Journal of Renewable Energies 28 (2025) 187 – 205

DOI: https://doi.org/10.54966/jreen.v28i1.1422

Journal of Renewable Energies

Revue des Energies Renouvelables

Journal home page: https://revue.cder.dz/index.php/rer

Research paper

HOMER sizing of a Diesel-PV-Battery hybrid system to supply an isolated site in southern Algeria

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ARTICLE INFO

Article history:
Received April 16, 2025
Accepted June 24, 2025
Available online June 25, 2025
Published June 26, 2025

Keywords:
Off-grid power plant,
Hybrid system,
HOMER software,
Sensitivity analysis,
Optimal Sizing.

ABSTRACT

Remote areas are often powered by oversized diesel generators, resulting in high investment and operating costs and significant greenhouse gas emissions. To address this issue, a methodology for optimal sizing of mini-hybrid PV/diesel/battery power plants, using HOMER software, has been presented. A case study was conducted to analyze a real hybridization project of a multi-generator diesel power plant located in the village of Moulay Lahcen, Tamanrasset, Algeria. The study aims to reduce the net present cost, the Levelized energy cost, and CO2 emissions. A comparison of different configurations of hybrid mini-power plants, with and without storage, has been conducted. The results show that a hybrid PV/diesel/battery system in AC/DC switched configuration is a reliable, cost-effective, and environmentally friendly option for the sustainable electrification of the studied remote areas. This configuration has the lowest net present cost (NPC) of $483443, a Levelized cost of energy (LCOE) of $0.132/kWh, a fuel consumption of 49868 liters/year and CO2 emissions of 130.434 tons/year. A sensitivity analysis of several parameters influencing the design of the studied systems was also carried out. This analysis highlighted that the price of fuel is one of the parameters that most influences the choice of the optimal hybrid system.

1. INTRODUCTION

In remote Algerian villages, far from the power grid, electricity is usually provided by diesel generators. Considering the shortage of fossil fuels, environmental pollution and high transportation costs,

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ISSN: 1112-2242 / EISSN: 2716-8247

alternative resources have been developed primarily based on renewable energy, such as photovoltaics, given that Algeria has significant solar potential, receiving an estimated irradiation of 169440 kW/m²/year (Bouzid et al., 2015).

However, the intermittent and unstable nature of renewable resources affects the supply-demand balance and can't completely replace fossil fuel. Therefore, the hybrid renewable energy system (HRES) which combined renewable sources, conventional sources, and/or energy storage system, presents a promising solution (Mokhtara et al., 2020).

Many research papers have been done on this topic using either optimization algorithms or commercial software like HOMER Pro (Mokhtara et al., 2020), which is a powerful tool for designing and optimizing HRES. It enables the modeling of various energy resources and the determination of the most cost effective and efficient combination of resources, system size, and storage capacity (Afonaa-Mensah et al., 2024). For example, AL Orabi et al. (2023) studied Egypt's capacity to generate green hydrogen using natural renewable resources to serve islanded electrical and hydrogen loads. The study is carried out using HOMER professional software, with three scenarios (PV, wind, and hybrid). The wind scenario on the coast of the Suez Gulf provided the lowest LCOE, ranging from 0.308 $/kWh to 0.353 $/kWh, and the COH ranged from 3.73 $/kg to 4.13 $/kg. Afonaa et al. (2024) studied the impact of agro-industrial productive loads on the performance of off-grid solar PV hybrid energy systems for rural electrification in Ghana using HOMER software. The results of the study showed an improvement in the rural community load factor and the correlation of solar load with the integration of productive load. Subsequently, increasing the fraction of renewable energy in the HRES solar PV/diesel system reduces the lifted cost of energy (LCOE), making electricity generation more cost-effective for rural electrification in Ghana. Aziz et al. (2022) developed a new dispatching strategy based on the HOMER-MATLAB Link controller for an isolated wind/diesel/battery power plant is proposed to overcome the limitations of the default HOMER strategies CC and LF. The results show that the proposed strategy offers the best economic and environmental performance with a current net cost of $56473 and annual CO_2 emissions of 6838 kg. Khaled et al. (2024) proposed an optimal hybrid microgrid design for Riphah International University (RIU), Lahore, Pakistan. The optimal system offered an NPC of $0.483 million and 99.3% renewable energy use, while the worst solution, using a national grid and diesel generator, resulted in an NPC of $1.89 million and 0% renewable energy integration. Khirennas et al. (2020) studied the hybridization of three power plants in southern Algeria with storage-free photovoltaic systems. Analysis of the 2019 data for the hybrid power generation systems thus set up highlights the benefits of this initial experiment in terms of fuel savings and reduction of CO_2 emissions, despite the low level of photovoltaic penetration. Kotb et al. (2020) compared five hybridization scenarios in terms of life-cycle cost, carbon emissions and reliability. The optimal solution consists of a photovoltaic generator, a wind generator, a diesel-genset, a battery bank and a power converter with a minimum net present cost of $351,223 and an energy cost of $0.2262/kWh among all configurations. The optimal system has a negligible capacity deficit of 0.0955% and produces the smallest amount of emitted gas of 50.43 tons/year due to the high renewable fraction (57%). What's more, the proposed optimal system can recoup its investment after just 3.4 years. Zebboudj et al. (2024) simulated two configurations of hybrid systems with battery storage using HOMER Pro to meet the electricity needs of a house located in Bejaia, one autonomous (off-grid) and the second grid-connected. Findings showed that the grid-connected system is the most economical in terms of initial capital cost by using less storage capacity, selling the surplus to the grid and buying in the event of a production shortfall. Salau et al. (2024) studied an off-grid power system suitable for the Shinshicho primary hospital, for a main load of 276 kilowatt-hours per day and a peak load of 40 kW. The study shows that the optimal system is made up of solar photovoltaic panels, diesel generators and battery storage, offering a total net present cost (NPC) of $216,155 and a cost of energy (COE) of $0.187 per kilowatt-hour. Kapen et al. (2022) examined for the first time ever, the techno-economic feasibility using HOMER Pro of two hybrid system scenarios, namely, PV/Fuel Cell/Electrolyser/Biogas (scenario 1) and PV/Battery/Fuel Cell/Electrolyser/Biogas (scenario 2) for energy and hydrogen production in the city of Maroua, recognized as being part of the sunniest region (Far North) of Cameroon. The study showed that the use of a battery bank in the architecture led to the lowest energy cost for each electricity demand community, also overall carbon dioxide and carbon monoxide emissions were relatively low for scenario 2 compared to scenario 1, and hydrogen production was higher in scenario 1 than in scenario 2.

