. NPC is a crucial indicator in this study's evaluation and comparison of the sustainability of the economy throughout time of the suggested hybrid energy system and the conventional diesel generator system. By incorporating all lifecycle costs and factoring in the time value of money, NPC facilitates a robust economic assessment, with a lower NPC generally indicating a more attractive and economically sound investment decision.

Equation1 is taken as the highest amount of NPC as an antitode.

$$NPC=PV(Benefit)- PV(Cost) \tag{1}$$

$$\text{NPC} = \sum_{n=k+1}^{t} \frac{B_n}{(1+i)^n} - \sum_{n=0}^{k} \frac{C_n}{(1+i)^n} \tag{2}$$

Over 25-year lifespan of the systems, this study accounts for both the annual benefits (Bn) and costs (Cn). These annual values are determined using Equation (1). The most significant factor contributing to the overall cost is the initial investment, which includes the expenses associated with power, installation, and operation.

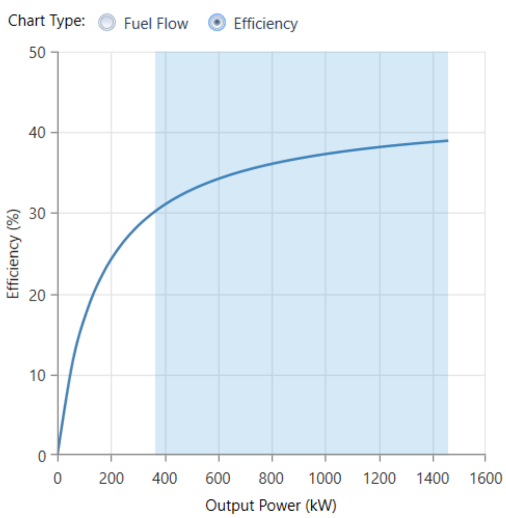

Figure 9: The diesel generator's efficiency graph

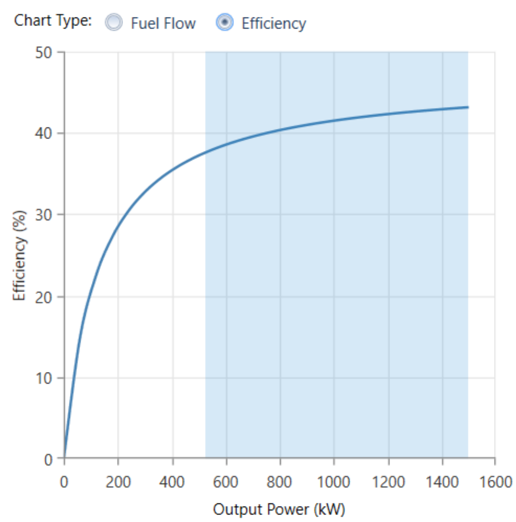

Figure 10: The Natural gas generator's efficiency graph

- **Cost of Energy (COE)**

It is also known as the levelled Cost of Energy (LCOE), is a crucial indicator used to evaluate the average cost of generating electricity over the tenure of a power generation system. Unlike the (NPC), which focuses on the total project capital, the COE is expressed in terms of unit price of electricity generated (typically dollars per kilowatt-hour or $/kWh). It's a useful metric for equating the economic viability of unique energy generation technologies, especially when they have varying lifespans, capital costs, and operating profiles. The COE is determined by taking the total lifecycle capital of a power generating system, represented as the Net Present Cost, and dividing it by the sum amount of electrical energy generated throughout its operational life. This method allocates all associated costs—such as initial capital investments, continuous executional and maintenance expenditures, and any costs related to replacements—over the system's total energy output. A reduced COE typically signifies a more economical energy generation technology. In the context of this research, the COE serves as a primary measure to investigate the economic competitiveness of the proposed hybrid system against the traditional diesel generator system, thus providing a clear picture of the value of generating electricity with each system. Therefore, by providing a normalized cost per unit of electricity, the COE serves as an easily understandable metric when comparing the economic performance of different power solutions.

$$COE=\frac{C_{ann,tot}-c_{boiler}H_{served}}{E_{served}} \quad (3)$$

- **Sensitivity Analysis**

To investigate the robustness of the findings and to understand the potential impact of varying key parameters, a comprehensive sensitivity testing was performed using the HOMER Pro software. This analysis is crucial to determine how changes in certain input values can affect the technological and economical regarding the suggested hybrid system and the baseline diesel system, thus assessing the robustness of the results. Specifically, the sensitivity analysis concentrated on two pivotal factors: the nominal discount rate (NDR) and gas price variations. The nominal discount rate, initially set at 8%, was increased in steps of 2% up to 12%, allowing us to evaluate the system's sensitivity to fluctuations in the cost of capital. This adjustment is particularly important because the discount rate significantly influences the NPC and, consequently, the overall economic attractiveness of a given project. A higher discount rate justifies a greater possibility cost of capital and a greater emphasis on present costs, so observing the system behavior at higher discount rates provides valuable insights on long-term economic stability. Furthermore, the analysis also incorporated variations in fuel prices, recognizing the inherent volatility in these markets and their potential to impact operational costs, particularly for the diesel generator in the baseline case, and for the natural gas generators in the proposed hybrid system. These fuel price variations enable a thorough assessment of how changes in input fuel prices have an impact on each system's overall economic performance and energy costs. By systematically exploring the effects of these variations in both nominal discount rate and the gas prices, the sensitivity analysis provides a more nuanced understanding of the key economic and financial drivers that affect the project’s performance. This allows for more reliable conclusions and more robust recommendations to be derived from the analysis.

7.Results and Discussion

As described in the previous sections, this study compares a base case scenario using a diesel generator with a modified scenario utilizing a hybrid model consisting of natural gas generators and photovoltaic (PV) solar panels. Both scenarios are designed to meet a similar electrical demand, with a capacity of approximately 1500 kW. Through simulations using HOMER Pro software, several performance metrics have been evaluated for both systems. The following section will present and discuss the results obtained from these simulations, comparing the two scenarios across multiple performance parameters to assess the technological, financial, and ecological practicability of the proposed hybrid system, and the overall benefits of using a hybrid system as opposed to the traditional diesel only backup. After doing simulation on software, we have got the following results.

