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A Hybrid Photovoltaic/Diesel System for Off-Grid Applications in Lubumbashi, DR Congo: A HOMER Pro Modeling and Optimization Study

Ilunga Kajila Rice [1], Hanhua Zhu [1,*], Cunquan Zhang [2] and Arnauld Robert Tapa [3]

[1] School of Naval Architecture, Ocean and Energy Power Engineering, Wuhan University of Technology, Wuhan 430063, China; riceilunga_kajila@whut.edu.cn
[2] School of Energy and Power Engineering, Wuhan University of Technology, Wuhan 430063, China; zhangcqbox@whut.edu.cn
[3] Institute for Advanced Study, Shenzhen University, Shenzhen 518060, China; tapaarnauld@szu.edu.cn
* Correspondence: hh.zhu@163.com

Abstract: In Lubumbashi, the capital of Haut Katanga in the Democratic Republic of the Congo (DR Congo), diesel power plants are a common source of electricity. The need to utilize local renewable energy sources in DR Congo has increased due to the unreliability of the state grid and the rising cost of running diesel generators. Solar photovoltaic (PV) panels and batteries, in particular, have recently recorded significant price drops. It is important for operators and suppliers to choose optimal generators together with a renewable energy system to lessen the energy deficit. Diesel generators are still widely used in DRC, but their efficiency pales in contrast to that of more recent power facilities. Consuming fossil fuels results in high expenses for upkeep and operation, in addition to severe environmental damage. This study assessed the feasibility of using local weather and technical data to evaluate the efficiency of a diesel power plant hybridized with a PV system. The Hybrid Optimization Model for Electric Renewable (HOMER) simulations suggest that the hybrid system schedule is preferable due to its many economic and environmental advantages for the local community and its inhabitants. The promotion of such a hybrid system may encourage the sustainable economic development of a stable source of electricity for the Congo Region.

Keywords: hybrid power system; diesel generator; PV system; simulation; carbon emissions

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1. Introduction

Several countries in sub-Saharan Africa could rely on renewable energy to meet their growing electricity needs in a sustainable, cost-effective, and environmentally friendly manner. The Democratic Republic of the Congo (DRC) is located in a very high *sun belt* with insolation values between 3.6 and 4.8 kW/m^2/day [1,2], making the construction of photovoltaic systems and the usage of thermal solar systems economically viable. Diesel fuel for diesel generators is the key component of the power plant, accounting for roughly 80% of the overall energy expenses in off-grid and bad-grid regions [1]. Diesel generator operators and owners must therefore assess design configuration, operation and maintenance, energy efficiency, greenhouse gas emissions, and equipment lifespan [3]. In addition to assisting in the fight against climate change (particularly through the reduction in greenhouse gas emissions from electricity and heat generation), PV power is poised to play a pivotal role in the imminent transition from a centralized to distributed generation scheme. In fact, thanks to the easily scalable small modular units on which PV power relies, microgrid implementation is now seen as viable and, in some cases, the best available solution. This is because PV power is able to improve energy system reliability, decrease CO_2 emissions and electricity generation costs, generate new employment opportunities, and optimize the utilization of local resources that are undervalued in rural areas [3,4].

Diesel power plants, also known as engine–generators, are a more practical option for providing electricity to rural areas [4]. However, a low load factor (below 40–50% of the generator's rated capacity) is inefficient for diesel generators and can reduce the generator's lifespan and increase maintenance expenses. Furthermore, incomplete combustion and carbon deposits on the cylinder walls induce premature engine wear due to low combustion temperatures during periods of operation with light loads [4–7]. Thus, a hybrid diesel–PV power system (integration of a PV plant with a diesel generator as a backup system for reducing the PV component sizes) supplies generally intermittent power from the PV plant to decrease the operating time of generators and reduce fuel consumption, operation and maintenance, and replacement costs. The generators only run during periods when a minimum load is exceeded [7–9].

Lubumbashi, the capital of Haut Katanga in DR Congo, relies heavily on diesel power plants due to frequent outages and a lack of access to the national grid. The diesel power plant efficiency is lower than that of newer plants, with expensive maintenance and operational expenses. To confirm the widespread applicability of converting pure diesel generators in Lubumbashi into such hybrid systems, we analyzed the effects of incorporating a photovoltaic (PV) battery and a diesel generator and then simulated the system's performance. The data were analyzed to show how a hybrid diesel–PV power system will be most efficient for grid operators and diesel generators to reduce emissions and also estimated how much carbon emissions can be cut down by incorporating solar PV into the power distribution network. Adopting a hybrid PV/battery/diesel power system will aid sustainable and economic growth in the Congo Region. Using the HOMER Pro software [10], we were able to establish the optimal hybridization of the power system for this specific geographic region in East Africa.

