


Design and Optimization of a PV-Diesel Hybrid System with Storage for Supplying an Off-Grid Site in Burkina Faso: Integration of a Smart Grid

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Abstract

Burkina Faso has a very low rural electrification rate (7.02 % in 2023), a situation exacerbated by a growing population. This work proposes a decentralized electrification solution. The country possesses significant solar potential (5.5 kWh/m²/day), which is harnessed here through a PV-Diesel hybrid mini-power plant equipped with a smart management system (Smart Grid). Designed to supply 100 off-grid households, this plant has the dual objective of facilitating production control and minimizing its cost. Sized to meet an average daily demand of 600 kWh/day, the designed plant integrates PV-Diesel generators, a storage system, an inverter, and a Smart Grid. Implementing the smart grid via the HOMER Pro software enabled the optimization of energy production from each plant component. A study of the influence of the plant's operational parameters on its performance showed that the size of the energy storage and the PV array reduces the operating time of the diesel generator. Furthermore, the solar fraction is more sensitive to the size of the PV array than to that of the batteries, whose influence becomes negligible beyond three days of autonomy. Five scenarios, obtained by removing one or several components from the initial system, were compared based on the Life Cycle Cost (LCC), the initial investment, and the Operation and Maintenance (O&M) costs over 20 years, while integrating pollutant emission abatement costs. The scenario including the PV-Diesel generators, storage, and the inverter proved to be the best compromise, combining economic optimization with environmental preservation.

Keywords

Rural Electrification, PV-Diesel Hybrid Power Plant, Smart Grid, Energy Efficiency

1. Introduction

In Burkina Faso, numerous remote localities remain outside the coverage zone of the national electricity grid. The electrification rate in rural areas increased from 2.9% in 2014 to 7.02% in 2023 [1]. Internationally, conventional energy sources such as gas, oil, and uranium are diminishing due to widespread diffusion and industrial development in recent years [2]. However, basic socio-economic development cannot be achieved without a reliable and sustainable energy source. In this context, access to electricity in rural areas is imperative for improving the quality of life of populations and fostering economic progress. The rural electrification process in Burkina Faso is built upon a robust framework, namely electricity cooperatives (COOPELs), which serve as a springboard for promoting and popularizing electricity access. COOPELs align with the same dynamic as the “Electricity for All” program implemented by the Electrification Development Fund (FDE) [3]. Each COOPEL undertakes the tasks of the National Electricity Company of Burkina (SONABEL) at the local level under the technical supervision of the FDE, ensuring production, transmission, supply, maintenance, and billing. Unfortunately, these cooperatives exhibit limitations in both management and service provision. Indeed, cooperatives are forced to implement rolling black-outs because certain days are heavily loaded, and the capacity of the diesel generators does not cover the needs of subscribers [4].

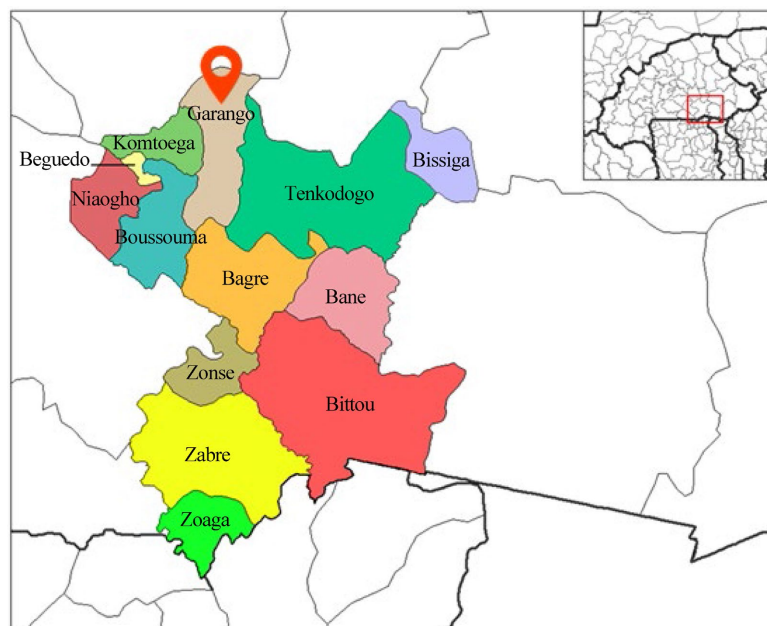
It is evident that efficient and effective management of this energy is necessary. Thus, for the most regular production possible, one solution involves hybridizing different types of sources by exploiting multiple renewable sources in a well-managed, well-coordinated, optimized, and efficient manner. Numerous studies have focused on these hybrid systems to master their operating principles and improve their performance. These primarily include PV-Diesel hybrid systems [5]-[8], PV-Wind or Wind-Diesel-Storage hybrid systems, or combinations of all three [9]-[13]. The solar-wind-geothermal-diesel combination is also a significant solution according to the results obtained by M. Ismail *et al.* [14]. This approach requires the integration of automatic and electronic control systems, such as Smart Grids, into energy production and distribution vectors. According to S. Balani [15], a Smart Grid is the integration of a set comprising an electrical network, a communication network, software, and hardware aimed at monitoring, controlling, and managing energy production, distribution, storage, and consumption. Smart Grids therefore differ from current networks in their aspect, operation, mission, and deployment [16] [17]. The deployment of smart electrical grids targets several objectives: optimizing the integration of decentralized renewable production, reducing

consumption peaks by controlling a portion of consumption to adapt it to production [18]. The communication architecture of the Smart Grid, according to the NIST, groups together seven (07) domains interconnected via an internet network using communication protocols [19] [20]. Based on the NIST model, the IEEE proposed an architecture allowing centralized management of surplus energy produced by defining a new domain named Distributed Energy Resources (DER) [21].

Smart Grids impact an electrical grid at several levels, including the meter, actuators, switching and storage devices, etc. In this work, we aim to develop an electronic platform integrable into the energy management system of a hybrid power plant, consisting of a Diesel generator set and a Photovoltaic (PV) solar plant with energy storage, intended to supply a village in the Centre-Sud region of Burkina Faso not connected to the national electricity grid. This electricity production management system, integrated into the HOMER Pro simulation software, will consider the possibility that the mini-plant could be connected to the national grid. Ultimately, it will enable us to define the optimal production scenario for each system component while reducing the cost per electrical kWh.

2. Materials and Methods

2.1. Study Area: Yakoungou Site



(Exact geographical coordinates, latitude and longitude—11.8088575, 0.5352355999999999. Altitude—288 meters. Source: <https://ms.maptons.com/3152998>).

Figure 1. View of the study site—Yakoungou locality (Garango, Burkina Faso).

Yakoungou is a locality constituting Sector 1 of Garango, which is not connected to the national electricity grid. Garango is a department and an urban commune in the province of Boulgou, located approximately twenty kilometers from the city of Tenkodogo (the capital of the Nakambé Region of Burkina Faso). **Figure 1** pre-

sents a view of the site [22].

Geographic coordinates: Latitude: 11.8088575; Longitude: 0.5352355999999999 and Altitude: 288 meters.

Thus, for the realization of the PV solar field:

- the optimal orientation for the photovoltaic solar panels is due south;
- according to the findings of Amèdédjihundé H. J. H. [23], the tilt angle “I” of the solar panels will be set equal to the latitude of the site.

