

Analysis of the technical, economic and environmental optimization of the implementation of a Mini Smart Grid for the electrification of the rural area of Koumnéré in Burkina Faso

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ABSTRACT: This study concerns the implementation of a Mini Smart Grid (MSG) to optimize the use of energy produced by a hybrid PV/Diesel power plant with storage. Since this network has more than two energy sources, an Energy Management System (EMS) is essential to optimize energy distribution between these different sources. An energy management algorithm was developed, and the HOMER Pro modeling and simulation software was used. Five (05) scenarios relating to the combination of the different sources were considered: a complete system (PV Generator, Diesel, Storage, DC/AC converter) called scenario 1, a combination (Diesel Generator, Storage, DC/AC converter) called scenario 2, a combination (PV Generator, Storage, DC/AC converter) called scenario 3, a limitation of the system to Diesel Generator alone which constitutes scenario 4 and finally a last combination (PV Generator, Diesel, DC/AC converter) which is scenario 5. An economic analysis using life-cycle cost and energy cost indicators revealed that the best scenario, in this sense, is scenario 3 (8.12 million FCFA; 10.40 million FCFA). It comes before scenario 1 (12.20 million FCFA; 15.63 million FCFA). This was followed by an environmental pollution analysis. It showed that the most environmentally friendly scenario is scenario 3 because it emits no harmful gases or particles; scenario 1 has very low emissions (2607 kg/year of CO₂), it is not perfectly environmentally friendly, but it is acceptable as a system. With population growth, energy intermittency may occur in this system. Scenario 1 will then become the best scenario. The integration of drawdown costs will not affect the results because the scenarios defined as best are also the least polluting.

KEYWORDS: energy, mini smart grid, scenarios, economic study, environmental study.

1 INTRODUCTION

Energy in general, and in particular its most convertible form, electrical energy, is at the heart of all development [1], [2], [3]. It is undeniable that fossil fuels alone cause significant environmental pollution [4]. The new paradigm is energy production that takes environmental preservation into account. This is why renewable energies are gradually being integrated into production systems, creating an energy mix [4]. To compensate for the intermittent production of PV generators and for backup needs, a diesel generator is often necessary. To increase the efficiency of an energy mix, an effective management system is essential.

The objective of this study is to implement smart management of a hybrid PV/Diesel mini-power plant for the electrification of a rural area in Burkina Faso called Koumnéré.

This production system, with its management capabilities, constitutes a Mini Smart Grid (MSG) capable of performing several optimization activities, including:

- Reducing fluctuations in renewable energy;
- Promoting the use of renewable energy;
- Smoothing the load curve;
- Ensuring energy exchange between sources, import/export.

2 MATERIALS AND METHODS

The Mini Smart Grid, which will be connected to a future electrical grid, will consist of several energy sources such as photovoltaic energy (PV), diesel generator energy (DG), and battery energy (BAT) to intelligently power a variable load (CHv). When a system (electrical grid) has more than two energy sources, the need to integrate a management system becomes essential to facilitate and optimize power sharing between the sources. System management and control will then be carried out by an Energy Management System (EMS) [5], [6], [7], [8], [9]. The configuration of the Mini Smart Grid (MSG) system is shown in Figure 1. Two possible scenarios have been presented:

- **Case 1:** The entire system is not yet connected to the electrical grid (future grid):

In this case, priority for powering the load is given to the PV generator, then to the storage batteries, before being transferred to the diesel generator (one after the other is depleted);

- **Case 2:** The entire system is already connected to the electrical grid (future grid): In this case, the main grid will supply energy when the load demand exceeds the combined power (PV, GE, BAT). When the power from decentralized production exceeds the load demand, the excess energy charges the batteries and is fed back into the grid if the batteries are charged. In all cases, the battery charge/discharge process and energy import/export can be managed autonomously.