The Need for Renewable Energy in Developing Countries

Electricity can be produced by using renewable energy systems, which include solar, wind, hydropower, and biomass technology. These innovations are crucial in offering the most effective energy resource alternatives. Each nation has its own unique renewable energy development potential. Several options exist for tapping into a nation's renewable energy supply. Due to regional differences in the components that go into energy production in countries such as DR Congo, regions with wind potential may provide additional support for this sector through regional industrial policy strategies (IPs) that complement national policies [11,12]. A study conducted by Mohamed et al. [13] revealed that the price of energy in Libya is significantly lower than in other countries. Payback periods for local investments are typically longer. Wang et al. [14] assessed the renewable energy potential of China and India, and their findings are informing efforts to curb rising energy consumption in both countries. They established a link between rising incomes, higher energy demands, and technological advances (lower energy intensities). A recent study by Strielkowski et al. [15] indicates that transitioning to renewable energy is a crucial aspect of Russia's development. Support for tourism-led growth was reported by Tang et al. [16] in India, however; the energy-led growth was found to be untrue. Interestingly, Bhattacharya et al. [17] studied how the utilization of renewable energy affected economies. Using renewable energy sources increases the GDP for 57% of the studied countries when considering long-run production elasticities. Access to locations that are difficult to wire for electricity, such as rural and remote areas, can be achieved by the use of alternative means [11,18,19]. The best performance of renewable energy sources can also be achieved by applying these technologies in metropolitan settings. Urban and rural areas have very distinct patterns of electricity use. The tariff function, real GDP, gas prices, and rural/urban population distributions have all been proposed as potential energy demand functions. Equally, due to the greater population and accessibility of electrical infrastructure, electricity consumption is substantially higher in urbanized areas than in rural areas [11].

At a yearly growth rate of 3.2%, the anticipated population of DR Congo in 2023 is 97,080,879 million people; and it is anticipated to reach 200 million by the year 2050 [20].

Lubumbashi region in DRC is situated in the southern part of the country. Energy needs, solar radiation, and fuel costs were all taken into account while deciding on the hybrid diesel–PV–battery system. The results were analyzed based on investment potential, resource availability, location suitability, and emission rates. Due to their fast-growing economies and populations, developing countries have become increasingly responsible for a rising proportion of global carbon emissions in recent years. The renewable energy sector in these nations, particularly solar, wind, and hydro power, has enormous untapped potential [2,21]. Setting renewable energy targets, giving financial incentives for the development of renewable energy, and establishing carbon pricing mechanisms are just a few of the policies that many developing countries, such as DR Congo, are enacting to stimulate the adoption of renewable energy and reduce carbon emissions. To further aid developing countries in making the switch to renewable energy sources and cutting their carbon emissions, financial and technical assistance are being championed by diverse stakeholders.

An integrated method for optimizing the economic dispatch and commitment (EDC) of hybrid thermosolar with power generating systems was reported by Papazis [22], utilizing matrix mathematics and MATLAB programming in northwest Greece. After analyzing data from seven different thermal units, the researchers found that carbon dioxide emissions were reduced when the units were not run at full capacity. However, fuel usage and, eventually, fuel cost impacted the operational cost of generating adequate energy via concentrated solar power (CSP) in the power generation system. Thus, the benefits of producing greener energy with a smaller carbon footprint still have to contend with the issue of operating at the lowest possible cost. New energy generation technologies, such as zero-carbon power plants that reduce carbon dioxide emissions and the effects of global warming, are being developed as part of the transition to sustainable energy systems [23,24].

Iñigo-Labairu et al. [25] simulated various hybrid power generation configurations on seven different sites by modifying their design parameters within specific boundary conditions to find the optimal configurations for both optimized systems and the operational cost of using renewable energy sources (RES) coupled with conventional power generation systems. The study concluded that PV–CSP hybrid power plants were the most efficient and cost the least to run compared to alternative configurations such as standalone CSP plants and PV–battery energy system storage (BESS). Additionally, their approach utilized a techno-economic analysis with the levelized cost of electricity (LCOE) and the percentage of electricity consumption during the night as independent variables. By projecting each configuration into 2030, Iñigo-Labairu et al. [25] were able to assess the impact of the system costs. The analysis concluded that hybrid power plants were more cost-effective than pure CSP plant layouts, mostly as a consequence of the decreased cost of PV power. Hybrid PV–CSP power plants had a lower LCOE than PV–BESS for the night power fractions between 20 and 25%, corresponding to roughly 4–5 h storage capacity.

Basheer et al. [10] analyzed integrating hybrid energy into Pakistan's cement industry to cut down on greenhouse gas (GHG) emissions from the sector's present reliance on thermal power while keeping cement production overhead costs low. The HOMER Pro software [10] was used to perform the hybrid energy models (HEMs). They collected primary data for analysis of five cement plants from four different types of HEMs: (1) a photovoltaic (PV), hydrogen tank, converter, electrolyzer, and fuel cell; (2) a single diesel generator; (3) a PV–converter–battery framework; and (4) a diesel generator and PV converter. A 0% GHG was only possible with a PV, hydrogen tank, converter hybrid system, or a diesel–PV–converter hybrid system. In the event of a power loss, however, the purchase of a single diesel generator remains the most cost-effective solution in terms of both installation and ongoing maintenance.

