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Sustainable Energy Integration in Geothermal Exploration: Conceptual Design and Innovation

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Abstract

Geothermal drilling operations in remote areas are commonly powered by diesel generators, leading to high fuel consumption and substantial carbon emissions. This study explores the integration of a hybrid solar PV–diesel generator system to enhance energy sustainability at a geothermal drilling base camp in Indonesia. The system design considers local renewable energy potential and incorporates integration with existing equipment. The integration strategy is evaluated through a feasibility analysis considering system efficiency, energy yield, and environmental impact. Using Helioscope software for solar simulation and load analysis based on equipment specifications, the results show that the PV system can supply up to 35% of the daytime energy demand, reducing daily carbon emissions by 8% and enhancing generator performance through optimized load sharing. Despite the absence of battery storage, the system demonstrates significant environmental and operational benefits, while also highlighting the potential for further improvements through energy storage integration, smart control systems, and targeted energy management.

1. Introduction

Sustainable energy has increasingly become a central focus in global efforts to address climate change and reduce greenhouse gas emissions [1, 2]. In response, the energy sector has witnessed a growing transition from fossil fuel dependence toward more sustainable and renewable energy solutions [3]. Indonesia, as a tropical archipelago with abundant solar irradiation, possesses an estimated solar energy potential of up to 112,000 GWp. Yet, despite this significant potential, only around 10 MWp has been utilized, underscoring the vast opportunity for integrating renewable energy into diverse sectors of the economy [4]. In recent years, Energy Management Systems (EMS) have gained traction as a means to enhance energy efficiency and facilitate the integration of renewable sources across multiple applications [5]. Notably, EMS has also been successfully implemented in institutional environments such as university campuses, where it fosters stakeholder engagement and structured energy-saving strategies, offering valuable insights that can inform off-grid or remote applications like geothermal drilling operations [6].

Geothermal drilling explorations play a critical role in unlocking sustainable energy resources; however, the exploration phase, particularly the drilling operation,

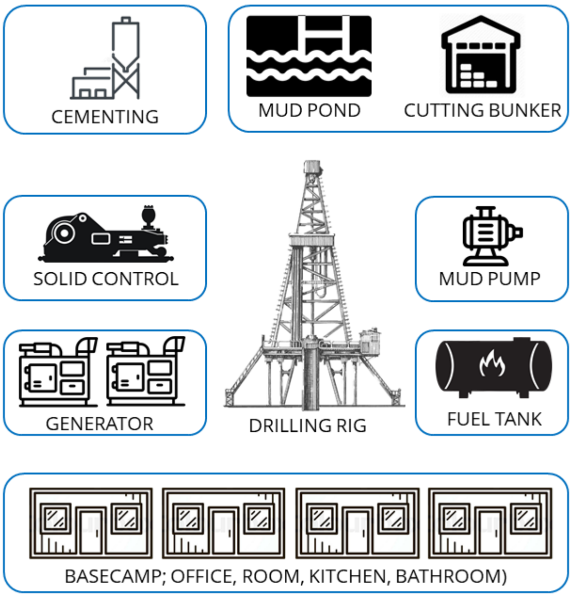

Figure 1. General component of the geothermal drilling rig.

remains heavily reliant on diesel generators. These generators supply power to drilling rigs and supporting facilities, resulting in considerable greenhouse gas emissions and presenting logistical challenges, especially in remote locations [7]. As global efforts intensify to decarbonize the energy sector, integrating renewable energy into geothermal drilling activities has emerged as a promising strategy to reduce environmental impact and enhance operational sustainability.

Previous studies have demonstrated the technical feasibility and economic benefits of hybrid energy systems, particularly those combining solar photovoltaic (PV) technology with diesel generators, in off-grid and remote environments. For instance, in Malaysia, PV–diesel–battery configurations have proven effective in rural electrification projects by reducing diesel fuel consumption and optimizing cost through simulation tools like HOMER Pro® [8]. Similar benefits were observed in Sarawak, where hybrid systems achieved the lowest net present cost (NPC) and cost of electricity (COE) compared to conventional diesel-only solutions [9]. In Algeria, both theoretical and experimental studies have validated the environmental and operational advantages of PV–diesel hybrids in isolated desert regions, citing reduced fuel storage requirements and lower carbon emissions [10]. Furthermore, in the offshore oil and gas sector, hybridization using local sources, solar and wind energy has also been proposed as a strategic approach to enhance sustainability, with studies indicating marked improvements in efficiency and emission reductions when integrated with existing thermoelectric generators [11].