- **Electrical Result**

Beyond the overall cost summary, HOMER Pro software offers a comprehensive suite of detailed electrical simulation results, providing a granular view of the system's operational performance. These results go beyond simple cost figures, offering detailed insights into the hourly power generation, consumption, and storage patterns for each component within the simulated system. Specifically, the software provides data on the electrical output from the photovoltaic panels and the natural gas generators (or diesel generator in the baseline case), as well as detailed information about the strength supplied by the utility grid. Furthermore, the electrical results include information regarding the state of charge and energy flow of the battery storage (if present), along with data concerning the strength delivered to the defined electrical load. The detailed analysis of these electrical simulation results offers a deeper understanding of the interplay between the various system components, such as the balance between renewable generation, backup power, and grid electricity. This data also allows us to assess system reliability, identify any potential bottlenecks, inefficiencies, or periods where the system may be underperforming, therefore, facilitating a detailed analysis of the systems as a whole, and providing a valuable understanding of how they perform under different conditions.

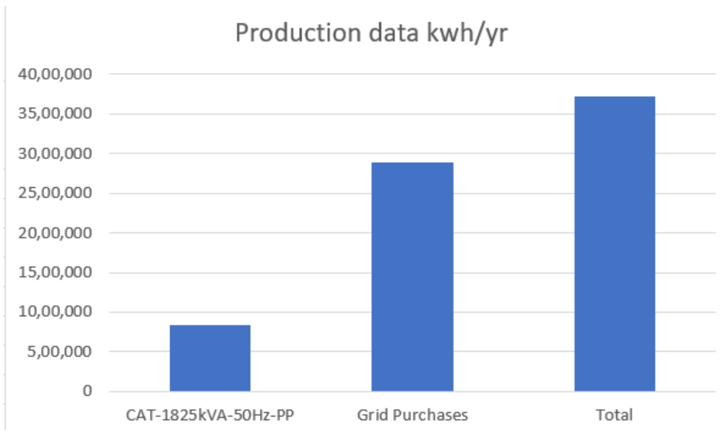

Figure 11: Electricity generation data of Diesel Generator.

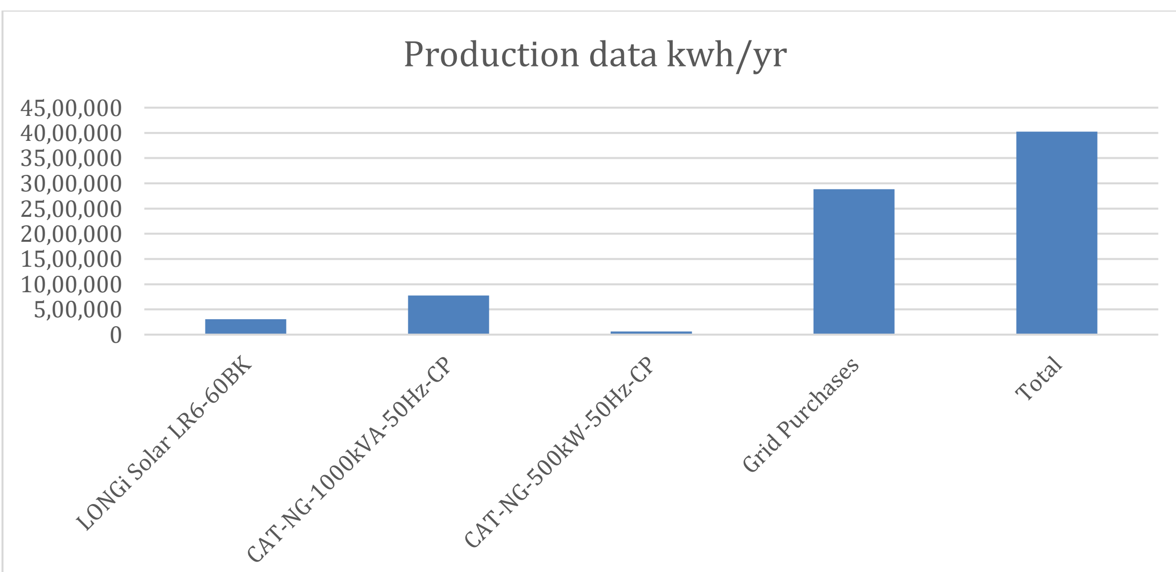

Figure 12: Electricity generation data of Hybrid model.

The above shown figure11 and figure 12 shows the electricity production in kwh/yr. With the help of these figure we can clearly see that our new hybrid model is experiencing a modest increase in electricity i.e 40,25,534 kwh/yr in comparison to 37,27252 kwh/yr that is produced by our base case that is diesel genset.

- **Time Series Plot**

To achieve a thorough comprehension of the electrical consumption patterns within the studied system, this research employs time series plots, which are graphical representations showing how electricity demand fluctuates across different time periods. These plots are crucial because they provide a visual depiction of load behavior, enabling us to identify specific times when electricity demand reaches its peak, as well as periods of low consumption. This level of granularity is essential for the accurate optimization of the hybrid energy system design and operational strategies, as it allows for the identification of key load patterns which determine proper component sizing and energy dispatch strategies. By observing the trend of electricity consumption throughout the day, it enables a more effective management of energy resources. To analyse these trends effectively, time series plots have been generated for two representative days, carefully selected from both a peak and a non-peak demand month. We have chosen one day in July, a month which corresponds to the period of peak electricity demand due to high usage of air conditioning, and one day in October, which represents a period of considerably lower electricity demand. These time series plots, generated using HOMER Pro software, will be utilized to provide detailed insights into the nature of the electrical consumption patterns and its response to variations in seasons and the variability of the system's load. This will allow for a more informed understanding of the overall performance of both the diesel and hybrid systems under different load demands.