In off-grid isolated places and many underdeveloped countries, regular blackouts mean that diesel generators remain the most popular choice for emergency electricity backup. Burning hydrocarbons releases numerous pollutants into the air, some of which are harmful to humans and others of which have a significant impact on the ecosystem [14,26–28]. Switching to greener forms of energy could end the global warming crisis. Making the switch to renewable energy sources may be a significant step in lowering atmospheric CO_2 concentrations [13,17,23,26,29]. Integration of various energy sources into the power generating and distribution network is necessary to facilitate the growth and development of HESs [9,26,30,31]. Hybrid arrangements offer a number of advantages, including lower operational costs, lower carbon dioxide emissions, and a longer service life for diesel generators (DG). The fuel consumption of the diesel generator can be reduced by 90% when a solar hybrid system is integrated with it. Power plant running and maintenance costs can be reduced by 90%, and reduced fossil fuel consumption resulting in a 30–75% reduction in carbon footprint [12,24,26,29,31–33]. In the case of conventional energy sources, power outages were reported to decrease by 50% [12,29,33,34]. Reduced usage means longer intervals between diesel generator replacements [24].

Some of the potential gains from installing a hybrid diesel–PV power system in Lubumbashi, DR Congo, include hybrid systems that offer greater energy security since they require less reliance on any one power source, such as diesel generators, which are susceptible to variations in fuel prices and supply. The adoption of a hybrid system may boost the availability of electricity in this rural area and may be connected to the grid. Benefiting from steadily falling prices, PV systems are cheaper to install and operate than conventional power plants in the study area. Eventually, this hybrid system may also save money on gas. Greenhouse gas emissions and air pollution are reduced when PV systems are used, which is good for the environment and the health of residents.

However, there may be obstacles to the adoption of a hybrid diesel–PV power system in Lubumbashi, DR Congo. The initial capital needed to get a hybrid system up and running might be substantial. The system necessitates routine upkeep and repairs, which can be challenging to undertake due to a lack of technical experience and infrastructure. PV system output can be diminished by environmental factors such as clouds and storms, making them less reliable. Storage capacity is limited in PV systems, which can reduce system dependability, especially during times of low sunlight. Optimal performance from a hybrid system demands thorough planning and design due to the complexity of system integration. Overall, a hybrid diesel–PV power system in Lubumbashi, DR Congo, could provide a cost-effective and reliable option for improving access to energy in the region; however, there are a number of considerations prior to the adoption and implementation of such a renewable energy program.

2. Methodology

The Hybrid Optimization of Multiple Energy Resources (HOMER Pro) software was used to assess the best strategies for implementing renewable energy in the Lubumbashi area of the Democratic Republic of Congo. System emissions, necessary investment, payback duration, net present cost, and current value for each scenario were estimated by simulation, which was broken down into three stages: specifying input data, simulating each scenario, and analyzing outputs.

2.1. The Homer Pro Software

The viability of renewable energy systems in terms of their technical, economic, and environmental aspects can be simulated using different tools [11,35,36]. The HOMER Pro software has become increasingly popular among researchers in recent years as a tool for simulating different kinds of microgrids. To model and optimize the design of hybrid renewable energy systems, the HOMER Pro software was employed in this study. The tool assists engineers, researchers, and energy experts in determining the ideal configurations for a given set of restrictions, as well as evaluating the technical and economic feasibility of various hybrid power systems [18,19,37]. Multiple renewable energy sources (such as solar, wind, and hydro) can be modeled in a single HOMER Pro simulation, as can conventional generators, batteries, and other energy storage devices. Systems with load management and other energy-saving components can be modeled as well. System sizing, cost and financial analysis, sensitivity analysis, and system optimization are among the analyses we run with the HOMER Pro software for this study (Table 1).

Table 1. Review of recent studies on microgrid configurations using HOMER Pro.

Configuration	Investment Analysis	References
• Diesel generator with battery (DG + b) • Fixed PV module with battery (FPV + b) • Dual-Axis PV module tracker system with battery (DPV + b) • Fixed PV module and wind turbine with battery (FPV + WT + b) • Dual-Axis PV module tracker and wind turbine with battery (DPV + WT + b) • 2 KW Pico-hydropower with battery (HP + b)	The optimal layouts with the lowest net present cost (NPC) and cost of energy (COE) are (FPV + b) followed by HP + b. The NPC and COE costs of FPV + b and HP + b are 17.45%, 16.45%, 15.9%, and 15.5% lower than those of diesel generators with a battery (DG + b), respectively.	[31]
• PV system only • Wind turbine only • A hybrid system of PV and wind turbine	The PV technology achieved the best option as it has the lowest initial cost per kW of USD 1150/kW, an LCOE of USD 0.051/kW, and a simple payback period of 18.6 years.	[10]
• 100% solar PV–battery system • 100% solar PV–P2H2P system • 100% solar PV and hybrid battery–P2H2P system	The most cost-effective scenario is a hydrogen-battery hybrid energy storage system. It revealed that it has the lowest NPC and COE over the 25-year project lifespan. In comparison to a battery-based storage system, it uses less excess energy.	[38]
• Diesel-only • Hybrid diesel/PV without battery • Hybrid PV/diesel with battery system	The design of PV/diesel with a battery system is the recommended solution. The system's initial capital cost and total NPC are USD 2,260,000 and USD 16,661,344, respectively. The COE of the system is USD 0.377/kW. The design can save 14.3% of diesel fuel consumption, and a carbon footprint can be saved. The most expensive design in electricity generation is diesel-only, while the second most expensive is hybrid diesel–PV without a battery system.	[30]
• Hybrid PV/diesel with battery system. • Hybrid diesel/PV without battery • PV/battery system • Diesel/battery System	PV/diesel with a battery system configuration is the ideal recommended hybrid system. The system's initial capital cost and total NPC are USD 8336.13 and USD 5794.18, respectively. With a levelized COE of USD 0.1090/kW. Under the given local climate condition, the diesel generator can remain unused throughout the whole year (0% of fuel consumption). This hybrid system can emit lower to no emissions all year round compared to other configurations.	Current study