An optimal design study using HOMER was applied to a laboratory (at NERIST) in Nirjuli, India (Suman et al., 2021). Various cases of energy source connectivity were examined, and their respective merits in terms of load satisfaction, cost, carbon dioxide emissions, and fuel consumption were assessed. The optimal solution obtained by HOMER, based on the laboratory's load, includes a photovoltaic generator, a diesel generator, and battery storage units. Although the cost of the proposed system is higher than the cost of grid electricity, this could be overlooked in the long term in the interest of protecting the environment. Moien (2025) assessed the techno-economic feasibility of implementing an off-grid energy system for a rural community in the northern West Bank, using HOMER software. He analyzed three energy systems: diesel-only, PV/battery and PV/diesel/battery hybrid. He confirmed that in contrast, the PV/diesel hybrid system significantly improves reliability while maintaining profitability. The study also examined the feasibility of a transition from diesel-only to PV/diesel hybrid systems. By adopting the hybrid system, customers would pay 78% of their previous diesel electricity tariff, enabling investors to recover their capital in 7.58 years, with a profit of USD 44,698 at the end of the project. In addition, the hybrid system reduces annual CO2 emissions. Khirennas et al. (2021) set out to determine the optimum capacity of a photovoltaic system without storage to hybridize, at a low penetration level, an existing large-scale, multi-unit diesel-fired power generation system (PGS), whit the lowest cost of electricity (LCOE). The proposed methodology is based on an algorithm for scheduling the operation of diesel generators in advance. They have evaluated the effect of the duration of this period on the annual values of the cumulative number of DG operating hours, the DG load factor, the number of DG starts and the total fuel consumption for diesel-only and PV-diesel systems. These operational results are then fed into the economic modelling of the system to calculate its LCOE for each value of PV system capacity. According to the study, the Tinelkoum diesel power plant can be hybridized with an optimal PV capacity without storage of 650 kWp to 750 kWp, depending on the period chosen between two successive start-ups. The simulation results reveal that the choice of the upcoming operational scheduling period is a compromise between fuel consumption and the total number of DGs started. This study proposes, for the first time, an in-depth comparative analysis of the three most commonly used hybrid mini-grid configurations: the series configuration (DC bus), the switched configuration (AC/DC bus) and the parallel configuration (AC bus), using HOMER software. The goal is to determine the optimal configuration through a multi-criteria analysis incorporating technical (maximizing system reliability), economic (reducing net discounted cost and discounted energy cost), and environmental (reducing CO_2 emissions and fuel consumption) parameters. In order to illustrate the proposed optimal sizing methodology, a case study was carried out on a real project involving the hybridization of a multi-generator diesel power plant with a solar photovoltaic installation and an electrochemical storage system. The hybrid system studied was designed to supply electricity to an isolated site in Moulay Lahcen, in the wilaya of Tamanrasset, in southern Algeria. In order to increase reliability of the results, a sensitivity analysis has been performed to examine the influence of various key parameters on system design and performance. The study concludes with a summary of the optimal sizing methodology used, a detailed presentation of the case study, and an analysis of the main results obtained.

2. METHODOLOGY

This research focuses on evaluating the techno-economic viability of an off-grid hybrid power system that combines diesel generator (DG), photovoltaic (PV), and battery components for rural electrification. The village of Moulay Lahcen in Tamanrasset, Algeria used as a case study. To determine the optimal component sizes and conduct a thorough techno-economic analysis, the hybrid power system configurations are designed using HOMER software. The method for optimal design and techno-economic analysis of hybrid system is detailed below, with the illustration provided in Fig 1.

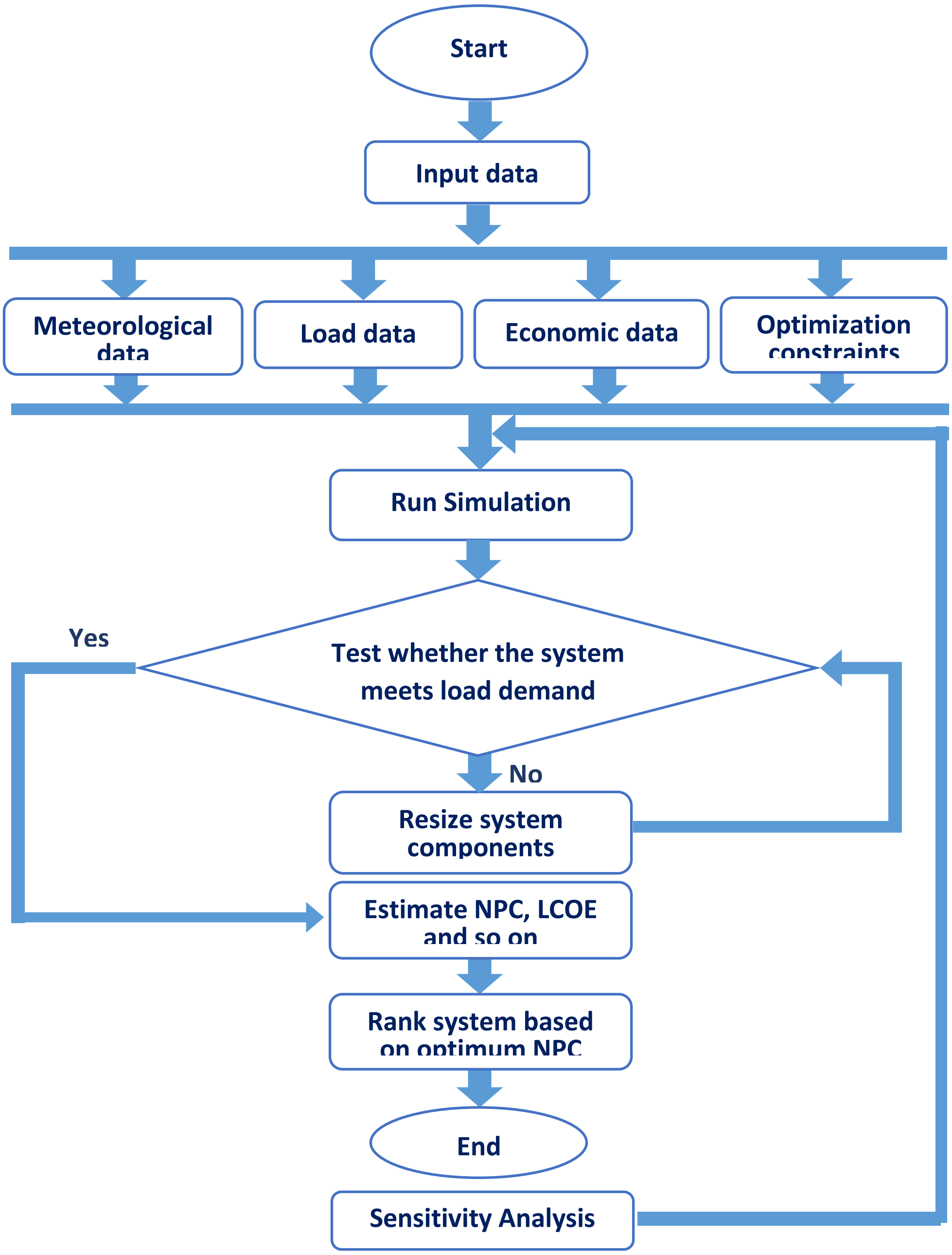


Fig 1. HOMER method for optimal design and techno-economic analysis

2.1 Input data

For the simulation, required input data include meteorological and resources data, load profile as well as economic and technical data. Meteorological and resources data include fuel price and its properties, temperature and solar radiation. These last two are fed into HOMER in the form of time-series data to calculate the output power of PV arrays. According to local market prices, costs data of the components are set. In addition, project lifetime and Nominal discount rate (NDR) are also considered. For one of optimization constraints, the load profile is represented in half-hourly time series data, so it is set to 30 minutes per time step.

2.2 Simulation and optimization

HOMER is used to perform simulation and optimization of the system. Some components of hybrid power system have different sizes, so the search space is used in simulation and optimization. Thus, considering all system types simulated in this study (conventional systems and configurations of hybrid system) the search space includes 1 + 4 x 3 + 3 x 3 x 3 + 1 + 4 + 3 x 3 x 3 + 3 x 3 x 3 + 3 x 3 x 3 = 126 plans.

2.3 Techno-economic analysis

For the economic analysis of the hybrid power system, indicators such as NPC and LCOE are considered. The total net present cost (NPC) corresponds to the present value of all costs incurred by the system over its lifetime (investment costs, replacement costs, operating and maintenance costs, fuel costs, emissions penalties and costs of purchasing electricity from the grid), minus the present value of all revenues it generates over its lifetime, such as the salvage value of all system components at the end of its lifetime and revenues from sales to the grid. The equation for NPC is as follows (HOMER® Pro Version 3.7 User Manual, 2016; Thirunavukkarasu and Sawle, 2020):

$$\mathrm{NPC} = \frac{\mathrm{C_{ann,tot}}}{\mathrm{CRF(i, R_{proj})}} \tag{1}$$

With:

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

Where $C_{ann,tot}$ is the total annualized cost of the system in \$/yr, i is the annual real discount rate in %, R_{proj} is the project lifetime in yr. and CRF() is capital recovery factor.