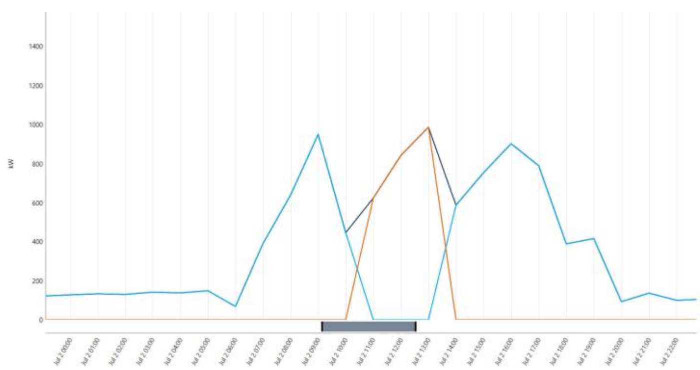

Figure 13: Diesel generator's series data for a July day

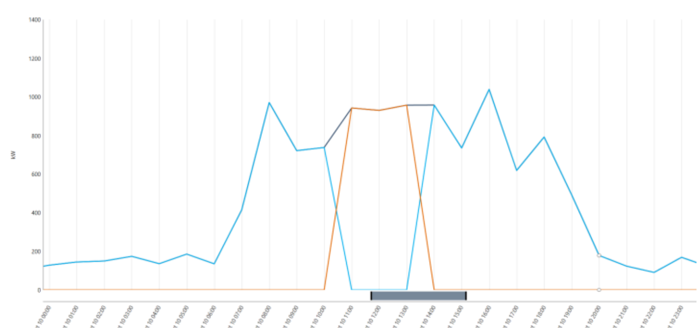

Figure 14: Diesel generator's series data for an october day.

Figures 13 and 14 present time series plots illustrating the interplay between a diesel generator, grid electricity, and total electrical load for two days in both a peak month (July) and a non-peak month (October). The plots reveal that the diesel generator, indicated by the orange line, operates only during periods when grid electricity is unavailable, specifically between 1100hrs and 1300hrs, while the blue line represents grid purchases and the black line depicts the total electrical load. This suggests a backup power system configuration, where the generator serves as a secondary power source. Notably, the month of July exhibits a significantly higher electrical load, highlighting a peak demand period, while October demonstrates more moderate energy consumption. This difference highlights seasonal variations in the institution's power usage. Overall, the data underscores the institution's reliance on the grid as the principal power roots, with the diesel generator functioning as a consistent backup, operating only during a two-hour window each day, and with peak consumption occurring in July.

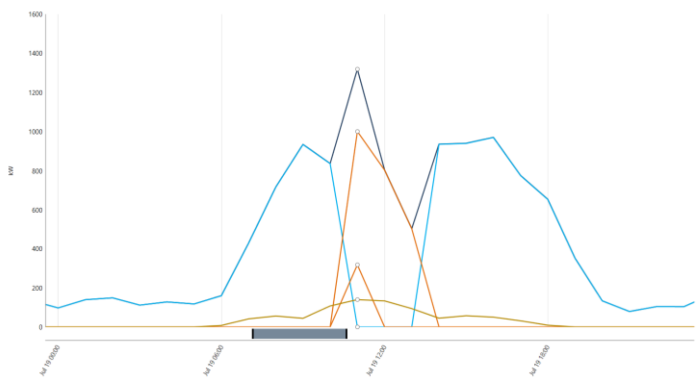

Figure 15: Hybrid model's series data for a July day

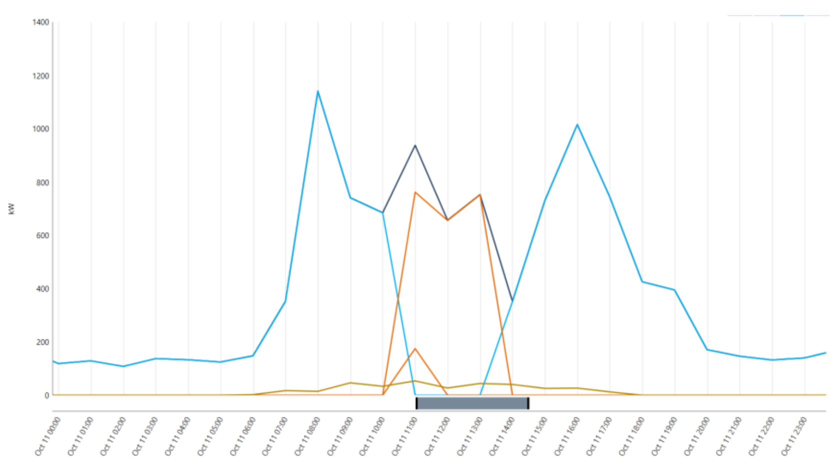

Figure 16: Hybrid model's series data for an october day

Figure 15 and figure 16 present time series plots illustrating the interplay between a hybrid power system, grid electricity, and total electrical load for two days in both a peak month (July) and a non-peak month (October). The plots reveal the operation of a hybrid power system, which encompass a natural gas generator (indicated by the orange line) and photovoltaic solar panels (represented by the brown line), alongside grid electricity (indicated by the blue line). The grey line depicts the total electrical load served. The plots show that the natural gas generator primarily operates only during periods when grid electricity is unavailable, specifically between 1100hrs and 1300hrs. Photovoltaic solar panels generate power during the day, contributing to the total load served. Notably, the month of July exhibits a significantly higher electrical load, highlighting a peak demand period, while October demonstrates more moderate energy consumption. This difference highlights seasonal variations in the institution's power usage. Overall, the data underscores the institution's reliance on the grid as the principal source of power, supplemented by the hybrid system, with the natural gas generator primarily functioning as a backup during a two-hour window each day, and with peak consumption occurring in July.