Different configurations of microgrids can be simulated, compared, and evaluated with HOMER Pro. In this study, the HOMER Pro software was used to model a hybrid off-grid energy system and compare it with a diesel generator-only system under varying load conditions in the study area. During the planning of the system layout, it is important to factor in a number of different parameters. As part of the simulation, HOMER Pro evaluates the hybrid system's ability to meet the hybrid electric and thermal needs. By calculating the energy entering and leaving each part of the hybrid system, the system can ascertain whether or not a given setup is practical. The hybrid system's electric and thermal demands are compared using modeling outputs from HOMER Pro. Whether or not a proposed configuration is workable is determined by calculating the energy input and output of each part of the hybrid system [38].

The diesel generator, solar PV, batteries, and converter were included in this study. This hybrid system can be utilized to support the electricity demand in the specified area and to perform a study of the solar potential to mitigate CO_2 emissions based on the chosen location in DR Congo. The economic feasibility of a system, including its operating hours, lifetime, and component attributes, as well as the system's annual carbon footprint, were all taken into account by HOMER Pro. The total net present cost (NPC) of the system, factoring in the annual real interest rate, was also considered as a representation of the system's overall life-cycle expenses. Considering the linear depreciation factor used by HOMER Pro, the recoverable value is proportionate to the amount of time left before the asset is considered completely unusable. We considered how variables such as component pricing and availability may affect the final product.

2.2. Input Data and Assumptions Used in the Analyses

By feeding the GPS coordinates into HOMER Pro, we modeled the solar resources using the surface meteorology and solar energy database. The average radiation followed a consistent pattern, and the annual radiation was greater than 4 $kW/m^2/day$ [38] so that the solar panels could reliably deliver electricity. In calculating the annual radiation readings, the peak month was found to be July in Lubumbashi.

2.3. Simulation of Each Scenario

The data was then imported into the HOMER Pro, where it was simulated using different equations. With the help of the latitude, radiation value, and month of the year, HOMER Pro was able to determine the clearness index, which is specified by equation (1). Atmospheric solar radiation at the Earth's surface was given by equation (2) in HOMER Pro as a solar radiation meter. After that, the HOMER Pro was used to determine the NPC using equation (3). As shown in equation (4) [29–31], the CRF is a measure of how much of an investment is returned. Salvage value, payback duration, and present value were calculated for each system with the help of the HOMER Pro software using equations (5–7). The annual cost of the system components was calculated by factoring in a number of different costs (including initial purchase price, cost per mile driven, cost per gallon of fuel, and cost to scrap the system).

$$K_T = \frac{H_{ave}}{H_{o,ave}} \tag{1}$$

H_{ave} = the Earth's monthly average radiation on its horizontal surface $\left[\frac{kW}{\frac{m^2}{day}}\right]$.

$H_{o,ave}$ = extraterrestrial horizontal radiation—radiation on a horizontal surface at the top of the Earth's atmosphere.

We used the equation below to calculate the intensity of solar radiation at the top of the Earth's atmosphere with HOMER Pro.

$$G_{on} = G_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right) \tag{2}$$

where the variables denote the following:

G_{sc} = solar constant [1.367 kW/m^2];

n = the day of the year [a number between 1 and 365].

2.4. Further Analysis of the Outputs

In order to recommend the best system for the hybrid renewable energy system in the Lubumbashi region of DR Congo, we ran simulations for each scenario and examined the payback period, components cost, current value, and net present cost based on each configuration.

$$C_{NPC} = \frac{C_{ann,tot}}{CRF\left(i, R_{proj}\right)} \tag{3}$$

where the variables denote the following:

$C_{ann,\,tot}$ = the total annual cost;

i = the annual real interest rate (discount rate);
R_{proj} = the project's lifetime;
CRF = the capital recovery factor.

$$\mathrm{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (4)$$

where i is the annual real interest rate, and N is the estimated number of years.

Using HOMER Pro, we calculated the value of each component at the end of the project lifetime (salvage value (S)) using the following equation [20,32]:

$$S = C_{rep}\frac{R_{rem}}{R_{comp}} \quad (5)$$

where S = salvage value; C_{rep} = cost of component replacement; R_{rem} = remaining life of the component; and R_{comp} = overall lifetime of the component.

$$\text{Payback period} = \frac{\text{Initial investment of asset/original cost}}{\text{Cash inflows}} \quad (6)$$

$$\text{Present worth} = \text{NPC base system} - \text{NPC current System} \quad (7)$$

2.5. Levelized Cost of Energy

The levelized cost of energy (LCOE) takes into account not only the estimated total expenses of operating a power plant but also its capital expenditures, costs of servicing, and return on investment. It also takes into consideration the expenses of operation and maintenance, the cost of fuel, as well as costs associated with CO_2 and other forms of emissions.