For the Levelized Cost Of Energy (LCOE), HOMER calculates it by dividing the annualized cost of producing electricity. The equation for LCOE is as follows:

$$\mathrm{LCOE} = \frac{\mathrm{C_{ann,tot} - C_{boiler}H_{served}}}{\mathrm{E_{served}}} \tag{3}$$

Where C_{boiler} is boiler marginal cost in \$/kWh, H_{served} is total thermal load served in kWh/yr and E_{served} is total electrical load served in kWh/yr. In this study, there is no thermal load, so the term (C_{boiler} * H_{served}) is equal to zero.

2.4 Sensitivity analysis

Sensitivity analysis is a method used to determine the impact of various factors, such as PV capital and fuel price, on system parameters. This analysis is essential for assessing reliability and aiding decision-making.

3. CASE STUDY

3.1 Site description

The village of Moulay Lahcen, located in the wilaya of Tamanrasset in Algeria, lies at latitude 24°43'42.1"N and longitude 4°39'27.2" E, at an altitude of around 915 meters above sea level. The region is characterized by rugged terrain, typical of the Hoggar Mountains and the Sahara Desert, with rocky soils and mountainous areas. The village is currently supplied with electricity by a mini-grid diesel power plant operated by Sonelgaz-Energies Renouvelables (S-EnR), a subsidiary of the Sonelgaz group.

3.2 Electrical load assessment

The village's electricity demand is estimated based on data collected from the Moulay Lahcen power plant. Active power data supplied by the Moulay Lahcen power plant were recorded throughout 2022 at half-hourly intervals. The load profile is shown in Fig 2.

The scaled annual average is 694.63 kWh/day. On August 28 at 2 p.m., the station recorded a maximum load of 65 kW, while the minimum load was 10 kW. The average annual load is 28.94 kW.

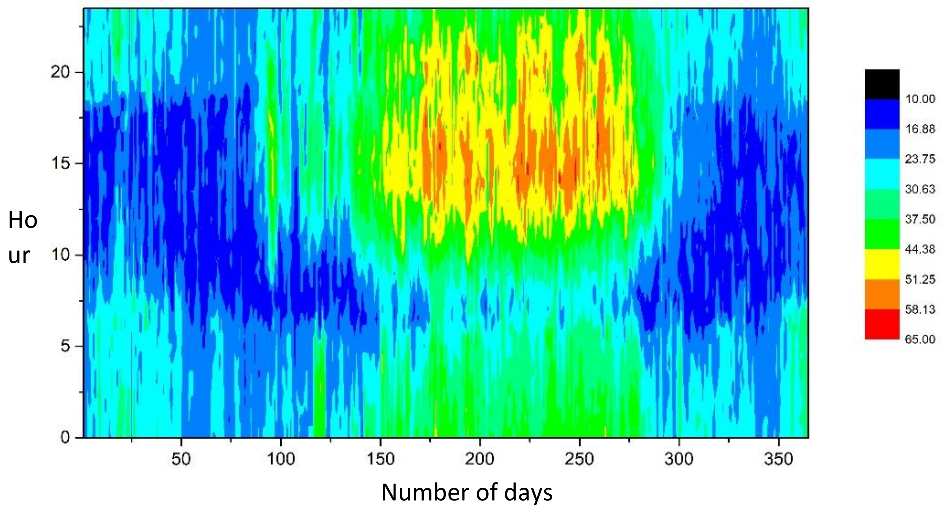


Fig 2. Annual Load Demand Distribution

3.3 Meteorological data

Solar radiation and temperature data for the Moulay Lahcen power plant were obtained from the NASA Surface Meteorology and Solar Energy website for the year 2022. Fig 3 and Fig 4.

On 8 Mai at 12 noon, global horizontal irradiation reached its maximum value 1.075 $kW/m2$, Winter months, transition months, summer months, and the annual average of diurnal global horizontal irradiation are 5.03 kWh/m2/day, 6.52 kWh/m2/day, 7.43 kWh/m2/day and 6.36 kWh/m2/day respectively. The minimum clearness index of 0.66 is a positive indicator for PV system performance, suggesting good levels of solar irradiation even during less favorable times. Ambient temperature ranges from 2.39 to 44.5°C, with an annual average of 25.4°C.

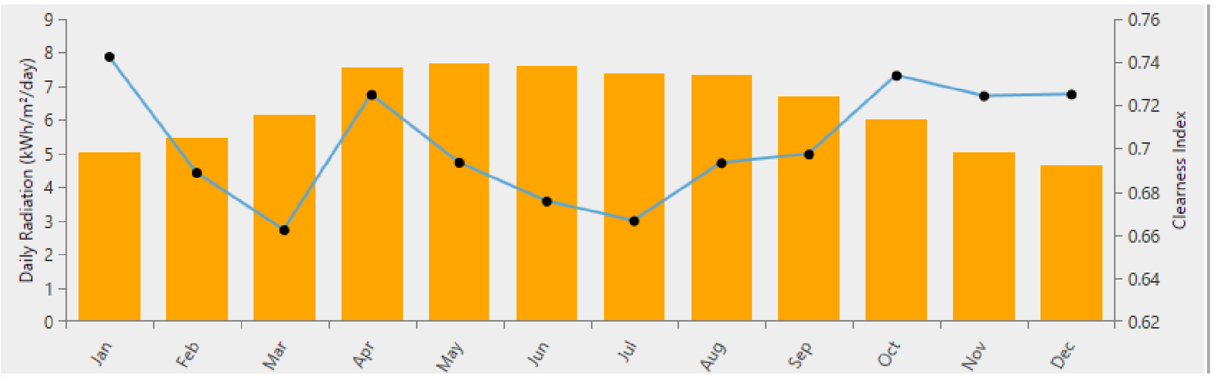


Fig 3. Annual solar radiation

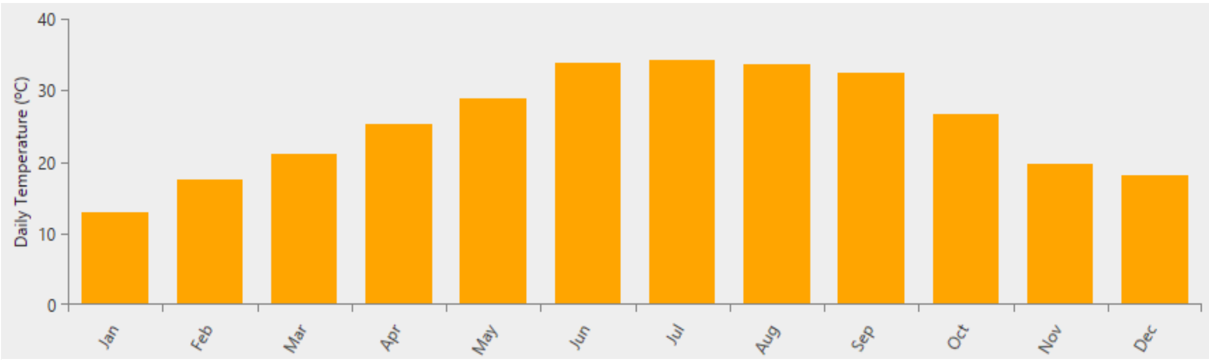


Fig 4. Annual ambient temperature

3.4 Design specification

There are three kinds of systems: conventional, renewable and hybrid systems. Starting with conventional systems, there are three configurations: single diesel generator, dual diesel generators and triple diesel generators, as shown in Fig 5.

Secondly, the renewable system, specifically a PV/battery system, where solar panels and batteries are connected to the AC bus through an inverter to feed the load, as shown in Fig 6.

Thirdly, the PV/diesel/battery hybrid systems that been classed by configuration types: series configuration, parallel configuration (AC Bus) with and without storage, AC-DC Switch Configuration and AC-DC Parallel Configuration, as presented in Fig 7, Fig 8, Fig 9, and Fig 10 respectively.