- **Cost summary**

The summary of cost is generated by HOMER Pro provides a comprehensive financial analysis of a proposed microgrid system. It details the initial capital costs, including component and installation expenses, and outlines recurring operational costs such as fuel, maintenance, grid purchases, and component replacements, all annualized for clarity. These costs are synthesized into key metrics like the NPC, representing the total lifecycle cost, and the LCOE, indicating the typical expense associated with each unit of electricity. Furthermore, the summary includes a cash flow analysis showing annual and cumulative cash flow, the straight forward payback duration, and the Internal Rate of Return (IRR), allowing for evaluation of project profitability and investment viability. This detailed cost breakdown is crucial for comparing different system configurations, making informed decisions about technology choices and system sizing, identifying key cost drivers, and securing project financing by clearly demonstrating economic feasibility and highlighting potential trade-offs.

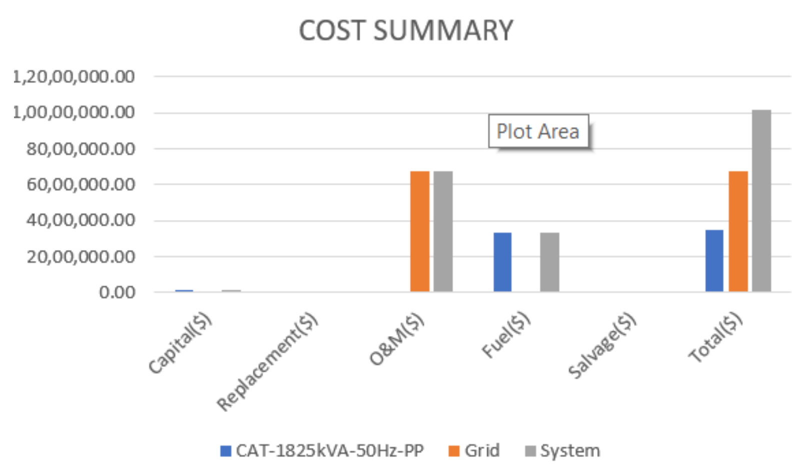

Figure 17: Overview of diesel generator costs.

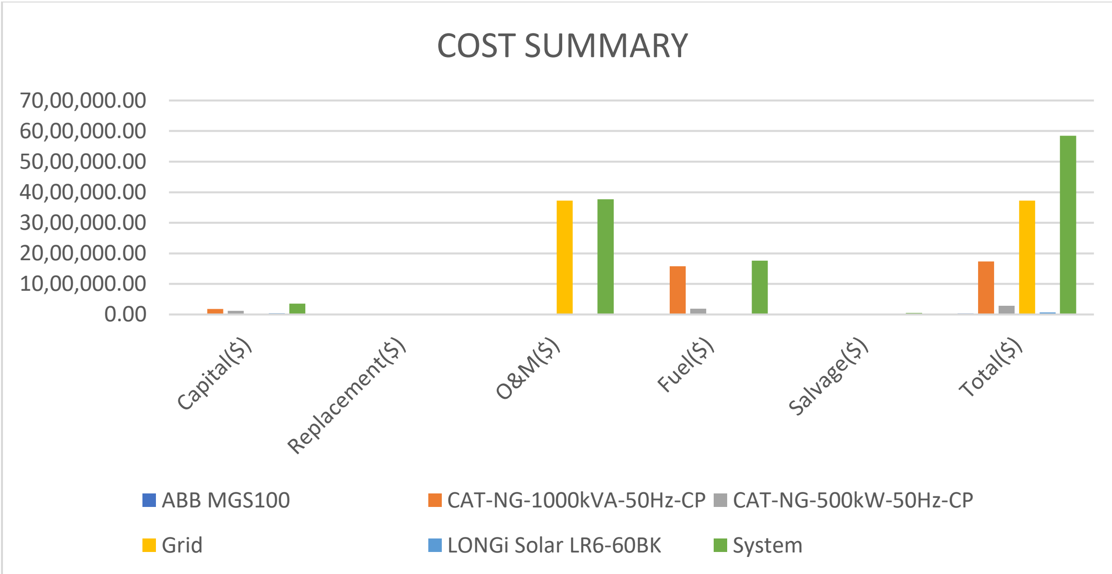

Figure 18: Overview of Hybrid model's costs.

Figure 17 and figure 18, generated from HOMER Pro simulations, provide a compelling cost comparison between two distinct energy system scenarios: a base case relying solely on a diesel generator and a modified case implementing a hybrid model. The base case, characterized by the use of a diesel generator, culminates in a total cost summary of USD $10,181,815.25. In stark contrast, the modified hybrid model, integrating natural gas generation and photovoltaic solar power, achieves a substantially reduced total cost of USD $5,845,200.51. This significant difference in overall project cost is further emphasized by the operational expenses. The diesel generator system incurs annual operating and upkeep costs of USD $1,415.56, while the hybrid model showcases significantly lower maintenance expenditures at USD $701.32. This represents a nearly 50% reduction in operating costs. The results highlight a crucial economic advantage of transitioning from a solely diesel system to a hybrid model, indicating that this approach can dramatically lower the overall project cost. The nearly 50% reduction in total project cost demonstrates an outstanding opportunity for enhanced profitability, presenting a strong case for the adoption of hybrid energy solutions.

- **Fuel Summary**

The fuel summary generated by HOMER Pro provides a detailed analysis of fuel consumption for systems that utilize combustion-based generators, such as diesel or natural gas. This summary typically quantifies the total fuel consumed over the simulation period, often expressed in litres or cubic meters, and breaks down fuel usage on an annual basis. It further specifies the types of fuel consumed, like diesel, natural gas, or propane, along with the total cost incurred for each. In addition, the fuel summary often includes important operational details, such as the average and peak fuel consumption rates, along with the generator's runtime hours. This information is vital for evaluating the operational costs and environmental impact of the chosen energy system. By presenting a clear picture of fuel usage, the fuel summary enables users to assess the economical viability and sustainability of various energy system configurations, allowing for informed decisions about fuel type and consumption optimization.