While these studies have demonstrated the potential of hybrid renewable energy systems, particularly PV–diesel combinations, in reducing fuel consumption and emissions in various off-grid applications. However, limited research has focused on their use in geothermal drilling operations, especially during the exploration phase. This study addresses that gap by proposing and evaluating a hybrid solar PV–diesel system specifically designed for a geothermal drilling base camp, operating without battery storage. The novelty of this research lies in its real-time load-sharing configuration, which reduces generator dependency during peak solar hours and eliminates the need for energy storage, making it more practical for remote, high-demand operations. The main objective of this study is to assess the technical feasibility and environmental benefits of this system through solar resource analysis, hybrid system design, and emission impact evaluation, ultimately offering a scalable solution for decarbonizing geothermal exploration sites.

2. Materials and Methods

This study investigates the feasibility and environmental benefits of integrating a hybrid solar photovoltaic (PV)–diesel generator system into the energy infrastructure of a geothermal drilling base camp where the general layout of drilling rig component shown in Figure 1. While previous research has largely emphasized stand-alone PV systems or PV configurations supported by battery storage, there is limited exploration of hybrid systems that employ real-time load-sharing between photovoltaic arrays and diesel generators. This is particularly relevant in the context of geothermal drilling base camps, which are typically temporary, located in remote areas, and heavily reliant on diesel fuel. These camps have

Photovoltaic (PV) [12]

Diesel Generator [13]

Figure 2. Hybrid material.

consistently high energy demands to support critical operations such as cold storage, communication, lighting, and other auxiliary systems. Despite the practical importance of such applications, current literature lacks tailored solutions that address the unique operational and logistical challenges of these environments, highlighting a significant gap in both academic research and field implementation.

The experimental set-up was designed to reflect the real-world operational conditions typically found at remote geothermal drilling locations, focusing on the practical application of solar energy in reducing fossil fuel dependency during exploration drilling activities. The research site selected for this study is located in Brebes, Central Java, Indonesia, where geothermal potential has been identified and drilling activities are commonly supported by temporary, off-grid base camps.

The base camp's energy demands were first assessed through a systematic load identification process. This approach involved surveying all energy-consuming equipment operating at the camp, including but not limited to lighting systems, heating, ventilation, and air conditioning (HVAC) units, refrigerators, water heaters, communications equipment, computers, and kitchen appliances. Each appliance's rated power was recorded in kilowatts (kW), and its average operational duration per day was measured in hours. The total daily energy consumption (in kilowatt-hours, kWh) for each device was calculated using the Equation 1 [14, 15]:

$$E_i = P_i \, x \, t_i \qquad (1)$$

where, E_i is the daily energy consumption of appliance (kWh), P_i is the power rating of appliance (kW), and t_i is the daily operational duration of appliance (hours). This method provided a detailed load profile for the base camp and formed the basis for sizing the solar PV system and diesel generator in the proposed hybrid configuration

To simulate the solar energy potential of the site, the Helioscope software platform was employed. Helioscope is a widely recognized, cloud-based simulation tool that enables advanced modelling of photovoltaic systems by integrating meteorological data, component specifications, and spatial layouts [16]. It allows for the simulation of solar irradiance profiles based on historical satellite-derived weather data and provides functionality for 3D terrain and obstruction modelling, which is particularly valuable in sites with complex topography or infrastructure such as drilling rigs. Shading analysis was conducted using the tool's built-in ray tracing engine to identify potential energy losses from obstructions. Helioscope provided estimates for daily and annual electricity generation, system efficiency, and the Capacity Utilization Factor (CUF), which indicates the actual output compared to the theoretical maximum under ideal conditions [17]. Additionally, a shading map was generated to visually assess areas where solar access was limited, informing optimal placement of solar arrays [18].