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n}\frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}} \quad (8)$$

where E_t = annual energy generation; F_t = yearly fuel cost; I_t = yearly investment; M_t = yearly operational and maintenance cost; and r = discount rate. Homer Pro's optimization depends on the generator being run 24/7/365, which is not always the case for private owners or grid operators. When optimizing the system, the majority of hybrid systems rotate between their various energy sources, with the renewable energy system taking precedence and the generator being the last configuration option [38].

2.6. Emissions

There were six main pollutants that were estimated within HOMER Pro: carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (UHC), particulate matter (PM), sulfur dioxide (SO_2), and nitrogen oxides (NO_X).

2.7. Modeling and Simulating the Hybrid Diesel–PV Power System

The components that make up the hybrid system are the diesel generator, PV array that houses the load, solar modules, converter, and batteries that were used for energy storage. The power that is produced by the diesel generator is delivered to the AC bus, where it is transformed into DC power before being distributed to the DC bus. The fuel cell and solar PV that together constitute the DC power source are directly connected to the DC. The batteries are used to store the excess electricity during the day so that it can be utilized as the primary source of power throughout the night. The HOMER Pro graphical representation of the system block as it appears in the simulation is displayed below (Figure 1).

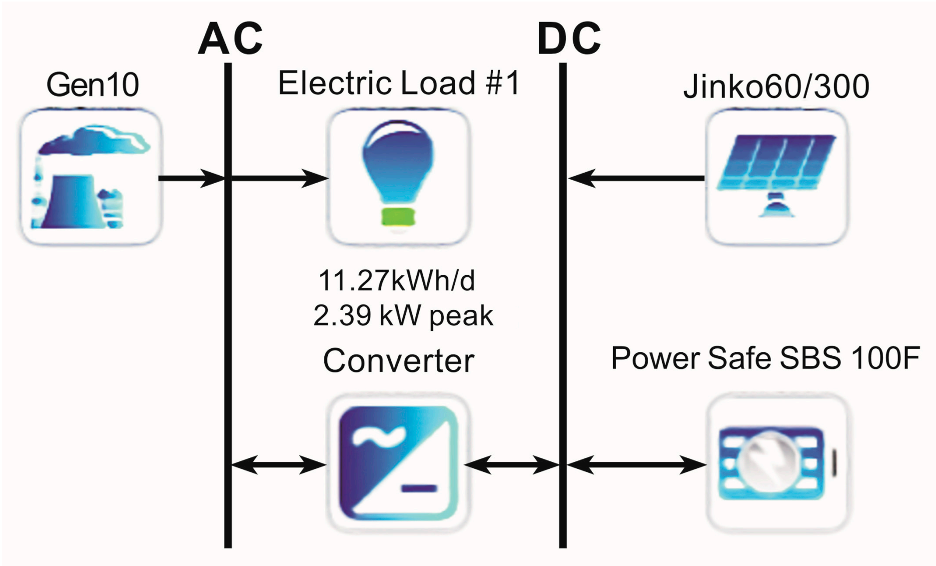

Figure 1. Schema of the simulated system.

Table 2 provides a comprehensive summary of the simulation design and serves as a valuable resource for understanding the experimental methodology used in the study.

Table 2. Scenarios and configurations.

Scenario	System Configuration	Limitations
PV provides the required energy to the power system and stores excess energy in the battery for the night and low radiation use. The generator starts only at the start of the complete discharge of the battery and has absolutely no solar radiation resource.	PV Battery Diesel Generator	Within the HOMER Pro system, the scenario for the selected location of DR Congo has the diesel generator out of work due to the vast available solar radiation on a daily basis and in all seasons.
Diesel generator only. In this scenario, power is fully provided by the diesel generator, which is used to make the comparison with the first scenario.	10 Kva Diesel Generator	HOMER assumes that the diesel generator is on 24/7 throughout the whole year. This configuration gives a perspective that all diesel Gen owners emit the same amount of CO_2 daily and simultaneously.

2.8. Input Parameters

The modeling procedure in HOMER Pro primarily makes use of three input factors, which are the equipment cost, load needs, and power cost. These parameters are variable in that they change depending on the locations and configurations. Due to the fact that the simulation was conducted in the same location and under the same conditions as the real-world scenario, the costs associated with both the available configurations have been standardized in this instance. Table 3 provides a rundown of the prices associated with each of the individual components.

Table 3. Summary of input cost for simulation results.

System Component	Capacity (kW/Unit)	Capital Cost, USD	Replacement Cost (USD)	Maintenance Cost
Diesel	10	1000	400	20
Battery	1	81.80	81.80	0
Solar PV	0.3	82.75	30	5
Converter	3	439	300	0

3. Results and Discussion

3.1. Technical Performance of the Hybrid Diesel–PV Power System

In conducting system comparisons, we utilized multiple LCOEs, energy production, solar PV system's energy contribution, solar PV adoption, fuel usage, fuel savings percentage, and carbon emissions. The LCOE for the two different configurations is based on the defined load of 11.27 kW/d (2.39 kW peak). The solar PV–battery systems are cost-competitive for a 2.39 kW load on a lifetime basis. The LCOE for the 2.39 kW load was estimated at USD 0.08857/kW compared to USD 0.1090/kW for diesel hybrid PV and battery systems (Table 4).