2.2. Data Collection

In this work, we will primarily use statistical data, standards, and previous studies on rural electrification provided by the National Institute of Statistics and Demography (INSD) of Burkina Faso. A considerable effort was made to develop a data collection form to gather the most plausible data possible on the electrical loads necessary for a meaningful and in-depth analysis.

❖ Site climatic data

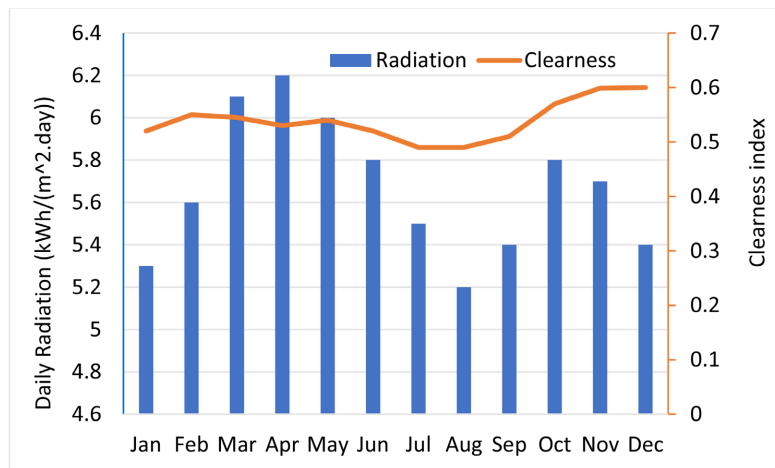


Figure 2. Monthly averages for global horizontal radiation over 22-years (Jul 1983-Jun 2005).

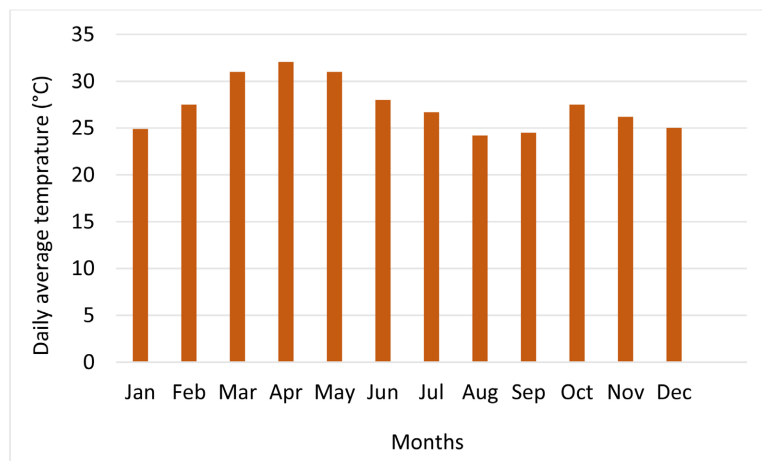


Figure 3. Monthly averages air temperature over 30-year period (Jan 1984-Dec 2013).

Climatic data such as solar radiation and temperature are generated directly by the HOMER Pro software using the input geographic coordinates. **Figure 2** presents the monthly averages of global horizontal irradiation per square meter per year, calculated over a 22-year period (July 1983-June 2005) [24]. **Figure 3** presents the monthly averages of ambient air temperature, calculated over 30 years (January 1984-December 2013). The annual averages recorded during these periods are 5.66 kWh. (m⁻²·day) for irradiation and 27.65°C for ambient temperature, respectively.

❖ Collection of specific energy data from the population

The analysis of energy needs takes into account all end-use devices whose operation requires electrical energy. These devices are therefore grouped into three categories:

- ✓ households: we consider a population of nearly one thousand (1000) inhabitants, distributed across approximately one hundred households, with an estimated connection rate of 65%. Equations 1 and 2 are used to estimate the total energy consumed.

$$N_{ap} = N_{me} \frac{65}{100} \quad (1)$$

$$E_j = P_u \times t_u + P_v \times t_v \quad (2)$$

E_j : daily energy in Wh; P_w , the power of a device in normal operation (W); P_v , the power of a device on standby.

- ✓ social Needs: these needs primarily concern requirements for public lighting and electricity supply for the school.
- ✓ economic Activities and On-Site Control System Consumption: economic needs mainly concern the requirements of small and medium-sized industrial activities in the locality. These activities are generally centralized in the market area.

❖ Assessment of the average electrical load demand of the locality

The collected data enabled the determination of the energy requirements for each activity sector and their hourly profiles. The sectors considered are residential, commercial, and services. **Figures 4-7** present, respectively, the profile of the instantaneous power demand over one year, the cumulative power demand per hour over a day, the monthly power demand over a year, and the energy demanded by the loads over a full day.

It is observed that the load's energy requirements are highly variable over a 24-hour operating day:

- From 12:00 AM to 4:00 AM, the load demand is low (on the order of approximately 5 kWh). This period generally concerns public lighting.
- At 5:00 AM, the load begins to increase, evolving to nearly 100 kWh around 9:00 AM. The use of high-power electrical equipment such as grain mills is highly probable during this time.
- The load starts to decrease again from 10:00 AM to a value of about 20 kWh

at noon, due to breaks.

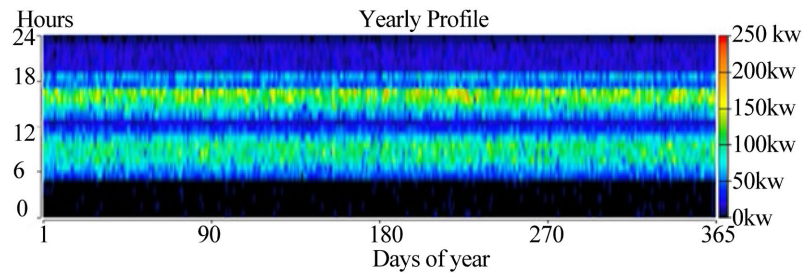


Figure 4. Instantaneous variation of the power demanded by the loads per day and over one year.

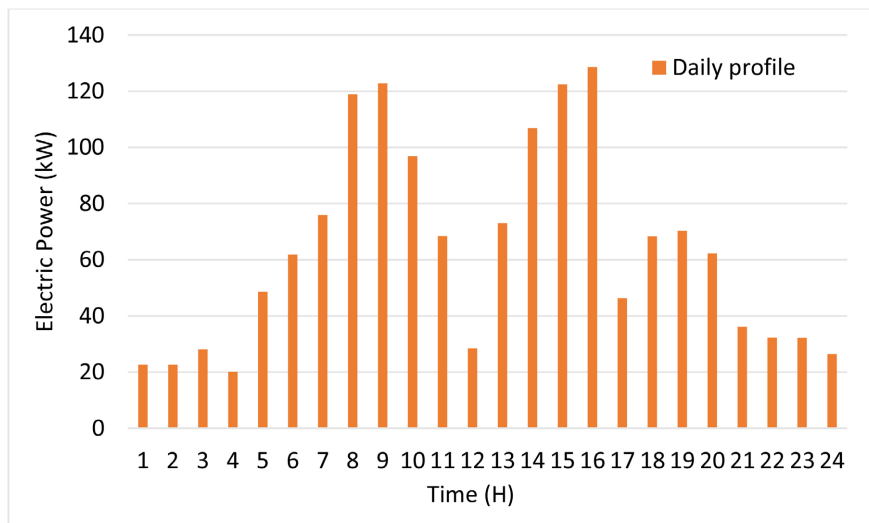


Figure 5. Profile of the power demanded by the entire site over the course of a day.