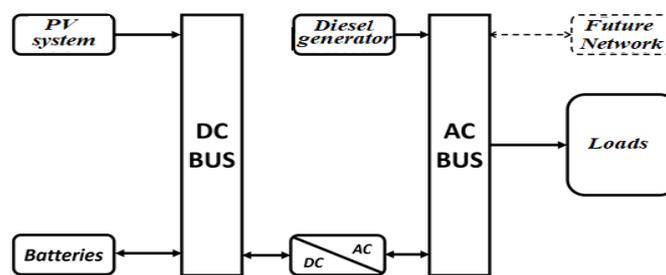


Fig. 1. Hybrid PV/Diesel System with Storage

The management system will therefore receive hourly values such as: solar irradiance, battery state of charge, diesel generator output, and load consumption, in order to set the programmed output power of the energy sources and the battery, as well as the input/export power with the main grid if the system is connected to it.

The energy management system (EMS) will be responsible for optimal energy management according to the programmed management algorithm.

Figure 2 details the desired functions of the EMS.

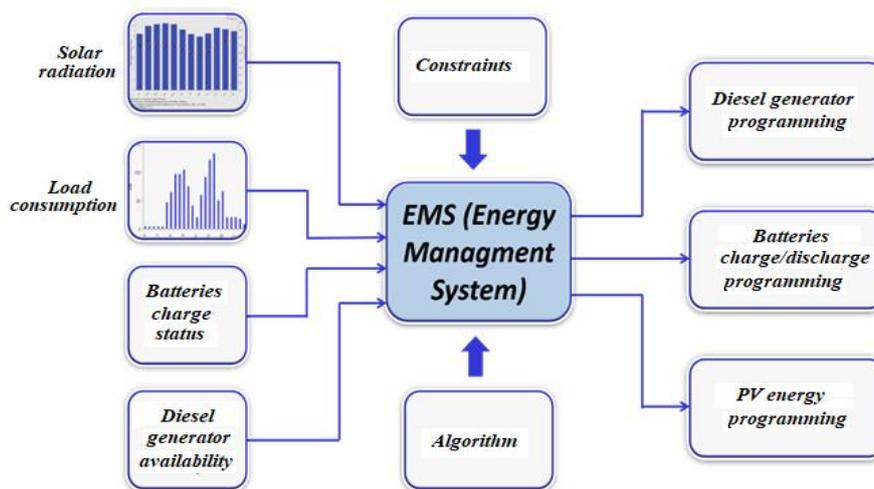


Fig. 2. Proposed EMS for the mini smart grid

The constraint management plan aims to maximize the use of renewable energy and to use diesel only when absolutely necessary. To achieve this, several rules apply:

- Photovoltaic energy is primarily used to power loads;
- The electrical energy storage system is charged by surplus renewable energy;
- The electrical energy storage system discharges when the photovoltaic system is insufficient;
- The generator supplies power to the load when the PV production system and the storage system are insufficient.

It is important to note that if the system gains access to the centralized grid, the following scenarios must be considered:

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

The constraints are defined as follows:

- Constraints on the output power of the storage system:

Equation (1) gives the constraints on the output power of the storage system.

$$P_{BATmin} \leq P_{BAT}(t) \leq P_{BATmax} \tag{1}$$

With P_{BATmin} : Minimum storage system power; $P_{BAT}(t)$: Storage system output power at time t and P_{BATmax} : Maximum storage system power;

- State of Load Constraints of the Storage Operational Capability (SOC):

The state of load constraints of the storage system are given by equation (2).

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{2}$$

With SOC_{min} : minimum battery charge level; $SOC(t)$: battery charge level at time t ; and SOC_{max} : maximum battery charge level.

2.1 SYSTEM ALGORITHM DEFINITION

The algorithm defined in Figure 3 ensures optimal management of this hybrid energy system.