Table 4. Levelized COE (USD/kW) for diesel–PV–battery and PV–battery systems.

Configuration	LCOE (USD)	Load (kW/d)
Diesel–PV–Battery	0.11	11.27
PV–Battery	0.89	11.27

However, operating a solar PV–battery system alone has significant capital costs; meanwhile, diesel generators require lower initial capital costs and are more accessible to consumers in developing countries. The cost of fuel for operating a single generator in Lubumbashi city is estimated at USD 1.34/l. If the operational cost of diesel generators and costs of components such as the battery could be reduced, there would be a lower LCOE. The price of batteries, a major component of the PV system costs, is rapidly decreasing, majorly driven by the global quest for a green energy transition. This will facilitate lower LCOEs for a PV system.

Use of the HOMER Pro optimized system results in the daily energy output of the hybrid system based on the solar irradiation resources in Lubumbashi (Table 5). The system was simulated to run for 24 h, from 1:00 A.M. to 12:00 A.M., when there is minimal or no sun exposure. The design results indicate that PV and battery supply is available from 7:00 to 22:00 P.M., with solar radiation peaking between noon and 2:00 P.M. The total daily solar irradiation in Lubumbashi is 2.5 kW with PV having a daily energy output of 2.3 kW while the battery system supplies 55.22 kW of energy (Table 5). A detailed analysis covering a span of 7 days, providing valuable insights into Lubumbashi's energy consumption dynamics during the peak month, july is shown in Figure 2.

Table 5. A summary of the overall daily load output for seven days in the peak month of July.

Time of the Day	Load Power (kW)	PV Power (kW)	Battery Power (kW)	Gen Power (kW)
1	0.06	0	0.05	0
2	0.09	0	0.1	0
3	0.12	0	0.16	0
4	0.4	0	0.24	0
5	0.59	0	0.52	0
6	0.48	0.08	0.93	0
7	0.42	0.2	1.21	0
8	0.36	0.28	1.37	0
9	0.42	0.45	1.43	0
10	0.4	0.05	1.41	0
11	0.55	0.02	1.66	0
12	0.69	0.38	2.03	0
13	0.48	0.33	2.25	0
14	0.35	0.12	2.37	0
15	0.21	0.06	2.53	0
16	0.36	0.17	2.62	0
17	0.46	0.1	2.75	0
18	1.06	0.06	3.03	0
19	0.91	0	3.71	0
20	0.66	0	4.34	0
21	0.49	0	4.8	0
22	0.22	0	5.13	0
23	0.17	0	5.26	0
24	0.08	0	5.32	0
Mean	10.03	2.3	55.22	

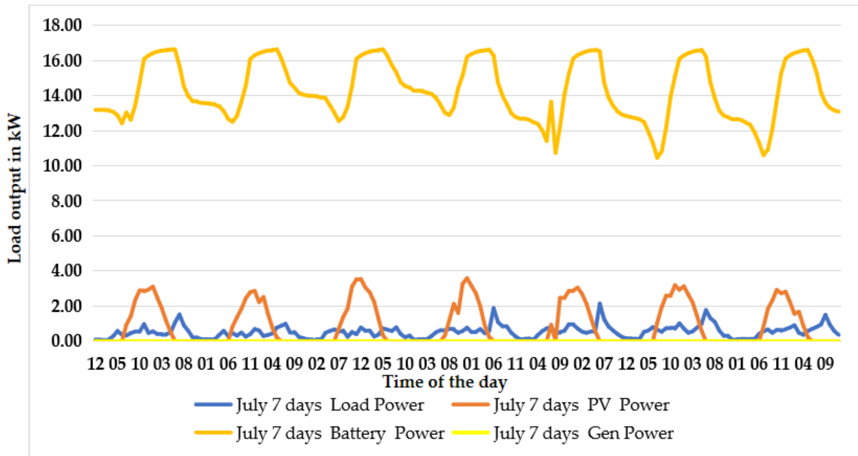

Figure 2. Overall daily load output for seven days in the peak month of July.

The yearly energy consumption and percentage of the solar PV system after optimization indicate that the solar PV system produces 100% of the energy, which is

7331 kW per year (Table 6). The excess energy produced was 2939 kW per year, equaling 40.1% of the yearly AC consumption capacity of 4113 kW/yr. With the optimized 11.27 kW/day diesel–solar PV hybrid system proposed, the renewable penetration rate reaches 2013kW/yr (Table 6). Additionally, the constant non-operation of the diesel generator under the proposed system could lead to fuel conservation, reduced carbon emissions, and increased renewable energy penetration (Table 6).

Table 6. Estimated energy production by solar PV System.

Production	Quantity (kW/yr)	Unit (%)
PV system	7331	100
Diesel gen	0	0
AC primary load	4113	100
DC primary load	0	0
Deferrable load	0	0
Excess electricity	2939	40.1
Unmet electric load	0	0
Capacity shortage	0	0
Renewable fraction	100	
Max. Renew. Penetration	2013	

NB: Where kW/yr refers to kilowatts per year.