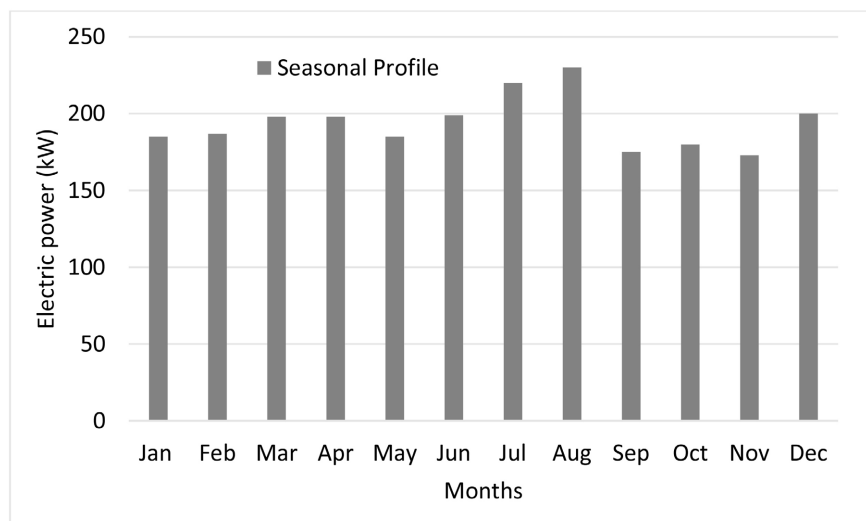


Figure 6. Profile of the power demanded per day over the course of a year.

Note that the cumulative load remains significant between 8:00 AM and 12:00

PM because needs such as those of the school, welding workshops, and grain mills are recorded during this period of the day.

- In the afternoon, demand increases again, reaching a peak at 4:00 PM due to a substantial load consisting of the school, mills, welding workshops, and some household needs.
- The load then decreases, stabilizing at approximately 20 kWh between 7:00 PM and 1:00 AM, as it essentially consists of household needs and public lighting.

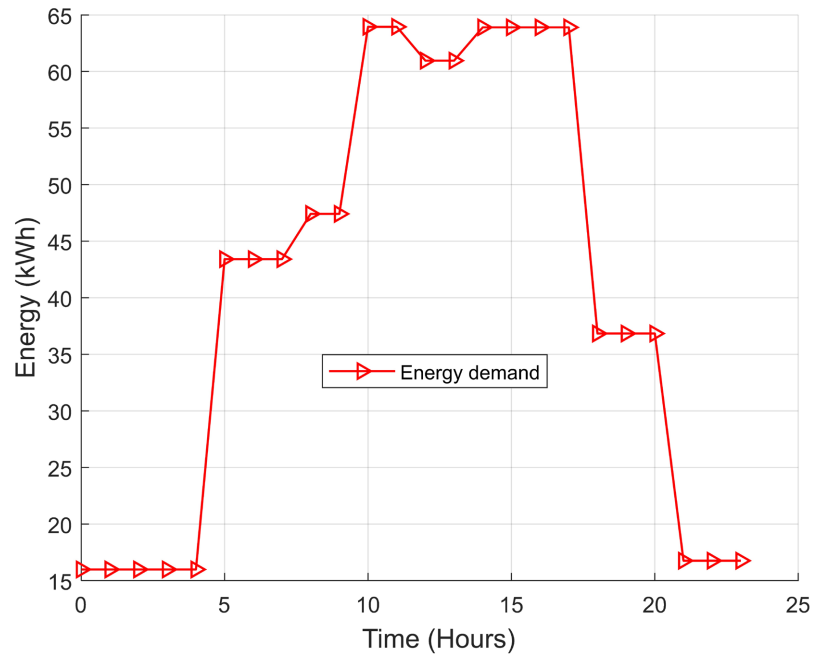


Figure 7. Profile of the energy demanded over a full day.

Table 1 summarizes the values of the power demanded and the corresponding energy over one day of operation for all loads in each defined category.

Table 1. Summary of power and energy requirements.

	Power in normal operation (kW)	Standby power (kW)	Daily energy (kWh)
Social needs	1.12	0.162	5.26
Social expenses	2.98	0.015	32.205
Economic activities and self-consumption	58.080	0	515.840
Total	72.432		600.645

2.3. Mathematical Model of the PV/Diesel Hybrid Power Plant

2.3.1. Description of the Hybrid System

The hybrid system under study is composed overall of:

- a photovoltaic (PV) solar generator;
- a Diesel electric generator;
- a battery pack;
- a reversible DC/AC converter that converts direct current and adapts it to supply the DC bus while simultaneously ensuring maximum power point tracking.

2.3.2. Overall Behavior of the Hybrid System

The design of a PV/Diesel hybrid system involves determining the optimal values for the peak power of the PV array, the capacity of the batteries, and the power of the Diesel generator. Here, we propose an iterative method for sizing the system's key parameters.

❖ Sizing of the PV source

Usual equations for sizing a PV array:

Peak power:

$$P_c = \frac{E_{cj}}{k_p \times E_i} \quad (3)$$

Average cell operating temperature:

$$T_c = T_\alpha + \frac{E_i \times (T_{nom} - 20)}{7.1 \times 800} \quad (4)$$

Maximum number of modules connected in series:

$$N_{ms \max} = \frac{U_{ec, \max}}{V_{oc} \times 1.15} \quad (5)$$

Number of modules connected in parallel:

$$N_{mbp} = INT \left(FS \times \frac{E_{cj}}{E_i \times \eta_m \times \eta_c \times S_{cel} \times N_{ms \max}} \right) \quad (6)$$

Total number of installed modules:

$$N_{tm} = N_{mbp} \times N_{ms \max} \quad (7)$$

Area of the photovoltaic array:

$$S_{pV} = N_{tm} \times S_{cel} \quad (8)$$

❖ Selection of nominal voltage

The work of Mohamed El Hacen Jed. [25] specifies the operating voltage based on the peak power of the PV array. Considering the value of the daily power demand, the operating voltage of the system is 48 V.

❖ Inverter selection

The choice of an inverter is based on the system's operating power, which must be greater than or equal to $k \times P_{ond}$ to account for current surges during device startup [26]. Here, k is a factor between 2 and 3, and P_{ond} is the nominal power of an inverter in VA.

For an isolated site, a stand-alone, bidirectional inverter is required. It must be

capable of managing batteries, the generator, and loads, delivering a sinusoidal grid voltage with an overload capacity of approximately 300% (providing short-circuit protection) and a variable power factor [27].