3.4.1 Solar Panels

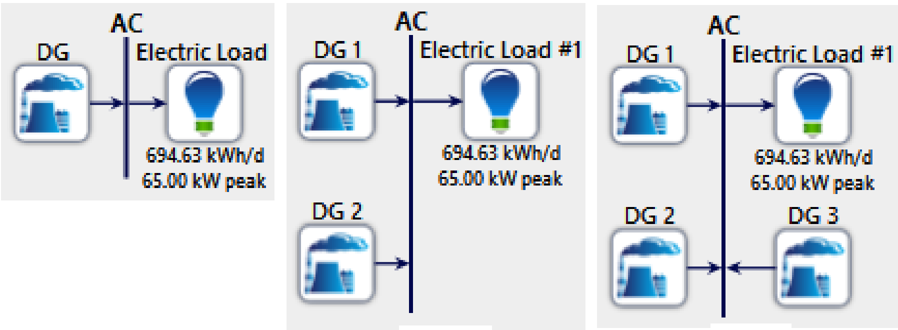
HOMER Energy® uses Eq. (4) to estimate the power produced by the PV array, which is directly affected by the incident irradiance and the operating temperature of the PV cell ("HOMER® Pro Version 3.7 User Manual," 2016) (Duffie and Beckman, 2006)

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G_T}}{\overline{G}_{T,STC}}\right)\left[1 + \alpha_P \left(T_a + G_T\left(\frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}}\right) - T_{c,STC}\right)\right] \quad (4)$$

Y_{PV} Rated power of the PV array [kW]
f_{PV} PV derating factor [%]
G_T Solar radiation incident on the PV array [kW/m²]
$G_{T,\,STC}$ Incident radiation at standard test conditions [1 kW/m^2, 25 °C]

α_P Temperature coefficient of power [%/°C]
T_c PV cell temperature in the current time step [°C]
T_a = the ambient temperature [°C]
$T_{c,NOCT}$ = the nominal operating cell temperature [°C]
$T_{a,NOCT}$ = the ambient temperature at which the NOCT is defined [20°C]
$G_{T,NOCT}$ = the solar radiation at which the NOCT is defined [0.8 kW/m^2]

The PV capital cost is established at $566 per kilowatt (kW), which includes installation cost and other expenses such as cabling, accounting for 40% of the PV panel price. Replacement costs are set at $500 per kW, and the operation and maintenance (O&M) costs are $10 per kW per year. The PV panels have a projected lifetime of 25 years. Key technical parameters include a derating factor of 80% and ground reflectance of 20%. The panels are installed without a tracking system, with the slope set to 24.73°. The temperature effect on power is specified as -0.5% per °C, with a nominal operating cell temperature of 45°C. At standard test conditions (STC), the panels achieve an efficiency of 20.5%.



(a) (b) (c)

Fig 5. Conventional system configurations: a) Single DG, b) Dual DG, c) Triple DG

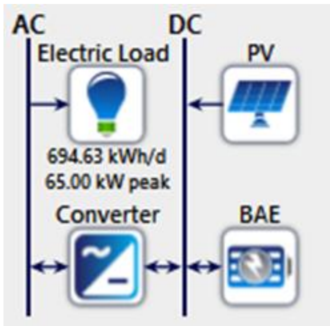


Fig 6. PV/battery system

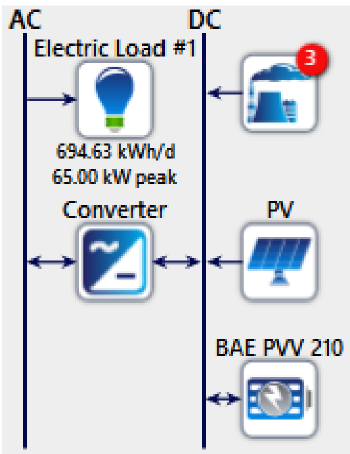
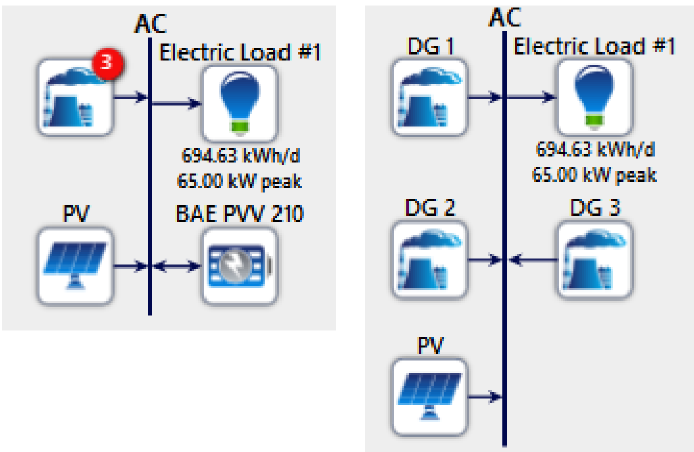


Fig 7. Series configuration



(a) (b)

Fig 8. Parallel configuration (AC Bus): a) with storage, b) without storage

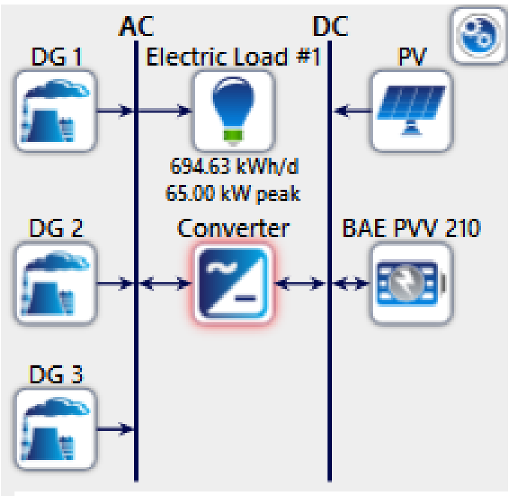


Fig 9. Switch Configuration

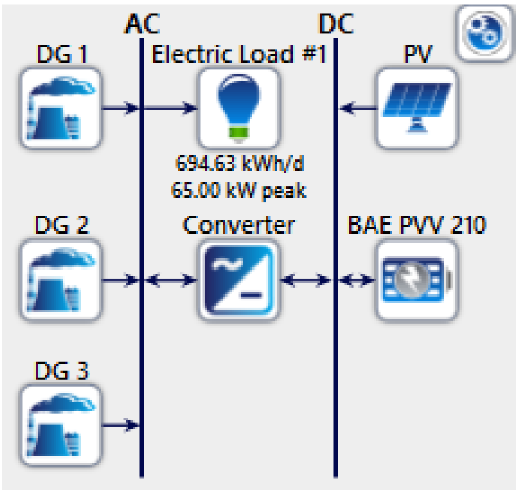


Fig 10. AC-DC Parallel Configuration

3.4.2 Battery

In the hybrid PV/diesel/battery system, batteries serve as a supplementary backup facility, ensuring consistent power supply and enhancing system reliability. The chosen battery model is the Kinetic battery (“HOMER® Pro Version 3.7 User Manual,” 2016), featuring a nominal capacity of 2.42 kWh and a nominal voltage of 12V. This model boasts a lifetime throughput of 2112.4 kWh and an impressive roundtrip efficiency of 90%. Financially, the capital and replacement costs for each are set at $417 per unit, while O&M costs are maintained at a reasonable $10 per year per unit.

3.4.3 Converter

The capital and replacement costs for the converter are set at $280 per kW, and O&M cost is $7 per year per kW. The converter has a lifetime of 15 years, with inverter and rectifier efficiencies at 95%.