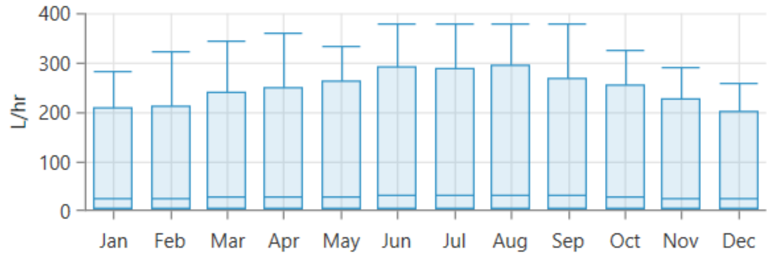

Figure 19: Data about the Diesel generator's monthly gas mileage

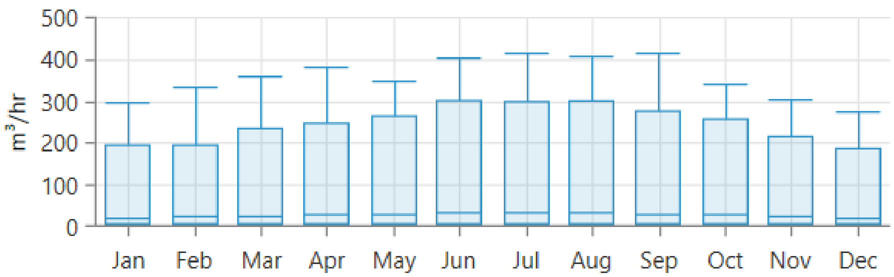

Figure 20: Data about the Natural gas generator's monthly gas mileage

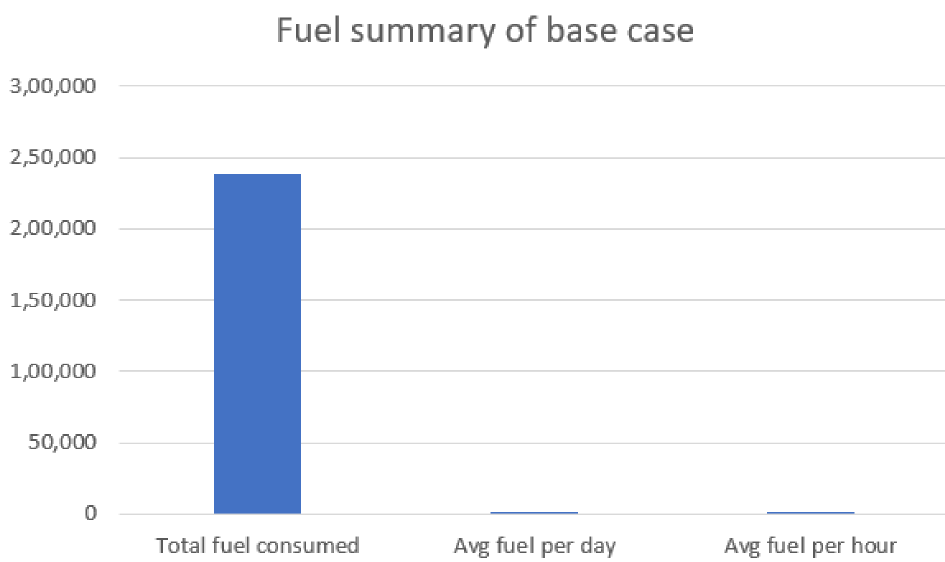

Figure 21: An synopsis of the diesel generator's fuel.

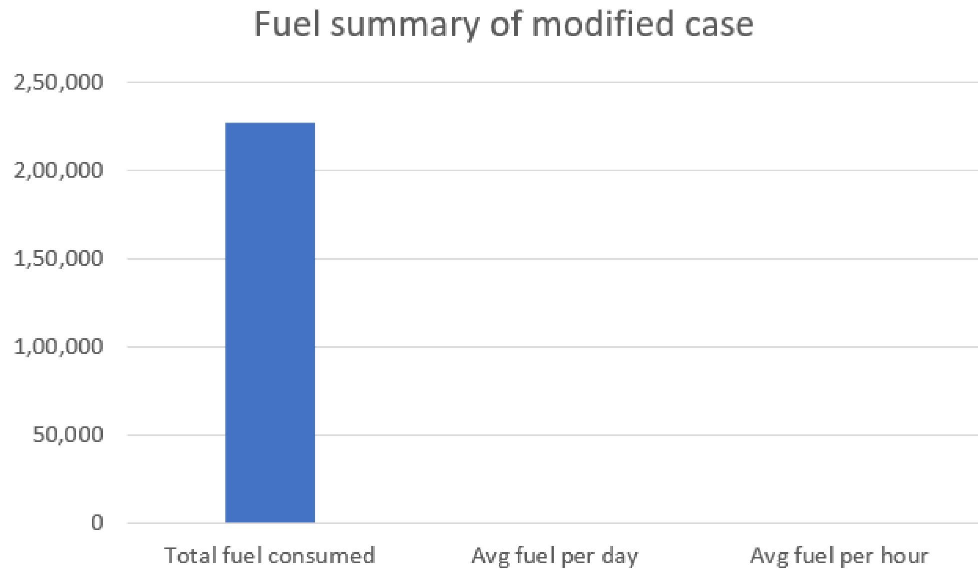

Figure 22: A synopsis of the Hybrid case.