❖ Modeling of the system storage capacity

Nominal capacity of the assembled batteries (Ah):

$$C = \frac{\max(E_{bat} - E_{GE} - E_{PV}) \times n_j}{V_{bat} \times \eta_{bat2} \times \eta_{ond} \times PD} \quad (9)$$

Minimum State of Charge threshold (SOC_{min}) at time t:

$$SOC_{min}(t) = SOC(t-1) + \frac{(E_{GE} + E_{PV} - E_{bat}) \times \eta_{bat1} \times \eta_{ond}}{V_{ond}} \quad (10)$$

Maximum State of Charge threshold (SOC_{max}) at time t:

$$SOC_{max}(t) = SOC(t-1) + \frac{(E_{GE} + E_{PV} - E_{bat})}{V_{ond} \times \eta_{bat2} \times \eta_{ond}} \quad (11)$$

Depth of Discharge (DoD):

$$PD = 1 - \frac{SOC_{min}}{SOC_{max}} \quad (12)$$

Constraints on the State of Charge:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (13)$$

Number of accumulators (batteries) in series in each branch:

$$N_{as} = \frac{V_{ond}}{V_{bat}} \quad (14)$$

Number of parallel branches:

$$N_{bp} = \frac{C}{C_n \times (SOC_{max} - SOC_{min})} \quad (15)$$

Total number of accumulators (batteries):

$$N_{Tbat} = N_{as} \times N_{bp} \quad (16)$$

❖ Sizing of the generator set

Calculation method for sizing the generator set.

Maximum power:

$$P_{max} = P_p \times \frac{f_p}{f_t} \quad (17)$$

Power demanded:

$$P_{app} = \frac{P_{max}}{\cos \varphi} \quad (18)$$

Service life [years]:

$$D_{GE} = \frac{T_{vie}}{(365 \times T_{marche})} \quad (19)$$

Fuel consumed [L]:

$$C_{vol,Fuel} = C_{Fuel} \times \left(\sum_{i=0}^{T_{marche}} P_i + 0.1 \times C_{bat} \right) \quad (20)$$

2.4. Configurations of PV/Diesel Systems

In any hybrid PV/Diesel (DG) energy generation system, the use of an inverter is sometimes necessary for DC/AC conversion. The PV generator can then operate in parallel or alternately with the DG. Three main configurations are distinguished: series, parallel, and switched. Each of these configurations has its own advantages and disadvantages [23] [28] [29]. The configuration of PV/Diesel systems also depends on the coupling bus. Options include the DC bus, the mixed DC/AC bus, and the AC bus [26].

For this study, we opted for the parallel-connected PV/Diesel configuration. The diesel generator is interconnected on the alternating current (AC) bus, while the photovoltaic installation is connected to the direct current (DC) bus. The two buses are connected via a bidirectional electronic converter. The advantage of this configuration is that the converter can operate either as a rectifier, when the generator covers the electrical consumption and contributes to battery charging, or as an inverter, when the load (or part of it) is supplied by the photovoltaic modules and/or the battery. Consequently, the load can be powered by both buses simultaneously.

2.5. HOMER Pro Simulation Software

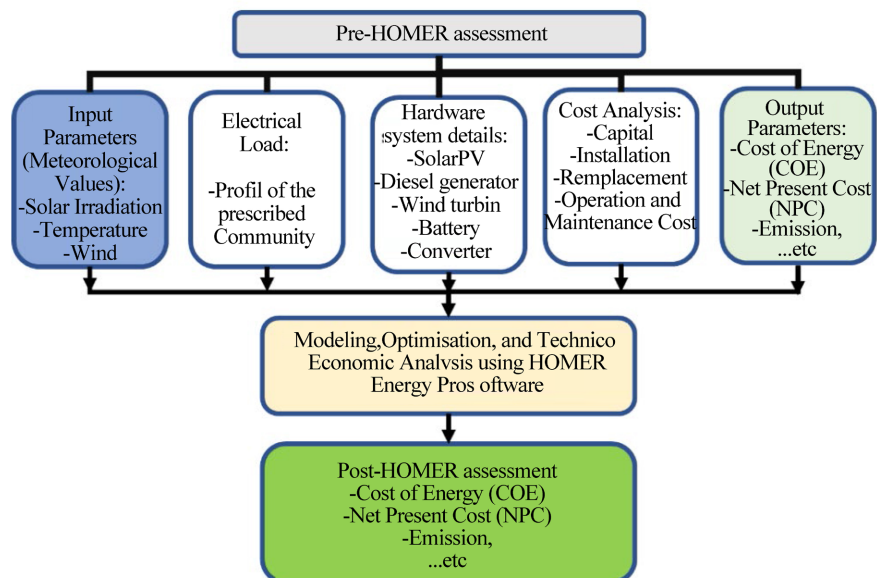


Figure 8. Simulation process.

HOMER Pro (Hybrid Optimization of Multiple Energy Resources) is a modeling and optimization software for decentralized energy systems. It is used to design

and analyze autonomous energy systems that incorporate various renewable and non-renewable energy sources, ensuring optimal cost-to-power ratio [8] [23]. For simulation purposes, input data must be provided. These primarily include the site’s geolocation, the energy demand of the load, and the configuration parameters of the solar PV array, the diesel generator and its fuel, the inverter, and the storage system. The flowchart in **Figure 8** summarizes the simulation process using HOMER [8].

2.6. Physical Modeling of the System

2.6.1. System Architecture

Figure 9 presents the 3D architectural plan of the smart grid power plant, designed using AutoCAD 2025 software. This plan takes into account all the components necessary for the implementation of the system, mainly: the Diesel and PV generators, the storage system, the technical room, the system management unit, and various other secondary components.

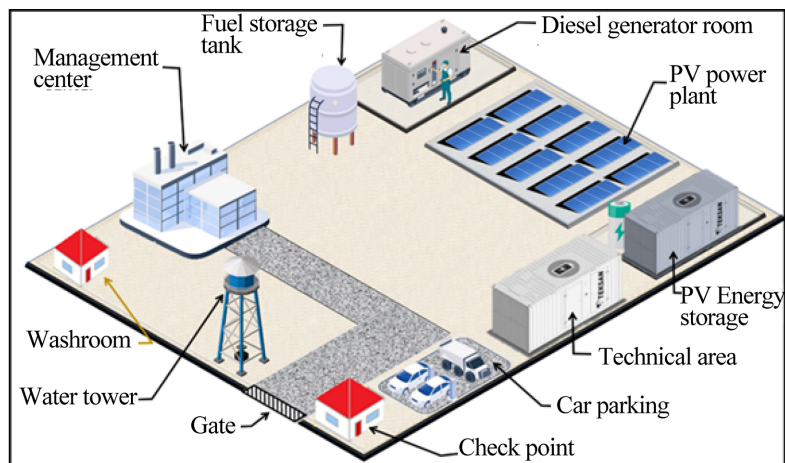


Figure 9. 3D view of control site.

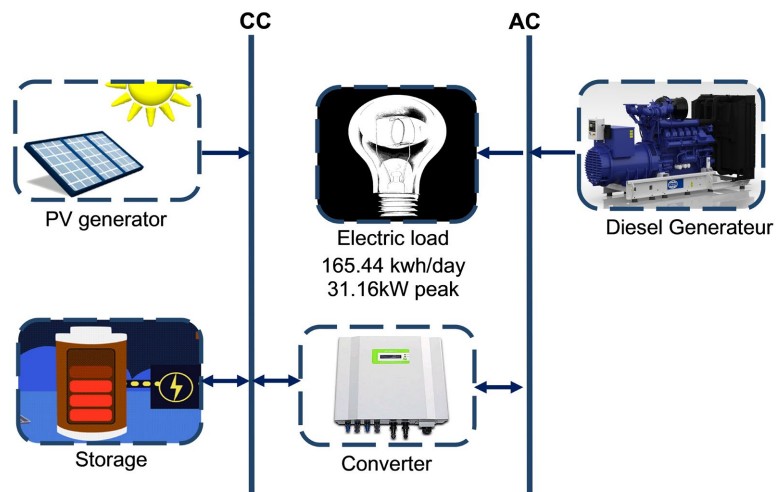


Figure 10. System overview diagram.