3.2. Economic Analysis of the System, including Costs and Savings

The economic analysis consists of the capital costs, replacement costs, and operations and maintenance costs of the diesel–PV–battery optimized system were performed based on various optimization configurations using the HOMER Pro software. The costs for the solar PV–battery system and the diesel–PV–battery system are summarized in Figure 3.

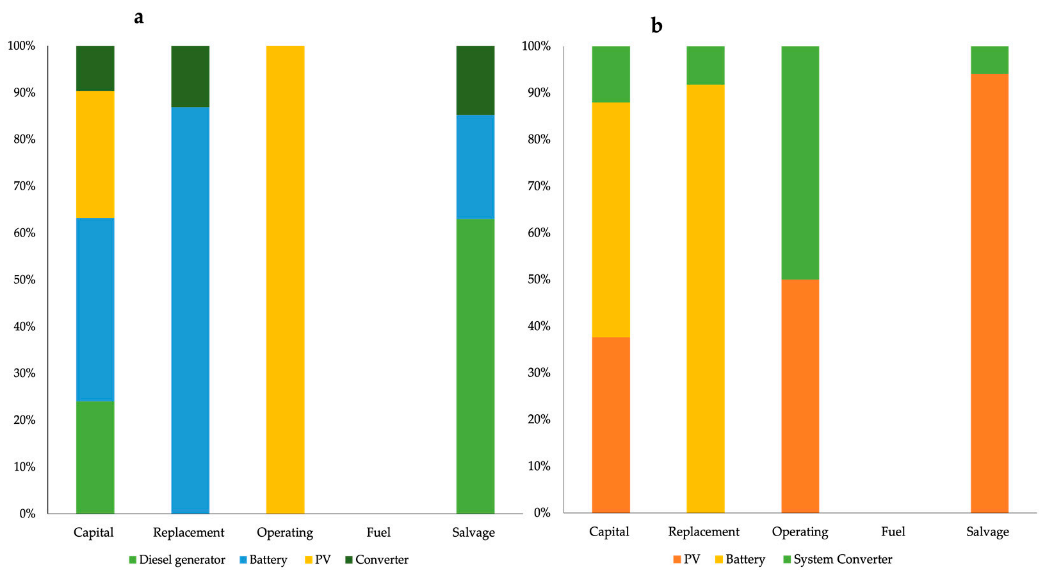

Figure 3. (**a**) Financial analysis of diesel–PV–battery optimized system. (**b**) Cost analysis for PV–battery optimized system.

Our financial analyses of the diesel–PV–battery and PV–battery optimized systems were based on the performance of the hybrid power plant during a specific week of July, which was selected during the dry season due to its even power demand. The operation of the diesel generator is triggered when the battery charge reaches 25% during periods of increased demand. The diesel generator will not only supply power to customers but also recharge the battery. The generator operates for approximately 2.5 h during the night and is supplemented by the PV generator during the day to recharge the battery. The diesel generator operates at an efficiency of 82–92% of its nominal output, which results in improved efficiency and decreased fuel consumption from 4500 to 1600 L per month, thus a reduction of 64% (Figure 4). This makes the hybrid power system a cost-effective solution for residents in the Lubumbashi region, where centralized power supply is expensive.

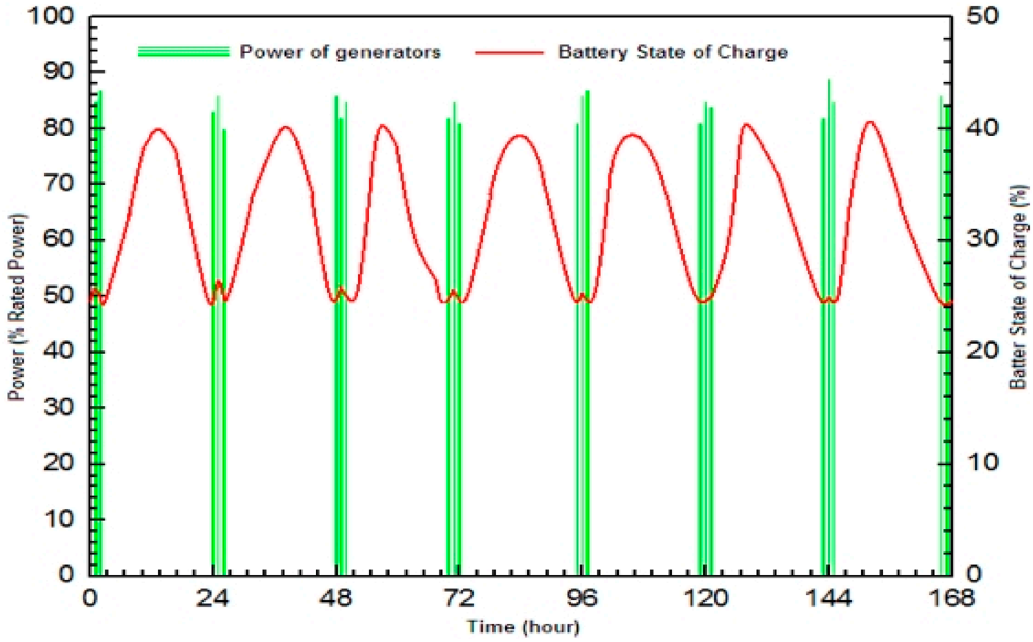

Figure 4. Power of generators and battery state of charge for a week in July.