The design methodology for the hybrid integration system between solar photovoltaic (PV) and diesel generator, as shown in Figure 2, employs a load-sharing approach without utilizing batteries for energy storage [19]. In this configuration, the energy generated by the solar PV system is directly distributed to meet power demands during daylight operational hours [20]. The generator is sized to operate at 100% load during night-time, while during the day, it functions at a reduced capacity in accordance with the energy contribution from the solar PV system [9].

The fundamental principles for ensuring that this hybrid configuration operates reliably include system stability and efficiency [21]. First, selecting the appropriate generator capacity is crucial, as it must be aligned with the daily load profile and the energy potential generated by the PV system [22]. The use of smart inverters with advanced power management technology facilitates automatic adjustments in load-sharing between the generator and solar PV, thereby minimizing fluctuations

Table 1. Material data specification.

Material	Generator	PV
Type	Diesel Engine	Monocrystalline
Rated Power	160,000 (W)	500 (Wp)
Dimension	3760 x 1410 x 1900 (mm)	2187 x 1102 (mm)
Weight	2,679 (kg)	30.1 (kg)

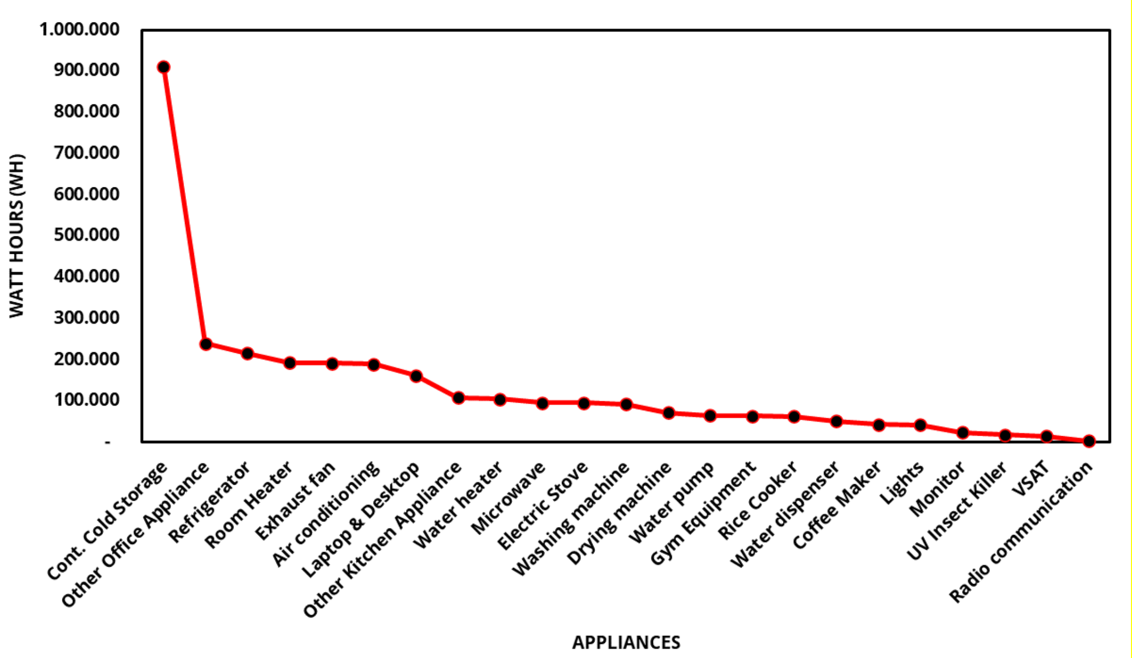

Figure 3. Identification of estimate energy consumption.

and ensuring a stable energy supply [23, 24]. The main materials for considerations in this configuration are specified in Table 1.

Moreover, real-time monitoring of the performance of both energy sources is essential to optimize energy utilization and maintain system efficiency. Evaluating the availability of roof space to ensure sufficient area for solar panels is also critical, as it directly affects energy output. Accurate calculations of estimated energy output based on sunlight exposure, which is anticipated to require 4 to 5 hours to reach peak wattage, must be performed diligently [25]. By considering reductions in emissions and fuel consumption, this method aims to achieve a sustainable and efficient solution for meeting the energy needs of the base camp while minimizing the carbon footprint of industrial operations.