The HOMER Pro software provides the block diagram of the power plant shown in **Figure 10**.

2.6.2. Performance Parameters

The solar fraction (f_s) and the ratio of renewable energy to load demand ($K_{s/c}$) are physical quantities used to characterize the performance of an energy system utilizing renewable sources. Equations (21) and (22) allow for monitoring the evolution of these quantities throughout the system's operation.

$$f_s = \frac{E_{PV} - E_{per}}{E_{PV} - E_{per} + E_{GE}} \quad (21)$$

$$K_{s/c} = \frac{E_{PV}}{E_{cj}} \quad (22)$$

2.6.3. System Optimization

1) Energy Constraints

The primary objective of optimizing the operation of our system is to determine the best scenarios capable of meeting the load demand at all times, at the lowest cost, and in a sustainable manner. The main constraint of this process is to have an efficient and reliable hybrid system. The objective of the constraint management plan here is to maximize the use of renewable energy and to utilize the Diesel generator only when necessary. To achieve this, a number of constraints are imposed:

- Phase 1: The energy produced by the PV array is greater than that demanded by the load ($E_{ch}(t) < E_{PV}$). The surplus energy is then sent, via the reversible DC/AC converter, to the batteries if the latter have not reached their maximum state of charge ($SOC_{max}(t)$).
- Phase 2: The energy produced by the PV plant is less than that demanded by the load ($E_{ch}(t) > E_{PV}$). The energy deficit is compensated for by the batteries, through the reversible DC/AC converter, provided that the state of charge of these batteries has not reached its minimum threshold ($SOC_{min}(t)$).
- If, during the second phase, the batteries fail to supply the missing energy required by the load, this energy deficit is compensated for by the Diesel generator (E_{GE}).

Should the power plant eventually be connected to the public electricity grid, the following scenarios are defined:

- When the electrical energy storage system is charged and production exceeds consumption, the surplus renewable energy will be injected directly into the grid.
- In the event of a deficit, energy is drawn from the grid to meet the demand.

2) Formulation of the optimization problem

The developed model is based on the definition of an objective function (cost), or Life Cycle Cost (LCC) [28] [30], which aims to minimize the production cost. This function takes into account the acquisition, operation, maintenance, and re-

placement costs of the diesel generator, the photovoltaic array, the storage system, and the reversible DC/AC inverter. It can be written as follows:

$$F = D_{PV} + D_{GE} + D_{BAT} + D_{OND} \tag{23}$$

Component sizing of the system

Based on meteorological data and the energy needs of the population, the HOMER Pro software defines the parameters for each of the essential components of the power plant. These parameters are summarized in **Tables 2-5**.

❖ **The PV array**

Table 2. PV generator settings.

Generator PV (generic PV system)						
Panel type	Rated capacity (kW)	Duration factor (%)	Lifetime (years)	Cost		
				Capacity (kW)	Capital (\$)	Replacement (\$)
Flat plate	160	80	25	1	33,600	33,600

❖ **Diesel generator**

Table 3. Diesel generator settings.

Diesel Generator (Cummins 100 kW DSGAA)											
Fuel curve		Site specific			Emissions				Cost		
intercept (L/hr)	slope (L/hr/kW)	Lifetime (Hours)	Minimum load ratio (%)	Unburned HC (g/L fuel)	CO (g/L fuel)	Particulates (g/L fuel)	Fuel Sulfur to PM (%)	NO _x (g/L fuel)	Initial capital (\$)	Replacement (\$)	Fuel price (\$/L)
5.75	0.278	15,000	30	0.33	2.29	0.24	2.2	4.26	8000	8000	1.8
Combustible (Diesel)											
Low Heating Value (MJ/kg)		Density (kg/m ³)		Carbon (%)		Sulfur (%)		Cost (\$/L)			
43.2		820		88		0.4		1.8			

❖ **Inverter**

Table 4. Inverter settings.

Inverter (generic system converter) Si—100K							
Inverter Input		Rectifier Input			Cost		
Lifetime (years)	Efficiency (%)	Relative Capacity (%)	Efficiency (%)	Capacity (kW)	Capital (\$)	Replacement (\$)	O&M (\$/year)
25	98.7	100	98.7	1	350	350	3

➤ Storage system

Table 5. Storage system settings.

Nom. Volt. (V)	Kenetic Battery Model					Lifetime				Cost		
	Nom. Cap. (kWh)	Max. Cap. (Ah)	Cap. Ratio	Round trip eff. (%)	Max. Charge Cur. (A)	Initial SOC (%)	Min. SOC (%)	Time (years)	Throughput	Cap. (kW)	Capital (\$)	Rep. (\$)
2	7.15	3,570	0.315	86	610	100	30	20	10118.30	120	1619	1619

System management strategy (EMS)

The proposed strategy for managing the available production sources pursues a dual objective: minimizing the operational cost over the system’s lifecycle through optimized operation, while ensuring its long-term viability. This strategy is based on the automation of the start-up and shutdown mechanisms of the diesel generator, enabling activation or deactivation as soon as the required conditions are met, without any human intervention.

The management system receives, on an hourly basis, input data including solar irradiance, load consumption, battery state-of-charge, generator output, and load demand. These data are used to impose the scheduled output power of the energy sources and the battery, as well as the power imported from or exported to the main grid, should the system be connected to it. Based on the operational constraints, the implemented algorithm intelligently controls the start-up and shut-down of the generator, the charge and discharge cycles of the battery, and the utilization of photovoltaic solar energy. The desired functionalities of the proposed Energy Management System (EMS) are detailed in **Figure 11**.

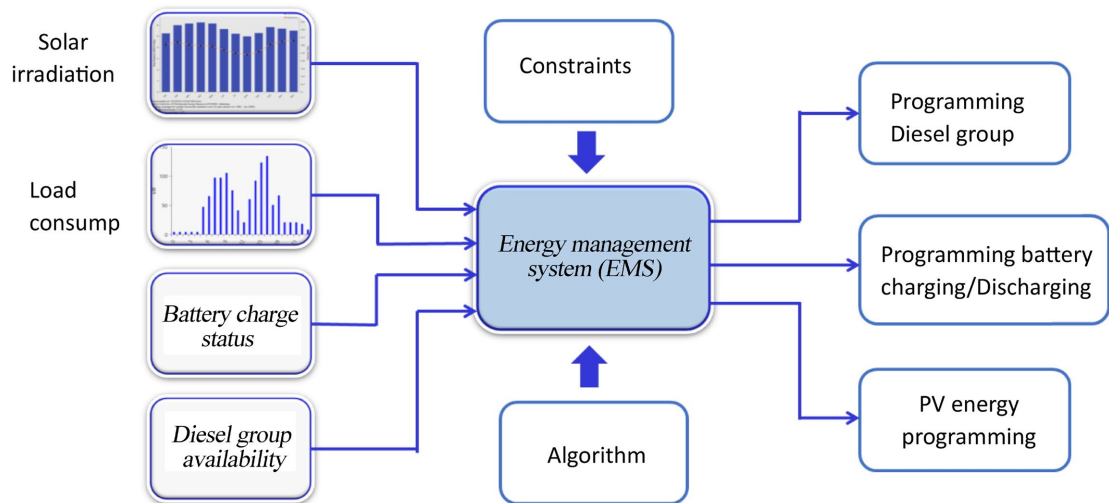


Figure 11. Schematic diagram of the proposed EMS for the mini smart grid.