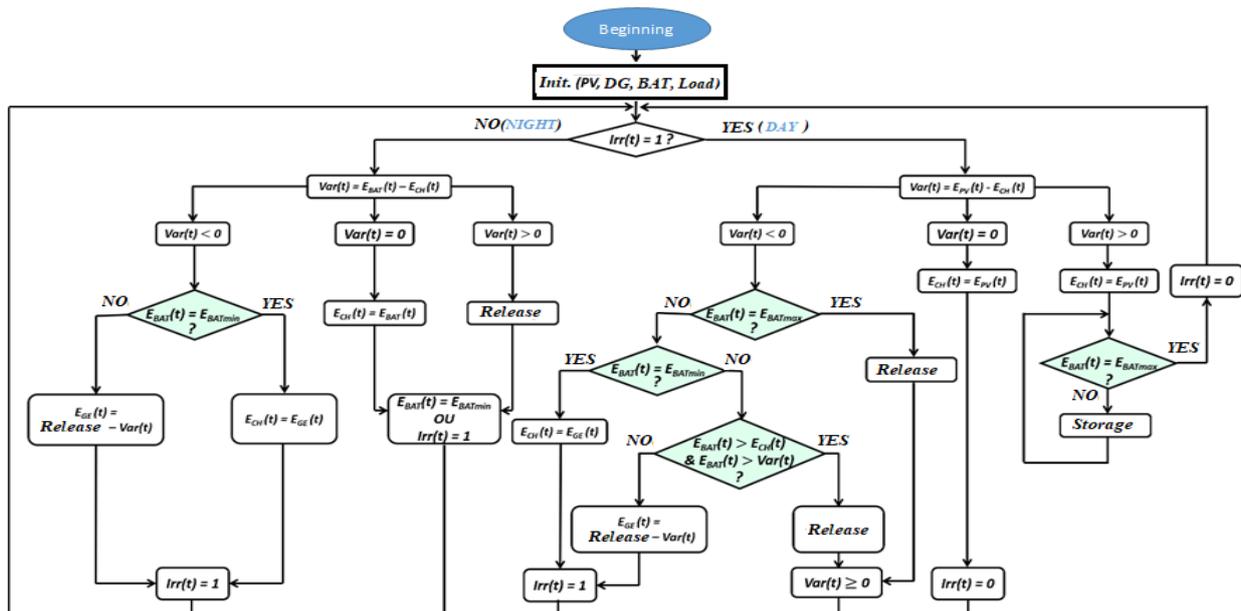


Fig. 3. Energy management algorithm for the mini smart grid

(Irr = 1) and (Irr = 0): presence and absence of solar radiation, respectively;

Var: Energy variation;

E_{CH} : Load energy (load energy requirement);

E_{PV} : Photovoltaic system energy;

E_{BAT} : Battery energy;

DGE: Diesel generator energy;
 E_{BATmin} : Minimum battery energy (depth of discharge reached);
 E_{BATmax} : Maximum battery energy (batteries fully charged);
 DG: Diesel generator;
 BAT: Energy storage system.

As a software tool, HOMER Pro (Hybrid Optimization Model for Electric Renewable) was used. It is a sophisticated energy modeling software designed to model and optimize hybrid energy systems [1].

It was developed in 1993 by the National Renewable Energy Laboratory for rural electrification programs and has been available under the HOMER Energy license since 2009 [1].

Due to its advanced features, it allows users to create flexible configurations integrating different energy sources such as solar, wind, hydropower, fuel cells, biomass, diesel, battery storage, and many others. The tool also assesses the economic viability of energy solutions by analyzing life-cycle costs and generating detailed reports.

Using optimization algorithms, HOMER Pro searches for the most efficient and cost-effective system configuration. Users can simulate different scenarios to assess the system’s robustness in the face of load variations or equipment failures. With its user-friendly interface, HOMER Pro facilitates the visualization of performance data and the comparison of different configurations, thus helping engineers, energy planners, and decision-makers design sustainable and reliable energy solutions.

Furthermore, a future connection of the system to the electrical distribution network could be envisaged, potentially leading to the flow of energy in both directions and requiring new considerations for its smart management and marketing [2], [3]. As the system becomes more complex with more components, the generated data will become increasingly massive. A data distribution service will then be necessary to enable real-time processing of this data in order to guarantee and optimize energy flow within the smart grid [4], [5], [6], [7], [8].

2.2 SYSTEM CONFIGURATION AND SIMULATION WITH HOMER PRO

To perform the simulation using HOMER Pro, several input data points are required [5]. These include the site’s geolocation within the software and the configuration of the PV generator, the diesel generator and its fuel, the inverter, and the storage system.