To evaluate the environmental impact of the proposed hybrid system, diesel fuel consumption was estimated under both conventional (diesel-only) and hybrid scenarios. The corresponding greenhouse gas emissions were calculated using a methodology recommended by the Intergovernmental Panel on Climate Change (IPCC), which is widely adopted by member countries under the United Nations Framework Convention on Climate Change (UNFCCC) [26, 27]. The conversion factor from diesel fuel to carbon emissions is 2.68 kg CO_2 per liter of diesel [26, 28], based on the assumption that all carbon in diesel fuel is converted into carbon dioxide (CO_2) during combustion. This method represents a standard approach for calculating the carbon footprint resulting from the use of fossil fuels, as outlined by various international environmental protocols. The formula used to calculate carbon emissions is as follows:

$$E_{CO2} = FC \ x \ EF \tag{2}$$

where, E_{CO2} represents the total carbon emission (kg CO_2) , FC denotes the fuel consumption (liters), and the EF is the emission factor for diesel fuel taken as 2.68 kg CO_2/liter.

3. Results and Discussion

Energy consumption data were collected for all electrical appliances in the base camp using manufacturer specifications. The results, shown in Figure 3, represent the estimated daily energy use of each appliance. The analysis reveals that the container cold storage unit is the most energy-intensive component of the base camp, consuming approximately 900,000 Wh per day. This high demand is attributed to its continuous 24-hour operation, which is essential for preserving temperature-sensitive materials and supplies. Additional high-

Table 2. Potential of solar PV system.

Description	Results
System Size (DC)	260.19 kW
System Size (AC)	250.00 kW
Annual Production	362.25 MWh
Solar Modules (pcs)	441
Inverters (pcs)	2

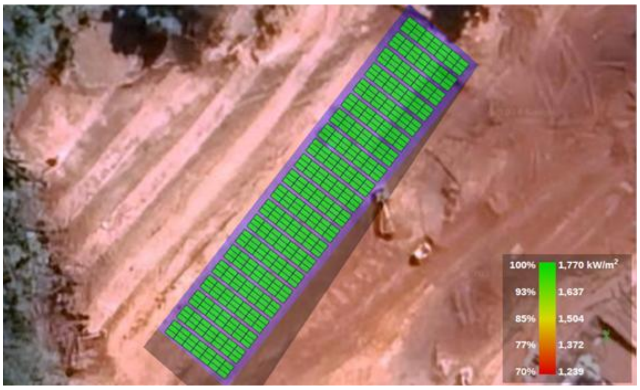

Figure 4. Shading heatmap results.

consumption devices include office-related equipment such as network servers and desktops, as well as residential-grade refrigerators, all of which operate for extended durations throughout the day. This assessment provides a foundational estimate of the total daily energy demand, essential for sizing the proposed solar PV system. Identifying high-demand appliances helps guide strategic integration of renewable energy to reduce diesel reliance and associated carbon emissions.

Following the energy demand assessment, solar energy potential in the area shall be determined. Based on the simulation of solar energy potential in the base camp area using Helioscope software, a comprehensive overview of the solar radiation availability that can be harnessed to support geothermal drilling operations was obtained. The potential of the solar PV system is presented in Table 2. This analysis includes the visualization of a shading heatmap, which identifies areas affected by shadows from surrounding environment. The shading heatmap, generated using Helioscope simulation software, reveals that approximately 100% of the base camp area receives optimal sunlight exposure, as illustrated in Figure 4. This indicates minimal shading interference, making the location highly suitable for effective solar PV deployment.

The simulation results of energy production potential over one year also include a calculated Capacity Utilization Factor (CUF) of 12%, as illustrated in Figure 5. This value represents the ratio of actual energy output to the maximum possible output under ideal conditions. While the CUF aligns with average performance levels for fixed-tilt PV systems in tropical environments, it also indicates opportunities for enhancement through improved system design. The total annual energy production from the proposed system is estimated at 362.25 MWh, based on a system size of 260.19 kW DC and 250.00 kW AC, utilizing 441 monocrystalline modules and two inverters. These results highlight the capacity of the system to significantly offset fossil fuel consumption, especially during peak solar generation hours.

Based on the previously conducted load assessment which identified the major energy-consuming appliances and quantified the total daily energy demand at the base camp, combined with the estimated solar energy potential of the site, a tailored hybrid energy system was developed to meet operational requirements. This system is designed to maximize the utilization of renewable energy sources while ensuring a stable and reliable power supply for critical base camp operations.