The Energy Management System (EMS) will ensure optimal energy management according to the algorithm shown in **Figure 12**.

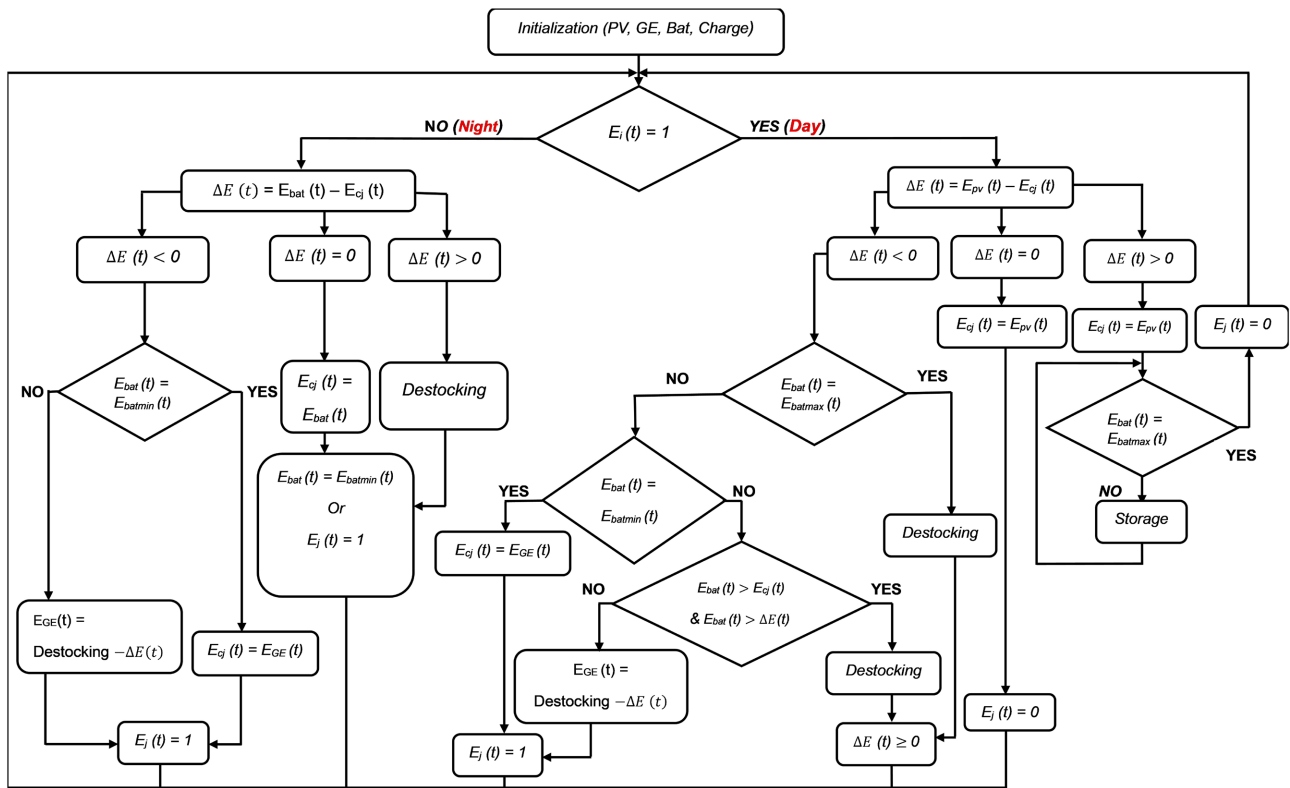


Figure 12. EMS management algorithm.

3. Results and Discussions

3.1. Influence of Operating Parameters on System Performance

To better assess the energy performance of the hybrid system, Figures 13-16 illustrate the evolution of the solar fraction (as defined in Equation (21)), the operating time, and the fuel consumption of the diesel generator over one year of operation, as functions of the PV array area and the battery bank autonomy.

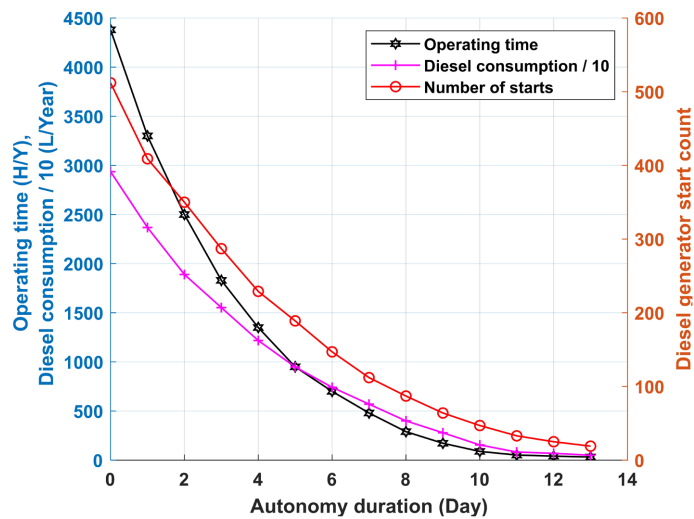


Figure 13. Effect of energy storage size on the operating parameters of a generator Set.

Figure 13 and **Figure 14** show the sensitivity of the diesel generator’s operating parameters—namely the number of start-ups, operating duration, and fuel consumption—to variations in PV array area and battery storage capacity, respectively. It is observed that the operating time, number of start-ups, and fuel consumption decrease more significantly as the storage capacity increases. The same trend is observed with increasing PV array area. Indeed, a larger storage capacity allows the battery bank to meet a greater portion of the energy demand, thereby reducing the frequency of diesel generator starts. This simultaneously explains the reduction in both operating time and fuel consumption. A similar influence is noted for the PV array size: its increase leads to higher PV energy production, which in turn reduces the operating time of the diesel generator.

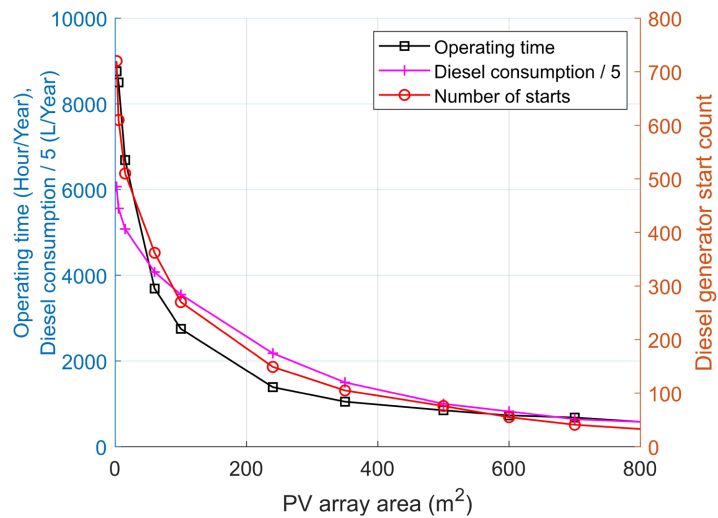


Figure 14. Effect of PV array size on the operating parameters of a generator set.