3.4.4 Fuel consumption

The following equation gives the generator's fuel consumption in units/hr as a function of its electrical output: (“HOMER® Pro Version 3.7 User Manual,” 2016)

$$F = AY_{gen} + BP_{gen} \tag{5}$$

Y_{gen} = Rated capacity of the generator [kW]
P_{gen} =Electrical output of the generator [kW]
A, *B* = Fuel consumption curve coefficients [units/hr/kW]

Where A = 0.246 l/kWh and B = 0.08415 l/kWh (Dufo-López et al., 2011)

3.4.5 Operational Control and Strategies

A dispatch strategy is a set of rules used to control generator and storage bank operation whenever there is insufficient renewable energy to supply the load. The strategies used in this study are Cycle Charging (CC), Load Following (LF), and Generator Order (GO). The choice of strategy depends on system configurations. For a parallel configuration (AC Bus) with storage, the GO strategy is used because it allows connecting the batteries directly to the AC bus through the converter in case of using more than one DG. For the AC-DC Switch Configuration, the LF strategy is applied because diesel generators feed the load without charging the batteries. This is the opposite of the AC-DC Parallel Configuration, where diesel generators can charge the batteries in addition to feeding the load, making the CC strategy appropriate.

The CC strategy states that whenever a generator needs to serve the primary load, it operates at full output power. Surplus electrical production is directed toward lower-priority objectives such as charging the storage bank. The LF strategy operates by having the generator produce only enough power to meet the primary load, leaving lower-priority objectives like charging the storage bank or serving the deferrable load to renewable power sources. Lastly, the GO strategy, used in HOMER, follows a defined order of generator combinations and utilizes the first combination in the list that meets the operating capacity requirements.

3.5 Sensitivity analysis

Sensitivity analysis is utilized to assess how varying specific variables within a defined range influences the system. In this study, the sensitivity variables considered are presented in Table1.

The analysis considers project lifetimes of 20, 25, and 30 years to account for various scenarios that might affect the system's longevity. While the typical lifetime of PV panels is around 25 years, environmental conditions, maintenance practices, and technological advancements can influence this duration. The nominal discount rate (NDR) ranges from 9% to 11%, with the inflation rate fixed at 5%. Additionally, three different fuel cost values were considered: 1$/L, 0.6$/L, and 0.3$/L, reflecting scenarios with fuel subsidies. Another critical variable is the initial investment cost of PV generator (includes both the purchase and installation costs). The values considered for the PV capital costs are 566$/kW, 452.8$/kW, and 339.6$/kW. The last two are in the case of subsidies of 20% and 40% respectively.

Table 1 Sensitivity variables

Parameters	Values
Nominal discount rate (%)	9, 10, 11
Project lifetime (years)	20, 25, 30
PV capital cost ($/kW)	339.6, 452.8, 566
Diesel price ($/L)	0.3, 0.6, 1

4. RESULTS AND DISCUSSIONS

In this study, a total of 2,681,509 simulations were performed in around 6 hours using HOMER Pro version 3.14.2. During this process, 38,232 optimization cases and 88 sensitivity cases were considered. The optimization results are presented in this section, along with a comparison between different configurations. Following this, the outcomes of the sensitivity analysis are discussed in detail. Then providing a closer look at the simulation results for the best optimal hybrid power system configuration.

4.1 Systems optimization results

The simulation economics of this study are set with NDR of 10% and a project lifetime of 25 years.

The results of simulation and optimization for each configuration are listed in Table 2 and Table 3. Starting with conventional configurations, the triple diesel generators configuration stands out as the best, exhibiting the lowest NPC, LCOE, fuel consumption, and Carbon dioxide (CO_2) emissions—amounting to 600,639$, 0.164$/kWh, 73,688 liters/year, and 192.738 tons/year, respectively. Utilizing three generators enhances fuel efficiency, increases operational flexibility, and improves redundancy.

Consequently, in this study, the triple diesel generator setup is included in the hybrid system configurations.

Table 2 Optimization results of the conventional systems

Configurations	1 DG	2 DG		3 DG		
Power (kW)	72	30	45	15	25	30
NPC ($)	926,030	651,325		600,639		
LCOE ($/kWh)	0.253	0.178		0.164		
Fuel consumption (liters/year)	88,034	75,780		73,688		
CO_2 emissions (tons/year)	230.439	198.208		192.738		

The renewable configuration stands out as the optimal choice in terms of CO2 emissions, achieving zero emissions operationally. However, with a high LCOE of 0.25$/kWh, issues like intermittency and the high costs associated with energy storage pose significant challenges. Moreover, the extensive land use required for large-scale renewable installations further complicates its practicality as a standalone solution.

Among the hybrid system configurations, The AC-DC parallel configuration is the best option in terms of cost efficiency and ranks second to the PV/DG/battery (Bus AC) configuration in terms of environmental friendliness. This configuration has the lowest NPC of 483,443$, LCOE of 0.132$/kWh, fuel consumption of 49,868 liters/year, and CO2 emissions of 130.434 tons/year. The system includes a 74.4 kW PV array, 16 batteries, a 39-kW converter and diesel generators of 10 kW, 40 kW and 20 kW, as shown in Table 3.

Table 3 Optimization results of the hybrid power systems

Rank	Architecture							Costs		Environmental impact	
	System	PV (kW)	DG 1 (kW)	DG 2 (kW)	DG 3 (kW)	Battery (unit)	Converter (kW)	NPC ($)	LCOE ($/kWh)	Fuel consumption (liters/year)	CO_2 emissions (tons/year)
1	AC/DC Parallel	74.4	10	40	20	16	39	483443	0.132	49868	130.434
2	PV/DG/battery (AC Bus)	73.4	20	20	15	20	61.2	549342	0.15	47976	125.486
3	PV/DG (AC Bus)	39.8	15	25	30	0	33.2	579288	0.158	61545	160.977
4	AC/DC Switch	4.78	10	40	20	4	0.172	608315	0.166	73642	192.616
5	PV/battery	308	0	0	0	392	76.3	914274	0.25	0	0

4.2 Sensitivity analysis results

The sensitivity analysis is applied to the AC-DC parallel configuration since it is the optimal system configuration.

To investigate the capability of this hybrid system configuration in different scenarios, the effects of variations in project lifetime, NDR, PV capital cost, and diesel price on the optimal system are analyzed. Compared with conventional or purely renewable systems, the hybrid system is the preferred architecture. The results demonstrate the extensive capability of the optimum design to adapt to changes in project lifetime, NDR, PV capital cost, and diesel price, ensuring its efficiency under various conditions.

4.2.1 Impact analysis of sensitivity variables on system metrics

Starting with nominal discount rate, an increase in NDR means future costs are discounted more heavily, reducing their present value and decreasing the NPC. This makes future savings from renewable energy less attractive, discouraging investment in renewable components and thereby reducing the renewable fraction (RF). Consequently, the present value of future operational savings from renewables is lower, leading to a higher LCOE. The system relies more on diesel generators due to reduced investment in renewables, resulting in increased fuel consumption and higher CO2 emissions, as shown in Fig 11.