The proposed hybrid energy system effectively integrates solar photovoltaic (PV) technology with a diesel generator to enhance energy efficiency in geothermal drilling base camp operations can be seen in Figure 6. With a total installed capacity of 250,000 Wp, the PV system is designed to contribute approximately 35% of the total energy demand during peak solar radiation hours, specifically from 10:00 AM to 3:00 PM. This energy supports essential base camp loads, including lighting, heating, ventilation, and air conditioning (HVAC) systems, as well as communication and office equipment. The integration of solar PV reduces the dependency on diesel generators during daylight hours, leading to lower fuel consumption and emissions. A smart inverter with an automated switching mechanism ensures seamless power transition between the PV system and the generator. During periods of maximum solar energy generation, the inverter prioritizes solar PV as the primary energy source, allowing the diesel generator to operate at a reduced load of 65%, thereby improving overall system efficiency.

The reduction in generator load during daytime operation enhances fuel efficiency and prolongs the operational lifespan of the equipment. Running the generator at optimal load conditions minimizes fuel wastage typically associated with low-load operation. This load-sharing strategy leads to measurable reductions in diesel consumption, directly contributing to lower greenhouse gas emissions. Preliminary estimations based on fuel consumption rates and standard emission factors indicate a significant decrease in CO_2 emissions when incorporating solar PV into the energy mix. The hybrid system also improves operational sustainability by

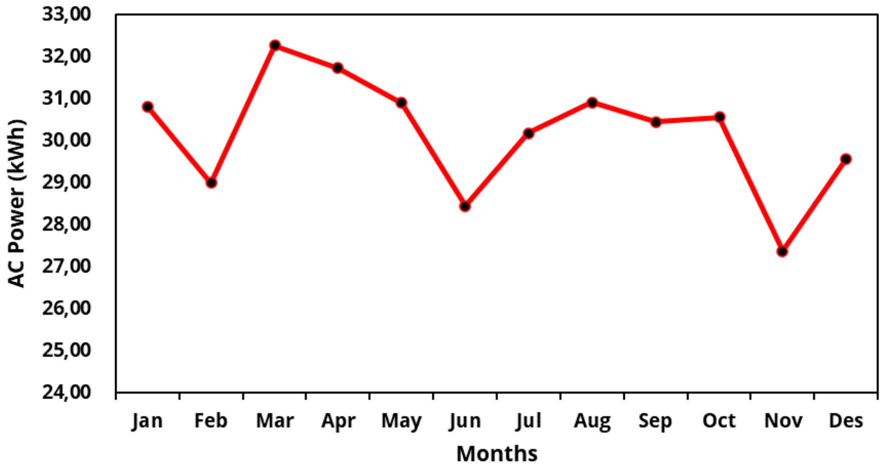

Figure 5. Potential production throughout the year.