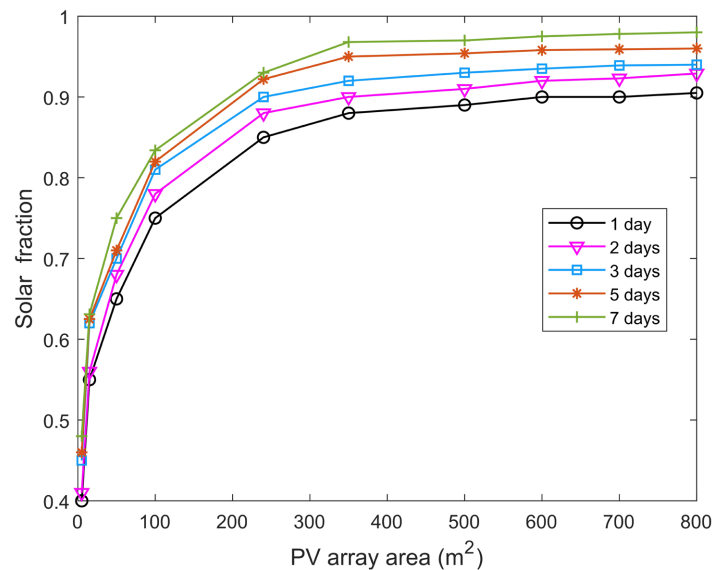


Figure 15. Evolution of the solar fraction with PV panel surface area for different storage sizes.

Similarly, an expansion of the PV array area augments solar energy production, further curtailing diesel generator usage.

Figure 15 and **Figure 16** respectively show the influence of the PV array size and the battery storage capacity on the solar fraction. It can be observed that the impact of the PV array surface area on the solar fraction is more significant than that observed when varying the size of the energy storage system. Beyond a PV surface area of 300 m², the solar fraction becomes almost insensitive to a storage capacity exceeding 4 days. These findings were predicted by the work of Ludmil Stoyanov [29] and M. Sidrach de Cardona and L.L. Mora Lopez [27].

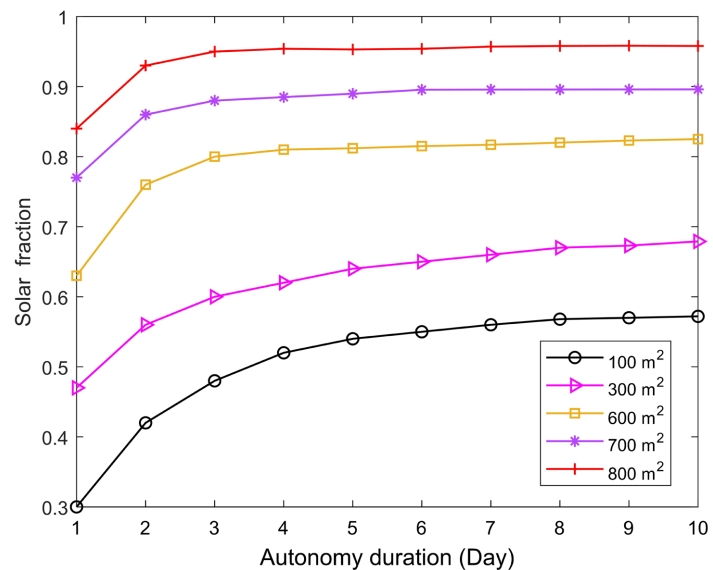


Figure 16. Influence of battery size for different panel surface areas.

3.2. Economic and Environmental Analysis of the Management System Results

Five (05) scenarios of the electrical energy production system were studied, each obtained by removing one or more components from the initial system. We primarily consider four (04) costs expressed in US dollars (\$): initial capital (IC), operating cost (OC), life-cycle cost (LCC), and cost of energy (COE).

Scenarios 4 and 5 are by far the least advantageous. They exhibit the highest LCC values, as well as the highest sum of initial capital and operating costs over twenty (20) years. Furthermore, they emit significantly more polluting gases and particles. Undoubtedly, these findings are attributable to the fact that electricity generation in these scenarios requires considerably more generator operating time and, consequently, a large amount of diesel fuel consumed.

Scenario 2 presents the lowest LCC and initial capital-operating cost combination. Moreover, it is the only scenario that does not include a PV generator. Scenarios 2 and 3 are those utilizing a PV generator and are advantageous.

Table 6 presents the results obtained from the implementation of the electrical production management system for the various scenarios.

Table 6. Financial details and performance metrics for each scenario.

▪ Cas 1: PV Generator (40 kW) + Diesel Generator (100 kW) + BAT (120) + Invertler (40 kW)														
Cost					BAT				Diesel Generator					
IC (\$)	OC (\$/yr)	LCC (\$)	COE (\$)	PV Capital Cost (\$)	PV Prod (kWh/yr)	IC + OC in 20 years (\$)	Autonomy (hour)	Annual Throughput (kWh/yr)	Nom. Capacity (kWh)	Usable Nominal capacity (kWh)	Hours	Prod (kWh/yr)	Fuel (L)	Fuel cost (\$/yr)
1.37 M	1.783 M	1.39 M	1.78	1.344 M	67,746	1.41 M	87.1	26512	858	601	70	2100	987	1777
▪ Cas 2: Diesel Generator (100 kW) + BAT ((120) + Inverter (80 kW)														
Cost					BAT				Diesel Generator					
IC (\$)	OC (\$/yr)	LCC (\$)	COE (\$)	PV CC (\$)	PV Prod (kWh/yr)	IC + OC in 20 years (\$)	Autonomy (hour)	Annual Throughput (kWh/yr)	Nom. Capacity (kWh)	Usable Nominal capacity (kWh)	Hours	Prod (kWh/yr)	Fuel (L)	Fuel cost (\$/yr)
37,619	43,625	601,584	0.771	0	0	910 119	87.1	58176	858	601	780	70,227	24,036	43,265
▪ Cas 3: PV Generator (80 kW) + BAT (72) + Inverter (40 kW)														
Cost					BAT					Diesel Generator				
IC (\$)	OC (\$/yr)	LCC (\$)	COE (\$)	PV CC (\$)	PV Prod (kWh/yr)	IC + OC in 20 years (\$)	Autonomy (hr)	Annual Throughput (kWh/yr)	Nom. Capacity (kWh)	Usable Nom. capacity (kWh)	Hours	Prod (kWh/yr)	Fuel (L)	Fuel cost (\$/yr)
2.7 M	130.46	2.7 M	3.47	2.688 M	135,492	2,702,609	52.3	18,643	515	360				
▪ Cas 4: Diesel Generator (100 kW) only														
Cost					Generator Diesel					Diesel Generator				
IC (\$)	OC (\$/yr)	LCC (\$)	COE (\$)	PV CC (\$)	PV Prod (kWh/yr)	IC + OC in 20 years (\$)	Hours	Prod (kWh/yr)	Fuel (L)	Fuel cost (\$/yr)	Hours	Prod (kWh/yr)	Fuel (L)	Fuel cost (\$/yr)
8000	226,791	2.94 M	3.77				4 543 820	8760	262,802	123,534	222,361			
▪ Cas 5: PV Generator (40 kW) + Diesel Generator (100 kW) + Inverter (20 kW)														
Cost					Diesel Generator					Diesel Generator				
IC (\$)	OC (\$/yr)	LCC (\$)	COE (\$)	PV Capital Cost (\$)	PV Prod (kWh/yr)	IC + OC in 20 years (\$)	Hours	Prod (kWh/yr)	Fuel (L)	Fuel cost (\$/yr)	Hours	Prod (kWh/yr)	Fuel (L)	Fuel cost (\$/yr)
1.36 M	216,165	4.15 M	5.32	1344 M	67,746	5,683,300	8348	250,440	117,723	211,902				