We can clearly see from the above figure 21 and figure 22 that the fuel summary generated by HOMER Pro offers critical insights into fuel consumption, particularly for systems reliant on combustion-based generators. In the scenarios examined, the base case, which uses a diesel generator, consumed a sum of 238,380 m^3 of fuel over the simulation period. Notably, the modified hybrid case, incorporating natural gas and solar PV, demonstrated a reduction in fuel consumption, using 227,489 m^3 – a clear improvement over the base case. This difference underscores the influence of incorporating renewable energy sources alongside a more efficient type of fuel. It's crucial to highlight that while natural gas is a cleaner burning fuel compared to diesel, the reliance on diesel generators, as in the base case, is associated with significant pollution, including the release of greenhouse gases, particulate matter, and other harmful pollutants. The fuel summary, therefore, not only allows for economic analysis but also emphasizes the environmental benefits of transitioning away from diesel power, illustrating how a hybrid system can reduce both fuel consumption and the associated pollution.

- **Environmental Analysis**

HOMER Pro conducts a robust environmental analysis as a core component of its microgrid modeling capabilities, going beyond purely economic assessments to give thorough insight of a project's environmental footprint. This analysis is crucial for evaluating the sustainability of different system configurations, particularly when comparing diesel generators against hybrid models. Diesel gensets are notorious for their substantial contribution to air pollution, emitting significantly higher quantities of several harmful gases compared to a well-optimized hybrid system incorporating renewable energy sources and energy storage. Specifically, diesel generators are major sources of nitrogen oxides (NOx), which are potent precursors to smog and acid rain and are strongly linked to respiratory illnesses and cardiovascular issues. They also produce high levels of particulate matter (PM), both PM2.5 and PM10, fine particles that can pierce deep into the lungs and creates major health problems, including asthma exacerbation and even lung cancer. Furthermore, diesel combustion releases sulfur dioxide (SO2), another contributor to acid rain and a respiratory irritant, as well as carbon monoxide (CO), a toxic gas that reduces oxygen uptake in the blood. In contrast, a hybrid system, particularly one maximizing renewable energy utilization and incorporating battery storage, dramatically reduces the need for diesel generation, consequently leading to substantially lower emissions of all these pollutants. Even when a hybrid design incorporates a smaller diesel generator serves as an alternative power supply, the curtailed operating hours result in a significantly smaller environmental impact than a diesel-only system. HOMER Pro accurately quantifies these emissions, providing detailed yearly projections for CO2, NOx, SO2, and PM, allowing users to make informed decisions that prioritize environmental sustainability. This data empowers project planners to select cleaner, more environmentally responsible energy solutions, aligning with goals of reducing air pollution and promoting a healthier planet. The software's detailed reporting on these pollutants helps in comparing and contrasting different technologies for minimizing their overall impact on the environment.

Table 2: Emission caused by Diesel generator (Kg/yr).

Carbon dioxide	**Carbon Monoxide**	**Unburned hydrocarbons**	**Particulate matter**	**Sulphur Dioxide**	**Nitrogen Oxides**
2,454,282	434	62	62	9473	7198

Table 3: Emission caused by Hybrid model (Kg/yr).

Carbon dioxide	**Carbon Monoxide**	**Unburned hydrocarbons**	**Particulate matter**	**Sulphur Dioxide**	**Nitrogen Oxides**
2,264,225	0	0	0	7,902	3,865

Table 2 and table 3 starkly illustrate the significant difference in emissions between diesel and natural gas generators, revealing the environmental hazards posed by diesel technology. As the data highlights, diesel generators release substantially higher amounts of harmful pollutants, including carbon monoxide, unburned hydrocarbons (HC), particulate matter (PM), sulfur dioxide (SO_2), and nitrogen oxides (NO_x). These emissions contribute directly to severe air pollution, posing a grave threat to both ecological systems and public health. The high levels of NOx contribute to smog formation and acid rain, while particulate matter, particularly PM2.5, deeply penetrates the lungs, causing respiratory and cardiovascular issues. SO2 exacerbates respiratory problems and also contributes to acid rain, and CO is a toxic gas that hinders oxygen absorption in the bloodstream. The sheer volume of these pollutants from diesel combustion makes it a significant contributor to global warming, respiratory illnesses, and other critical health problems, underscoring the urgent need to transition towards cleaner energy solutions, and prioritize renewable energy and battery storage solutions. This stark contrast not only emphasizes the environmental burden of diesel generation but also highlights the importance of adopting cleaner technologies for sustainable development and the well-being of our planet and all living beings. Furthermore, the long-term cumulative impact of these pollutants from diesel generators can lead to irreversible environmental damage and significant societal costs, making the transition to cleaner energy imperative.

A comparative analysis of Table 2 and Table 3 unequivocally demonstrates the superior environmental performance of our modified hybrid model in contrast to the base case scenario, particularly in terms of harmful gas emissions. The data reveals a dramatic reduction in the emission of critical Contaminants such as CO_2, SO_2, and NO_2 with our hybrid model. In stark contrast, the base case, presumably relying heavily on traditional fossil fuel-based generation, exhibits alarmingly high emission levels across the board. This significant disparity underscores the effectiveness of our hybrid approach in mitigating environmental damage. The lower CO2 emissions from the hybrid model directly contribute to reducing the overall carbon footprint, a crucial step in combating climate change. Furthermore, decreased SO2 and NO2 emissions translate to improved air quality, lessening the risks of respiratory problems and other health complications associated with these pollutants. This demonstrates a clear and substantial environmental advantage of our hybrid design, not only in terms of reducing greenhouse gases but also in promoting a healthier and more sustainable environment. Beyond the numbers, this reduction in harmful gases is not just an environmental win; it's a social win, contributing to improved public health and a a much appropriate method for everybody. The base case, with its high emissions, represents a continuation of unsustainable practices that need to be addressed, further emphasizing the need for widespread adoption of our innovative hybrid approach.