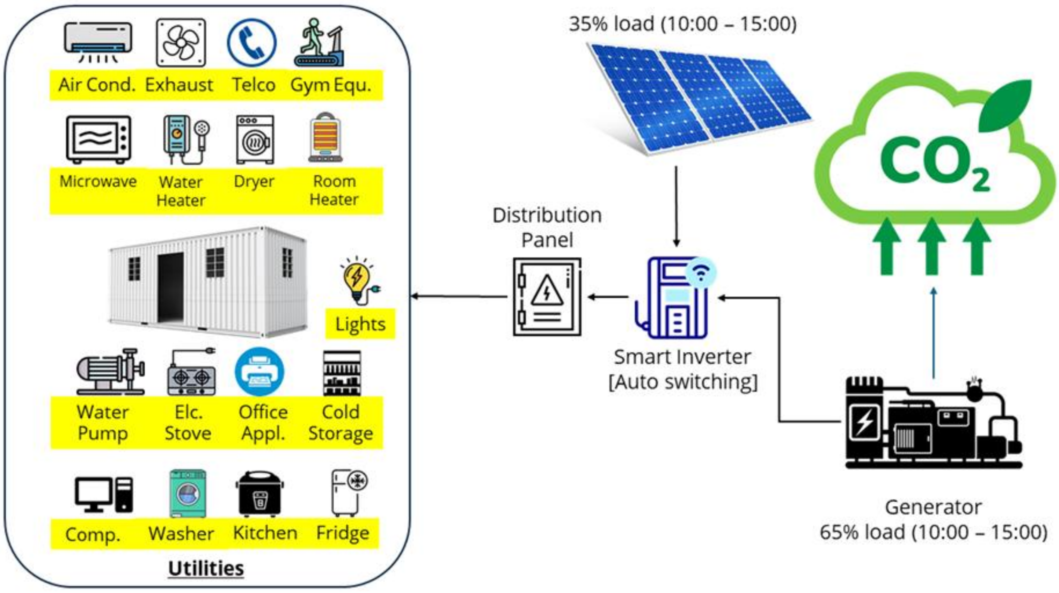

Figure 6. Proposed configuration system.

mitigating the environmental footprint of continuous drilling activities.

Ensuring system reliability is a key consideration in hybrid energy integration, particularly in managing fluctuations in solar irradiance. While this system does not incorporate battery storage, real-time monitoring and adaptive control mechanisms optimize PV utilization and maintain energy stability. Additionally, site-specific assessments of solar potential and available installation space influence the feasibility of maximizing solar energy harvesting. Future scalability options, such as the potential integration of battery storage or an expansion of PV capacity, could further enhance energy autonomy and sustainability. The findings of this study highlight the feasibility of hybrid solar PV and diesel generator configurations as an effective strategy for reducing fossil fuel dependency and promoting energy resilience in geothermal drilling operations.

Following the development of the hybrid energy system configuration, its environmental impact was assessed to evaluate the potential reduction in carbon emissions resulting from decreased diesel generator usage. This evaluation focuses on quantifying the difference in fuel consumption and associated CO_2 emissions between the conventional diesel-only setup and the proposed hybrid configuration. Based on the existing system, the total daily energy consumption at the drilling rig base camp reaches 3,072 kWh. All primary and secondary utility needs are supplied by a 200 kVA diesel generator operating continuously for 24 hours each day. This generator consumes approximately 56 liters of fuel per hour, resulting in a total daily fuel consumption of 1,344 liters. Utilizing the carbon emission factor for diesel,

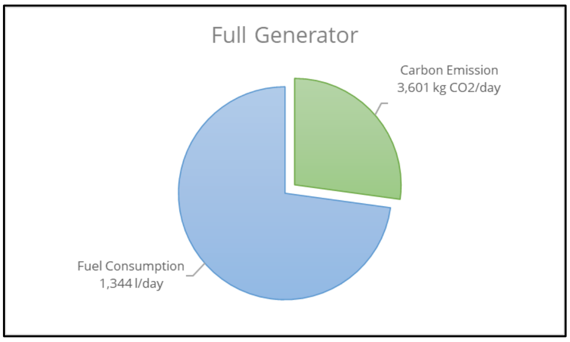

Figure 7. Carbon emission before integration.

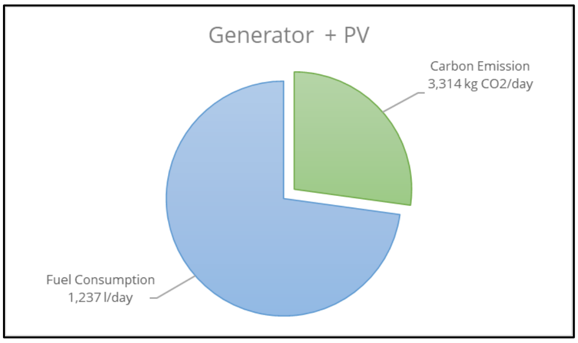

Figure 8. Carbon emission after integration.

which is 2.68 kg CO_2 per liter of fuel, the total carbon emissions generated from the operation of the diesel generator amount to 3,601 kg CO_2e per day. This figure reflects the significant contribution of carbon emissions from diesel generator use in supporting drilling operations at the base camp.