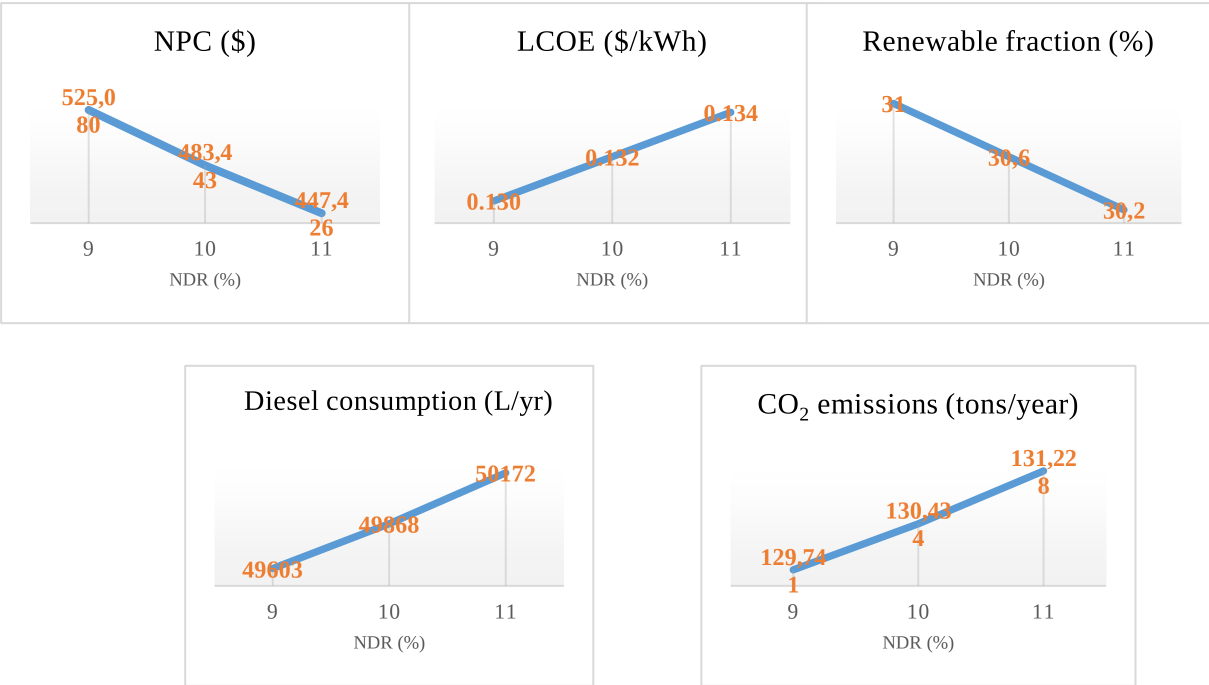


Fig 11. Effect of the nominal discount rate (NDR) on the economic and environmental performance of the hybrid system

For the project lifetime, as it increases, replacement, and O&M costs accumulate, raising the NPC. However, the initial capital investments are spread over more energy units, reducing the LCOE. Extended operation of the diesel generator over more year's results in higher fuel consumption and CO2 emissions. Regardless of the project duration, the renewable fraction remains constant, as it is determined by the system's design and capacity, as shown in Fig 12

When the capital cost of PV increases, the initial investment and total lifetime costs rise, leading to higher NPC and LCOE. This higher cost may deter the installation of sufficient PV capacity, resulting in greater reliance on diesel generators. Consequently, fuel consumption and CO2 emissions increase, while the renewable fraction decreases. As presented in Fig 13.

As diesel prices rise, the operational costs for diesel generators increase, leading to a higher overall NPC and LCOE. The increased fuel cost makes diesel-generated electricity less attractive, prompting the system to prioritize cheaper renewable energy sources, which raises the renewable fraction. Consequently, reduced diesel consumption results in lower CO2 emissions, as shown in Fig 14.

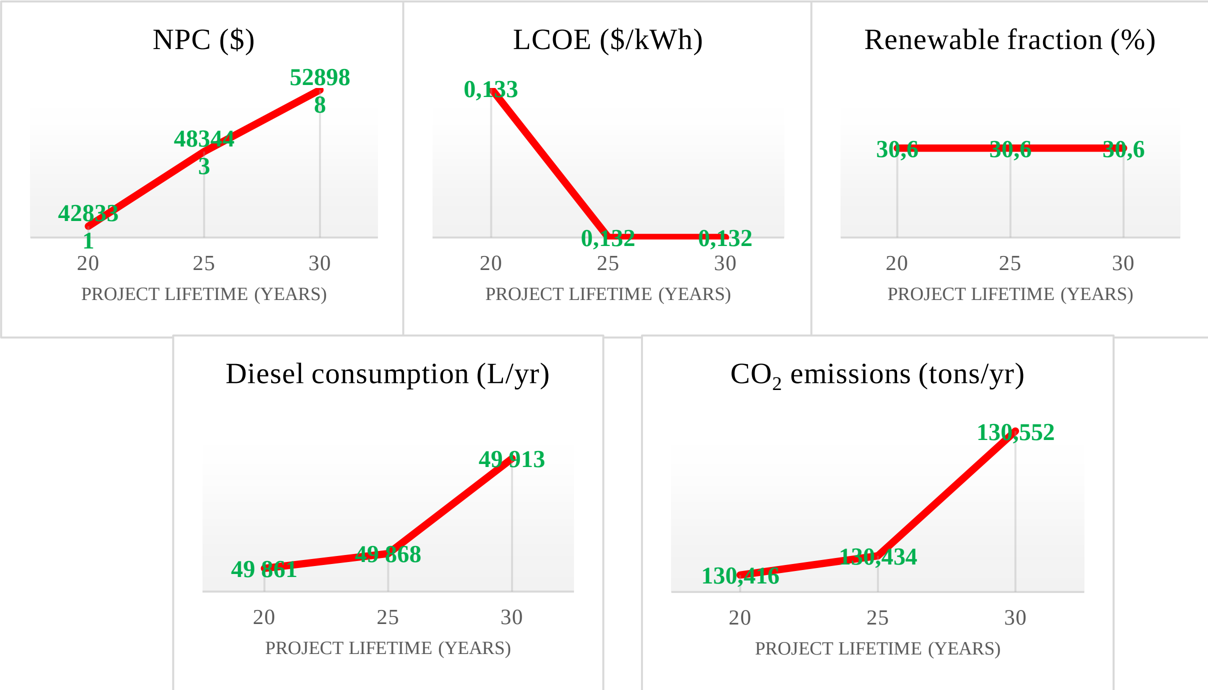


Fig 12. Influence of project lifetime on NPC, LCOE, CO_2 emissions, and fuel consumption.

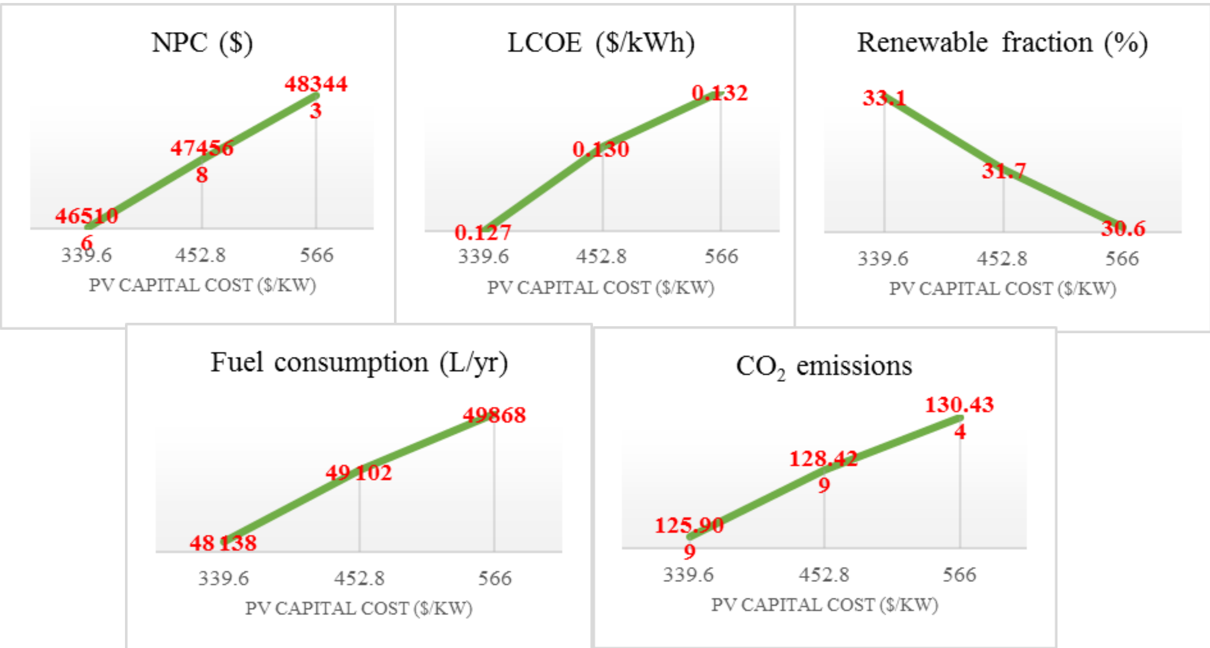


Fig 13. Impact of PV capital cost on system performance

4.2.2 Rank-up

In order to draw up a relevant ranking of the impact of the various specific variables (NDR, project lifetime, diesel price, investment cost of the PV system) on the system performance indicators (NPC, LCOE, RF, fuel consumption and CO_2 emissions), we need to compare them under equivalent