- **Sensitivity Analysis of Nominal Discount Rate (NDR)**

The sensitivity analysis of the NDR within HOMER Pro is a critical step in evaluating the long-term economic viability of a microgrid project. By varying the NDR, we can understand how changes in the perceived cost of capital impact the project's profitability and optimal system configuration. In this specific analysis, we've explored the impact of the NDR by examining values ranging from 8% to 12%, incrementing by 2% in each case (8%, 10%, and 12%). This range is representative of typical discount rates used in project evaluations and accounts for the uncertainty around future economic conditions. HOMER Pro allows us to observe how variations in NDR affect key performance metrics like NPC, LCOE, and desirable system sizing and technology choices. A higher NDR typically places more emphasis on near-term costs, potentially favouring lower initial investment options even if they have higher long-term operational expenses. Conversely, a lower NDR gives more weight to long-term benefits and may make systems with higher upfront costs but lower lifetime expenses more attractive, such as those incorporating renewable energy components. By observing the shifts in NPC, we can determine how the overall project cost changes with varying discount rates, giving us a clearer picture of its economic resilience. Likewise, changes in LCOE demonstrate how the cost per unit of energy produced is affected, highlighting which system configuration provides the most economically efficient output at different NDR values. The analysis will allow us to pinpoint the NDR at which particular system designs become more or less cost-effective, thereby aiding in the selection of robust options that remain economically viable across varying economic scenarios. This provides a robust understanding of the project's financial sensitivity to fluctuations in the discount rate and therefore enables us to make informed investment decisions.

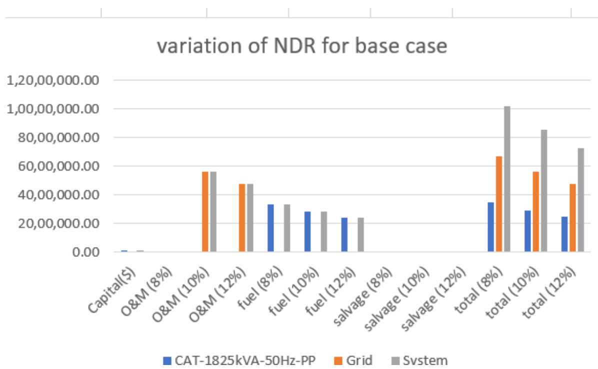

Figure 23: Base case cost summary for NDRs of 12%, 10%, and 8%.

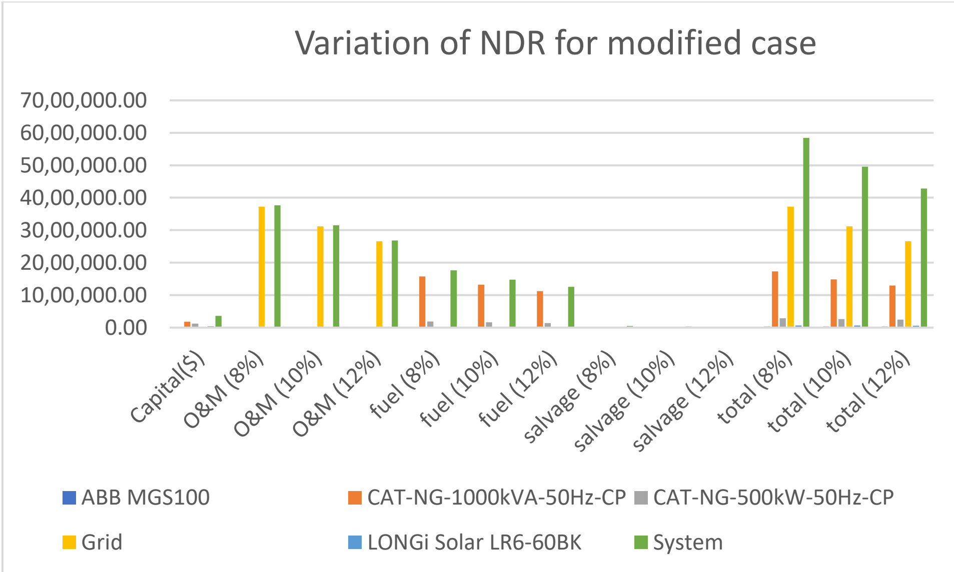

Figure 24: Hybrid case cost summary for NDRs of 12%, 10%, and 8%.

A comparison of the Net Present Costs (NPC) derived from Figure 23 and Figure 24 reveals a compelling economic advantage of the modified case over the base case across different Nominal Discount Rates (NDR). At an NDR of 8%, the base case exhibits a significantly higher NPC of $10,181,815.25, while the modified case demonstrates a much lower NPC of $5,845,200.51. This difference is substantial, indicating a notable reduction in the total lifecycle cost associated with the modified system at this discount rate. Similarly, at an NDR of 12%, the base case shows an NPC of $7,297,728.42, compared to the modified case's NPC of $4,283,849.55. Notably, this represents approximately a 40% reduction in NPC for the modified system, showcasing a consistent pattern of cost savings across varying discount rates. This considerable cost reduction underscores the economic robustness of the modified approach. The consistent and significant decrease in NPC for the modified case, across both the 8% and 12% NDRs, underscores the value of the modifications implemented. These substantial savings, which are close to 40% at the 12% NDR, suggest not just better economics but also a potentially lower risk profile. This enhanced cost-effectiveness at a 12% NDR demonstrates that the modified system offers superior financial viability, even under less favorable economic assumptions, making it a more attractive option for long-term investment and sustainability. The substantial reduction in the NPC of the modified case showcases not only the efficiency gains but also highlights the long-term financial sustainability of incorporating innovative technologies.