Based on the results presented in Figure 7 and Figure 8, there is a clear reduction in carbon emissions following the integration of the solar photovoltaic (PV) system with the diesel generator. Prior to this integration, carbon emissions were recorded at 3,601 kg CO_2 per day, accompanied by a fuel consumption of 1,344 liters per day. After the implementation of the PV system, carbon emissions decreased to 3,314 kg CO_2 per day, with fuel consumption also reduced to 1,237 liters per day. This reduction indicates that the hybrid system combining solar PV and diesel generators can effectively lower carbon emissions by approximately 8% per day, thereby contributing directly to decarbonization efforts within the geothermal drilling base camp operations.

The findings of this study offer several important insights into the technical feasibility and environmental benefits of integrating a hybrid solar PV–diesel generator system in geothermal drilling base camp operations. One of the primary considerations is the distribution of energy consumption within the base camp. The load analysis reveals that cold storage, HVAC systems, and office appliances are among the highest contributors to daily energy demand. This highlights an urgent need for targeted energy efficiency interventions, such as optimizing thermal insulation for refrigerated storage, implementing programmable thermostats for HVAC systems, and promoting low-power electronics. Addressing these high-load appliances is crucial not only to reduce baseline energy consumption but also to maximize the effectiveness of renewable integration [25].

In terms of solar energy availability, simulation results using Helioscope confirm that the site has strong solar potential, with minimal shading and favorable irradiance profiles during peak hours. The calculated capacity utilization factor (CUF) of 12% aligns with typical fixed-tilt PV system performance in tropical regions, yet suggests room for optimization [29]. Enhancing panel orientation, increasing tilt angles, or employing single-axis tracking systems could yield higher solar harvests. Furthermore, the land availability for PV deployment, typically not a constraint in base camp setups—supports the scalability of such systems for larger capacity installations in the future [16].

The integration of solar PV into the existing diesel-based infrastructure demonstrates substantial operational advantages [30]. By offsetting approximately 35% of the daytime load, the hybrid system reduces generator runtime and allows the diesel engine to operate at more efficient load levels. This not only results in lower fuel consumption and extended generator lifespan but also offers operational cost savings and improved energy security [31], key concerns in remote drilling operations [32]. However, the absence of battery storage in the current configuration limits the ability to store excess solar energy, meaning that solar generation is only usable in real time [33]. Although this trade-off improves system simplicity and reduces capital costs, future research should explore the technical and economic viability of incorporating battery storage to further enhance energy autonomy and smooth out solar intermittency [34].

Environmental performance is another critical outcome of this study. The implementation of the hybrid system leads to an 8% daily reduction in CO_2 emissions, demonstrating its potential as a decarbonization strategy for geothermal exploration [35]. While this reduction is meaningful, it also points to additional opportunities for improvement. such as increasing PV capacity, integrating other renewable sources or applying demand-side management strategies [36]. Assessing cumulative emission reductions over the system's operational lifetime would provide a more comprehensive understanding of its contribution to climate goals and carbon neutrality in geothermal development [37].

Finally, the outcomes of this study underscore the need for continued exploration into hybrid energy system optimization in geothermal and other remote industrial settings. Integrating predictive algorithms for load forecasting, real-time performance monitoring, and adaptive energy management strategies could further enhance operational efficiency [38]. Expanding the scope of future studies to include different geographical locations, geological conditions, and drilling rig configurations would also contribute to the generalizability and scalability of the proposed solution [39].

4. Conclusions

This study demonstrates the technical and environmental feasibility of a battery-free hybrid solar PV–diesel generator system to reduce fossil fuel reliance in geothermal drilling base camps, directly addressing the research objective. The system successfully offset up to 35% of daytime energy demand, resulting in an 8% reduction in daily CO_2 emissions and improved generator performance. Dominant energy loads—primarily container cold storage, HVAC, and office equipment—highlight the critical need for targeted energy management strategies. An unexpected yet important finding is that even without storage, substantial emission reductions are achievable through intelligent inverter-based load control. The novelty of this work lies in its focus on real-world, off-grid geothermal applications using a simplified, cost-conscious design. However, the absence of energy storage limits nighttime renewable utilization, and discrepancies between theoretical solar potential and actual system capacity utilization suggest the need for refined panel orientation or tracking systems. To fully optimize such hybrid systems, future research should explore battery integration, advanced control algorithms, and demand-side management. The integration of battery storage systems and AI-based control mechanisms may further enhance system performance and reliability.

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