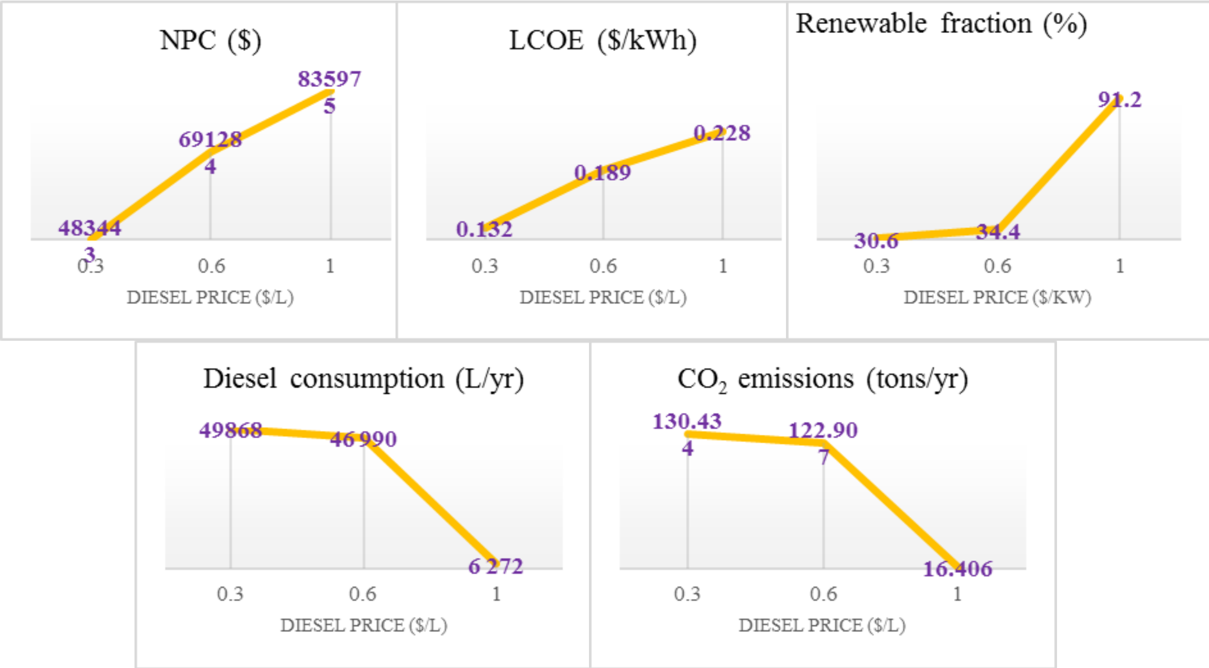


Fig 14. Impact of diesel price on system metrics

conditions. For this purpose, we have chosen to express these variables in relative values with respect to their reference values presented in Table 4.

Spider-leg graphs are drawn for each performance indicator as a function of the specific variables. In this way, each figure corresponding to an indicator groups together 12 values, i.e. three values for each of the four specific variables. (See Fig. 15 to Fig. 19). The slope of the curve associated with each variable is used to assess its influence on the indicator: the steeper the slope, the greater the impact of the variable on the parameter in question. The best estimate point chosen to plot spider graph is introduced in Table 4.

Table 4. The best estimate point.

NDR (%)	Project lifetime (years)	PV capital cost ($/kW)	Diesel price ($/L)
10	25	566	0.3

In Figure 15, it can be seen that the "nominal discount rate (NDR)" variable has the steepest slope of all the specific variables, indicating a major impact on the NPC. This slope is negative, which means that a decrease in the NDR leads to an increase in the NPC, and conversely, an increase in the NDR reduces the NPC. Indeed, a higher discount rate reduces the present value of future costs, resulting in a lower NPC. In contrast, the project lifetime shows a positive slope, but less steep than NDR, indicating a relatively smaller impact. This positive relationship can be explained by the fact that a longer lifespan leads to an increase in cumulative replacement and operating costs, which increases the NPC.

The other two specific variables, the initial cost of the PV system and the price of diesel fuel, also show positive slopes. Their influence on NPC is more moderate, although the effect of fuel price is slightly more perceptible than the effect of initial capital.

Figure 16 illustrates the sensitivity of the Levelized cost of energy (LCOE) to variations in the various specific variables. It shows that the steepest slope corresponds to the price of fuel, indicating that this variable has the most significant impact on the LCOE.

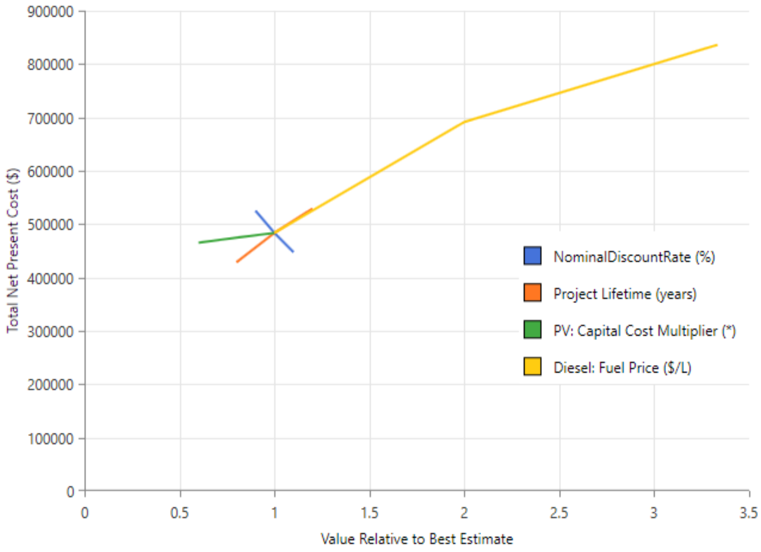


Fig 15. NPC according to sensitivity variables

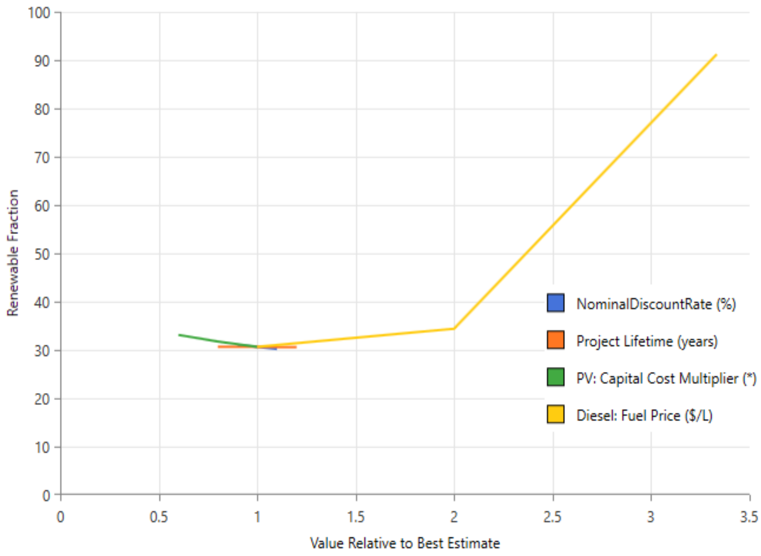


Fig 16. Spider graph displaying the sensitivity of LCOE to the parameters studied.

All the slopes are positive, except for the one linked to the lifetime of the system, which is negative. Indeed, a longer lifetime allows the initial investment to be amortized over a higher energy output, leading to a reduction in the LCOE.

Figures 17 to 19 present the sensitivity of the following parameters: renewable energy fraction, fuel consumption and CO_2 emissions, respectively.

These two indicators show identical sensitivity to the variables, which can be explained by the direct relationship between fuel consumption and CO_2 emissions.