- **Sensitivity Analysis of Fuel Price Variation**

The sensitivity analysis of fuel price variation is a crucial aspect of evaluating the long-term financial resilience of our proposed microgrid systems, particularly given the volatility often observed in energy markets. This analysis specifically examines how changes in fuel costs impact the overall project economics, comparing the base case (presumably a diesel-heavy system) against our modified hybrid model. Initially, the diesel fuel cost was set at $1.09/gallon, and we have incremented it by $0.2/gallon intervals up to a maximum of $1.5/gallon. This range allows us to simulate the effect of potential fuel price increases on the cost of operating the diesel-based system. For the modified hybrid system, which incorporates a natural gas generator, we've conducted a parallel analysis. The initial cost of natural gas was $0.6/gallon, and we've incremented it by $0.2/gallon intervals, reaching a maximum of $1.0/gallon. By analyzing the financial outcomes across these escalating fuel prices, we can determine how sensitive each system is to fuel cost fluctuations. This sensitivity analysis directly affects key metrics such as the Net Present Cost (NPC) and the Levelized Cost of Energy (LCOE), allowing us to understand how the financial attractiveness of each system changes under varying fuel market conditions. The diesel price sensitivity provides essential insight into the vulnerability of traditional diesel generators to fuel price increases, while the natural gas price sensitivity will highlight the economic response of the hybrid model to potential fluctuations in natural gas costs. This comparative assessment is essential for selecting the optimal system design that remains financially viable across a range of plausible fuel cost scenarios and offers insights into which system provides the more secure investment over the long term in the face of fluctuating fuel prices. Ultimately, this analysis provides a realistic and comprehensive view of the financial robustness of both systems under varying economic conditions and informs critical decision-making.

Table 4: Diesel price variation effecting other components.

Diesel fuel cost($/yr)	**Net Present Cost NPC($)**	**Cost of Energy COE ($/kWh)**	**Operating price($/L)**
1.09	10.2	0.211	7,78,325
1.3	10.8	0.225	8,28,385
1.5	11.4	0.238	8,76,061

Table 5: Natural gas price variation effecting other components.

Natural gas cost($/yr)	**Net Present Cost NPC($)**	**Cost of Energy COE ($/kWh)**	**Operating price($/m^3)**
0.6	5.56	0.115	4,16,282
0.8	6.12	0.127	4,59,418
1.0	6.68	0.139	5,02,544

The sensitivity analysis of fuel price variation, as demonstrated through Table 4 and Table 5 generated by HOMER Pro, clearly illustrates the superior performance of the hybrid system over the base case across key economic indicators. By incrementing the price of both natural gas and diesel by $0.2/m3 in each step, we've effectively simulated the impact of fluctuating fuel costs on both system designs. The analysis reveals that as fuel prices increase, the hybrid model consistently demonstrates a lower NPC, a lower COE, and lower operating when expenses equated to the base case. This underscores the inherent economic resilience of the hybrid configuration. The base case, presumably relying heavily on diesel generation, exhibits a more pronounced increase in NPC, COE, and operating costs with each increment in diesel price, highlighting its vulnerability to fuel price volatility. Conversely, the hybrid system, benefiting from a greater proportion of renewable energy and potentially less reliance on a fuel-dependent generator, shows a significantly milder response to rising fuel prices. This is primarily due to the reduced fuel consumption of the hybrid system. The substantially lower NPC, COE, and operating costs of the hybrid case across all fuel price points clearly demonstrate its economic advantage and long-term financial sustainability. In essence, the HOMER Pro analysis reveals that even as fuel costs escalate, the hybrid system maintains a more stable and favorable economic profile. This makes it a more attractive and secure investment in a volatile energy market, highlighting its ability to provide reliable and cost-effective power, while simultaneously mitigating the risks associated with fluctuating fuel prices. The results strongly advocate for the implementation of the hybrid model as a more economically viable and resilient option compared to traditional fuel-dependent energy systems.

8.Conclusion

Expanding on the conclusion, our findings underscore the transformative potential of the modified hybrid model in achieving a more efficient and durable sound energy future. Beyond the previously mentioned 50% reduction in harmful emissions and the substantial cost savings demonstrated through lower NPC values across various NDRs, the hybrid model also offers greater resilience to fuel price volatility. The sensitivity analysis clearly shows that the hybrid system's economic performance is less susceptible to fluctuations in both diesel and natural gas costs, providing a more stable and predictable financial outlook compared to the base case. This resilience is crucial in the context of uncertain global energy markets and long-term project planning. Moreover, the hybrid approach, which often incorporates renewable energy sources, advocates for self-sufficiency in energy production and diminishes reliance on fossil fuels, further enhancing its sustainability credentials. The lower operating costs associated with the hybrid system, particularly as fuel prices rise, translate to significant long-term savings and reduced financial risk. The data-driven analysis, supported by HOMER Pro simulations, clearly illustrates the multi-faceted advantages of the hybrid system, encompassing superior environmental performance, enhanced economic viability, and increased resilience to market fluctuations. This comprehensive assessment positions the modified hybrid model not just as a marginally better option, but as a transformative solution that delivers both environmental and economic benefits, making it the clear choice for a responsible and sustainable energy future. The hybrid system offers a powerful combination of reduced environmental impact, enhanced economic returns, and long-term stability making it a far superior choice for energy generation.

Furthermore, beyond the compelling economic and environmental advantages, our analysis indicates that the modified hybrid model is also exceptionally well-suited for practical implementation at our specific project location. The design considerations of the hybrid system, often incorporating modular and scalable components, allow for seamless integration into the existing infrastructure and geographical conditions. This adaptability ensures that the system can be easily deployed and operated at the intended site, without necessitating extensive and costly modifications. The ability to tailor the hybrid system to the unique characteristics of our project location, such as available renewable energy resources and specific energy demand profiles, further optimizes its performance and maximizes its benefits. Unlike more rigid, centralized energy solutions, the modular nature of the hybrid model allows for phased implementation and expansion, reducing upfront capital costs and enabling gradual integration into the existing energy landscape. This flexibility also allows for future upgrades and adaptations as new technologies become available, safeguarding the long-term viability of the project. The hybrid system is not just theoretically superior; its practicality and ease of deployment at our specific project location make it a pragmatic and highly desirable solution for addressing our energy needs in a sustainable and economically sound manner. This seamless fit eliminates potential logistical and operational hurdles, further strengthening the case for adopting the modified hybrid model. The combination of environmental benefits, economic advantages, and ease of deployment at our project site makes the modified hybrid model the optimal solution.

Acknowledgement

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Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

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