To further our analyses and account for green energy production aspects, we conducted a cross-analysis of the economic and environmental benefits of the three best scenarios and integrated abatement costs. **Table 7** and **Table 8** summarize the results of the environmental impact and abatement costs for Scenarios 1 and 2, respectively. The results show that integrating long-term pollutant emission abatement costs can reduce the economic gap between these two scenarios, but does not eliminate it. Consequently, from a purely economic standpoint, Scenario 2 (Diesel Generator—Storage System—Inverter) remains the most optimal, as it yields the most favorable life-cycle and energy costs. However, given the context of environmental preservation and the consequent need to integrate the con-

cept of green energy into electricity production systems, it is essential to focus more on Scenario 1 (Diesel Generator—PV Generator—Storage System—Inverter). This scenario best reconciles economic optimization with environmental protection.

Table 7. Analysis of environmental impact.

Cas	Energy production (%)		Fuel Consumption (L/day)	Emissions (kg/an)					
	PV	Diesel		CO ₂	CO	Unburned Hydrocarbon	Fine Particulate Matter	SO ₂	NO _x
1	97	03	02.7	2.607	2.26	0.326	0.237	6.33	4.21
2	00	100	65.9	63.485	55	7.93	5.77	154	102

Table 8. Abatement costs for Scenarios 1 and 2.

	Carbon dioxide (CO ₂)	Carbon monoxide (CO)	Unburned Hydrocarbon	Fine Particulate Matter	Sulfur dioxide (SO ₂)	Nitrogen oxide (NO _x)	Total Cost (\$)
Abatement Costs (\$/kg) [31]-[33]	0.27	0.27	0.156	0.3	0.156	0.189	-
Scenario 1 Emissions (kg/an)	2.61	2.26	0.326	0.237	6.33	4.21	-
Scenario 2 Emissions (kg/an)	63.48	55	7.93	5.77	154	102	-
Scenario 1: 20-Year Abatement Cost (\$)	14.078	12.204	1.021	1.422	19.825	15.914	64.464
Scenario 2: 20-Year Abatement Cost (\$)	342.82	297	24.837	34.62	482.33	385.56	1567.164

4. Conclusions and Perspectives

In this paper, we have designed and optimized a mini hybrid power plant to meet the daily electrical load of Yakoungou, a village in the Nakambé region of Burkina Faso. Using satellite data and field survey data, we were able to assess energy needs and size the essential components of the system. The study of the power plant's performance parameters showed that the various energies involved in the operation of this hybrid system depend more on the surface area of the PV modules than on the battery storage capacity. It is not advisable to configure the system with a storage capacity exceeding three days of autonomy, as beyond this value, the impact of increasing storage capacity becomes negligible.

Using the Energy Management System (EMS) designed and integrated into Homer Pro software, with the collected data as input parameters, we were able to study five scenarios by combining PV and diesel generators, batteries, and the inverter. The execution of the EMS made it possible to control the contribution to energy production of each component of the power plant. For example, by comparing the LCC and the sum of initial capital and operating costs over 20 years, while accounting for abatement costs related to pollutant emissions, it emerges that the scenario combining a diesel generator, PV generator, storage system, and inverter best reconciles economic optimization with environmental protection.

In terms of perspectives, we believe that implementing the Energy Management System for real-time testing could make it possible to validate the results of this study or, if necessary, improve the management algorithm to account for certain critical situations that may arise during power plant operation, particularly when considering grid connection, which can be a source of network instability.

CRedit Authorship Contribution Statement

Hassime GUENGANE: Writing—original draft, data collection, data processing and analysis, visualization, software, investigation, formal analysis.

Salifou OUEDRAOGO: Writing—review & editing, methodology, investigation, analysis of results.

Nébon BADO: Writing—review & editing, methodology, investigation, interpretation of results.

Boureima DIANDA: Review & editing, supervision, methodology, conceptualization, documentation.

Sié KAM: Supervision, methodology, investigation, documentation.

Dieudonné Joseph BAHIEBO: Review & editing, supervision, investigation, formal analysis.

Declaration pertaining to the use of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Deep Seek exclusively to enhance the English language quality and improve the readability of the text. Following its use, the content was reviewed and revised as needed. The author(s) assume full responsibility for the final content of the publication.

Conflicts of Interest

We declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

Symbol	Description
E_{ej}	Daily energy consumption (Wh/day)
K_p	Loss coefficient, $Kp = 0.50$ to 0.70
K_{slc}	Ratio of renewable energy to load demand
f_s	Solar fraction
E_t	Daily site irradiation (kWh/m ² /day)
T_α	Ambient temperature (°C)
T_{nom}	Nominal module operating temperature (°C)
η_m	Average module efficiency
$U_{cc.max}$	Maximum controller voltage
1.15	Reduction coefficient for calculating MPP voltage at 20°C
V_{oc}	Open-circuit voltage
INT	Integer part of the expression in parentheses
F_s	Safety factor
η_c	Converter efficiency
S_{cel}	Module surface area (m ²)
N_{ms}	Number of modules connected in series
E_{GE}	Daily energy production of the generator set
E_{PV}	Daily energy production of the PV array
E_{per}	Daily energy loss
E_{bat}	Energy demanded by the load at time t
$SOC(t)$	Battery state of charge at time t
$SOC(t-1)$	Battery state of charge at the previous time ($t-1$)
SOC_{min}	20% of the nominal capacity of the assembled batteries
SOC_{max}	95% of the nominal capacity of the assembled batteries
η_{bat1}	Battery energy efficiency during charging phase
η_{bat2}	Battery energy efficiency during discharging phase
η_{ond}	Efficiency of the reversible DC/AC battery converter
V_{ond}	DC input voltage of the reversible dc/ac converter on the battery side (48 V in this study)
n_j	Number of days of storage (autonomy)
R_{bat}	Battery efficiency (75% - 90%)
P_D	Depth of discharge
V_{bat}	Battery bank voltage
N_{as}	Number of batteries in series
N_{bp}	Number of parallel branches
T_n	Nominal battery voltage

Continued

C_n	Nominal battery capacity
D_{PV}	All PV array-related expenses
D_{GE}	All generator set-related expenses
D_{BAT}	All storage system-related expenses (investment, maintenance, operation, replacement)
D_{OND}	All inverter-related expenses