The renewable energy fraction is mainly influenced by the fuel price, followed by the initial cost of the system and then the nominal discount rate (NDR). On the other hand, it is shown to be insensitive to variation in project lifetime, as indicated by a zero slope.

Likewise, the impact of specific variables on fuel consumption and CO_2 emissions can be classified according to the absolute value of the slope.

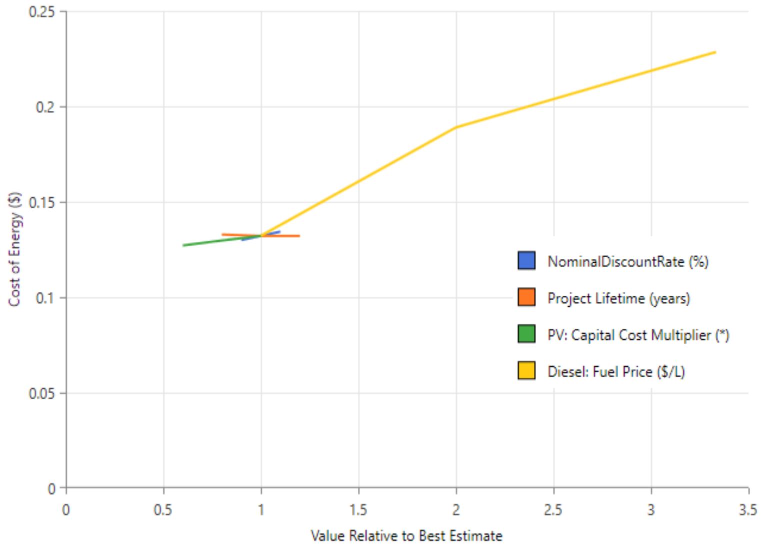


Fig 17. Spider graph of Renewable fraction according to sensitivity variables.

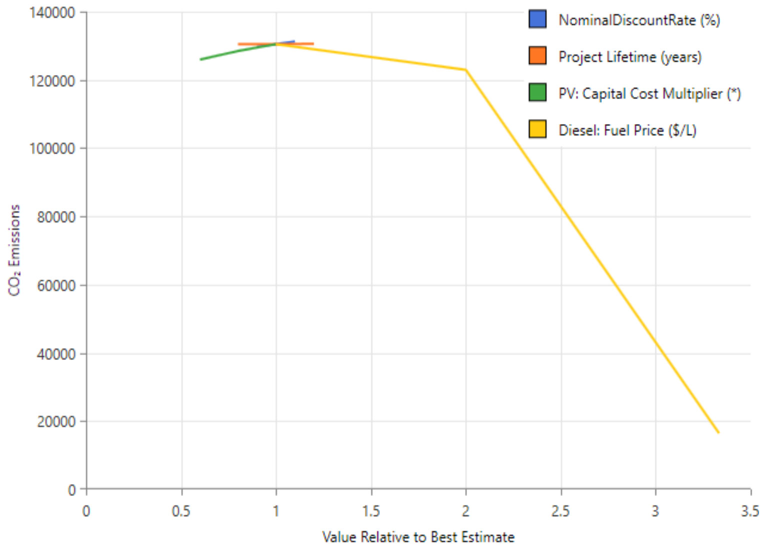


Fig 18. Fuel consumption according to sensitivity variables

Table 5 summarizes the results of the ranking of the impact of specific variables on performance indicators.

Table 5 Ranking of sensitivity variables

Rank	NPC	LCOE	RF	Fuel consumption	CO_2 emissions
1	NDR	Diesel price	Diesel price	Diesel price	Diesel price
2	Project lifetime	NDR	PV capital cost	PV capital cost	PV capital cost
3	Diesel price	PV capital cost	NDR	NDR	NDR
4	PV capital cost	Project lifetime	Project lifetime	Project lifetime	Project lifetime

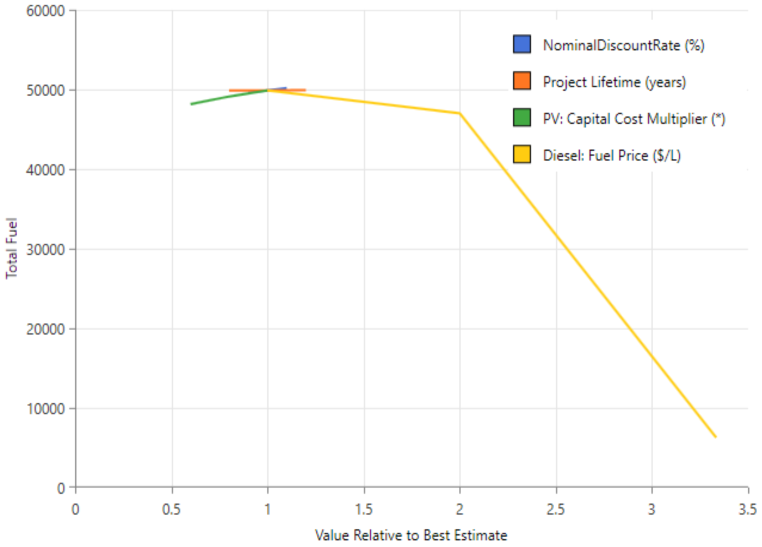


Fig 19. Spider graph illustrating the sensitivity of CO_2 emissions to the parameters studied

5. CONCLUSION

This study proposes an optimal sizing methodology for PV/diesel/battery hybrid mini-grids, based on HOMER software. It is applied to a real case located in the isolated village of Moulay Lahcen, in the wilaya of Tamanrasset, Algeria. The aim is to assess the technical and economic feasibility of different hybrid configurations for rural electrification, considering technical reliability, economic profitability and environmental sustainability. Local meteorological and radiometric data (including solar radiation and temperature), a half-hourly load profile and economic data have been integrated into the model to ensure high-reliability simulations.

Three hybrid configurations were analyzed: the series configuration (DC bus), the switched configuration (AC/DC bus) and the parallel configuration (AC bus), each evaluated with and without a battery storage system. The simulation results show that the switched PV/diesel/ battery configuration with storage offers the best performance. It records the lowest net present cost (NPC), estimated at $483,443, a Levelized cost of energy (LCOE) of $0.132/kWh, an annual fuel consumption of 49,868 liters, as well as CO_2 emissions amounting to 130,434 kg per year. A detailed sensitivity analysis has been carried out to assess the influence of several key parameters, such as the life of the project (20 to 30 years), the nominal discount rate (between 9% and 11%), the price of fuel (between $0.30 and $1/L), and the capital cost of photovoltaics (between $339.6 and $566/kW).

The results showed that the price of fuel was the most important factor in choosing the optimum system configuration. In addition, the study demonstrates that PV/diesel/battery hybrid systems represent a technically reliable and economically viable solution for off-grid electrification of isolated areas. It also proposes a robust multi-criteria optimization framework to assist decision-makers and planners in the implementation of sustainable and cost-effective energy systems adapted to comparable geographical and socio-economic contexts.

ACKNOWLEDGEMENTS

The authors would like to thank Dr Khirennas Abdelhamid and all the staff at SKTM-Ghardaia (Shariket Kahraba wa Takat Moutadjadida) for their valuable contribution to the development of this work.

DECLARATION OF COMPETING INTEREST

The authors assert emphatically that they have no financial interests or personal relationships that could have influenced the work reported in this paper.

NOMENCLATURE

$C_{ann,tot}$	Total annualized cost	i	Annual real interest rate
C_{boiler}	Boiler marginal cost	LCOE	Levelized Cost Of Energy
CC	Cycle Charging	LF	Load Following
C_{NPC}	Total net present cost	NDR	Nominal Discount Rate
CRF	Capital Recovery Factor	NPC	Net Present Cost
E_{served}	Total electrical load served	O&M	Operating and Maintenance
GO	Generator Order	RF	Renewable Fraction
HOMER	Hybrid Optimization Model for Electric Renewables	STC	Standard Test Conditions
H_{served}	total thermal load served		

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