3.3. Emissions

The emissions were collected from the simulated results of HOMER Pro software to determine the amount of each type of pollutant produced yearly by the power system in kg/yr. The emissions that were produced for each of the systems in the simulation results indicate that carbon dioxide was the most dominant pollutant, with 4014 kg/yr for the diesel and battery configurations, followed by nitrogen oxides, with 34.5 kg/yr and 30.4 kg/yr for the carbon monoxide (Figure 5a). The emission results from the diesel–solar PV–converter system with no energy storage indicate a 24,730 kg/yr carbon dioxide yearly value, followed by the nitrogen oxides, with 213 kg/yr and 187 kg/yr of carbon monoxide (Figure 5b). However, when considering the diesel–PV–battery configuration, there was no emission recorded (Figure 5c). This is due to the fact that HOMER Pro primarily optimizes and promotes the use of renewable energy sources in microgrids.

Given our simulation's emphasis on renewable energy, the diesel, solar photovoltaic, and battery configuration produced zero annual emissions. However, we generated sufficient emission data by simulating alternative setups. Thus, a combined solar PV and diesel Gen system generated 24,730 kg of CO_2 per annum, compared to the 43,711 kg/yr emitted only by the diesel generator. Subsequently, the combined output of a diesel and battery setup was 4014 kg of CO_2 per year. Consequently, increasing the percentage of renewable energy in the electricity grid lessens the burden on the environment, generates a quicker financial payback, and saves money, which is consistent with [14,30]. The NPC and CO_2 emission of the renewable energy system were sensitive to the availability of renewable energy resources and cost of capital, as evidenced by the sensitivity analysis. Our findings suggest that the optimized solar PV–battery hybrid system may be preferable to either a diesel and solar PV or a hybrid diesel and battery system in the Lubumbashi region, both in terms of energy economics and environmental impact. These analyses, however, solely considered household power consumption. Power companies and smaller manufacturers should also assess the type of hybrid system that is most appropriate for their geographic location and power needs.

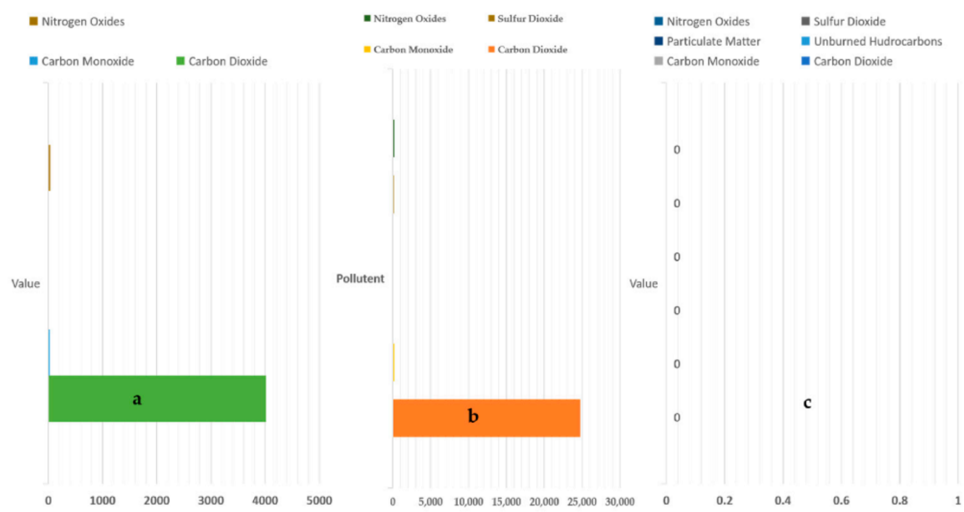

Figure 5. (**a**) Diesel battery configuration emissions. (**b**) Diesel–solar PV converter configuration emissions. (**c**) Diesel–PV–battery configuration emissions.

4. Conclusions

Our results indicate that the PV and battery architecture would be most suited for a 4-kilowatt (kW) power plant in the Lubumbashi region. Thus, the solar PV system can generate 7331 kW annually, which is more than enough to meet the needs of local households. Only 4111 kW of electricity per year was used by the AC primary load. About 38% of the energy is in surplus, that is 2777 kW each year. Thus, we suggest that 18 batteries be installed in parallel with 24 V bus voltage to fully meet the electricity needs of the Lubumbashi area, allowing the city to transition to renewable energy.

Policies and regulations from governments are a major boost in the development and deployment of renewable energy projects. Hybrid diesel–PV power systems are one example of a renewable energy source that could benefit from policy actions that promote its adoption. Capital constraints have stymied renewable energy growth in DR Congo and other low-income countries for far too long. Hence, it is crucial that renewable energy initiatives, such as hybrid diesel–PV power systems, are supported by both government and private sector investments. The impact of hybrid diesel–PV power systems on the livelihoods and economy of Lubumbashi cannot be overemphasized. Environmental impacts of hybrid diesel–PV power systems, including carbon emission reductions and air and water quality impacts, must be studied to understand their long-term viability. Integration of hybrid diesel–PV power systems into the current Congolese state grid infrastructure may require further study to evaluate its technical and economic viability.

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