Site Geolocation within the Software: You can enter the site’s geographic coordinates or search directly by site name [9].

Figure 4 shows the geolocation of the Koumnéré site with its various geographic coordinates.

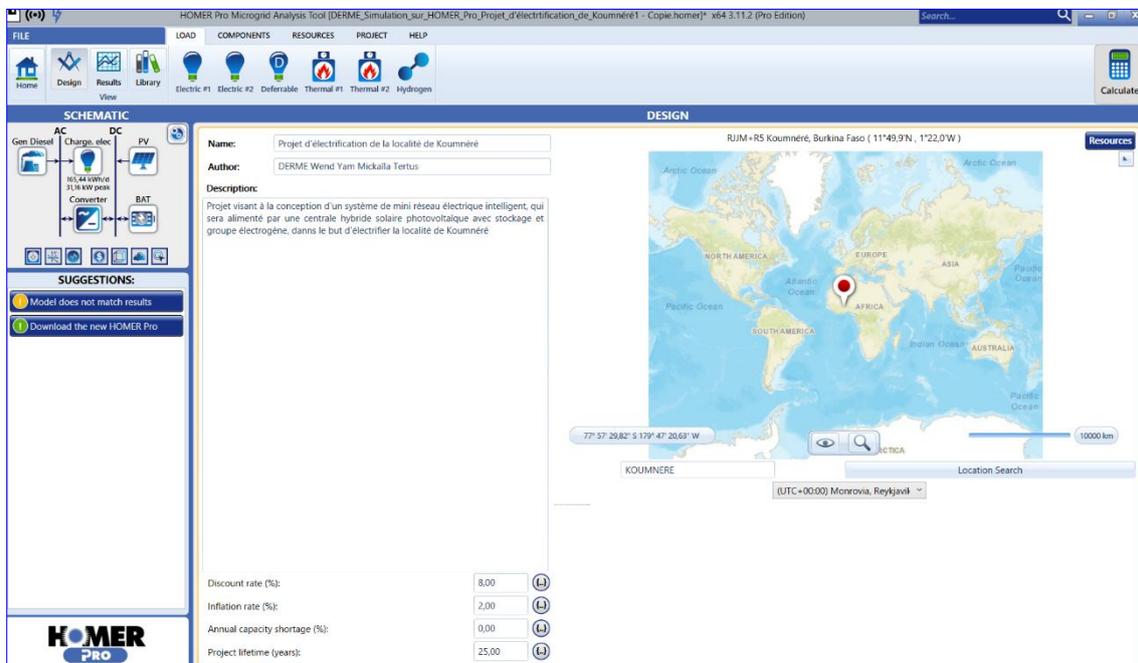


Fig. 4. Geolocation of the Koumnéré site

- Energy requirements of the load: These are highly variable; indeed, we have proposed a load model based on certain assumptions for a 24-hour period.
- From midnight to 4: 00 AM, the load requirements are low (around 5 kWh), as they generally relate to public lighting;
- At 5: 00 AM, the load begins to increase; it rises to over 100 kWh around 9: 00 AM because the mills are likely to be in use at this time; the load begins to decrease again from 10: 00 AM to around 20 kWh at noon, due to breaks.

Note that the load remains significant between 8: 00 AM and 12: 00 PM due to the high demand from various sources, including the school, welding workshops, and mills.

- In the afternoon, demand increases further, peaking at 4: 00 PM due to the high demand from the school, mills, welding workshops, and some household needs.
- The load then decreases and stabilizes at approximately 20 kWh between 7: 00 PM and 1: 00 AM, primarily due to household needs and public lighting. Figure 5 illustrates the daily energy demand of the Koumnéré area, showing the daily variation in power required to supply these loads.



Fig. 5. Energy requirements of the load

- Parameterization of the PV generator, the Diesel generator and its fuel, the inverter and the storage system: Parameterization consists of entering the prices and characteristics of the systems concerned. Figures 6, 7, 8, 9 and 10 respectively give an idea of the respective parameters of the PV generator, Diesel generator, fuel, inverter and storage system [10].

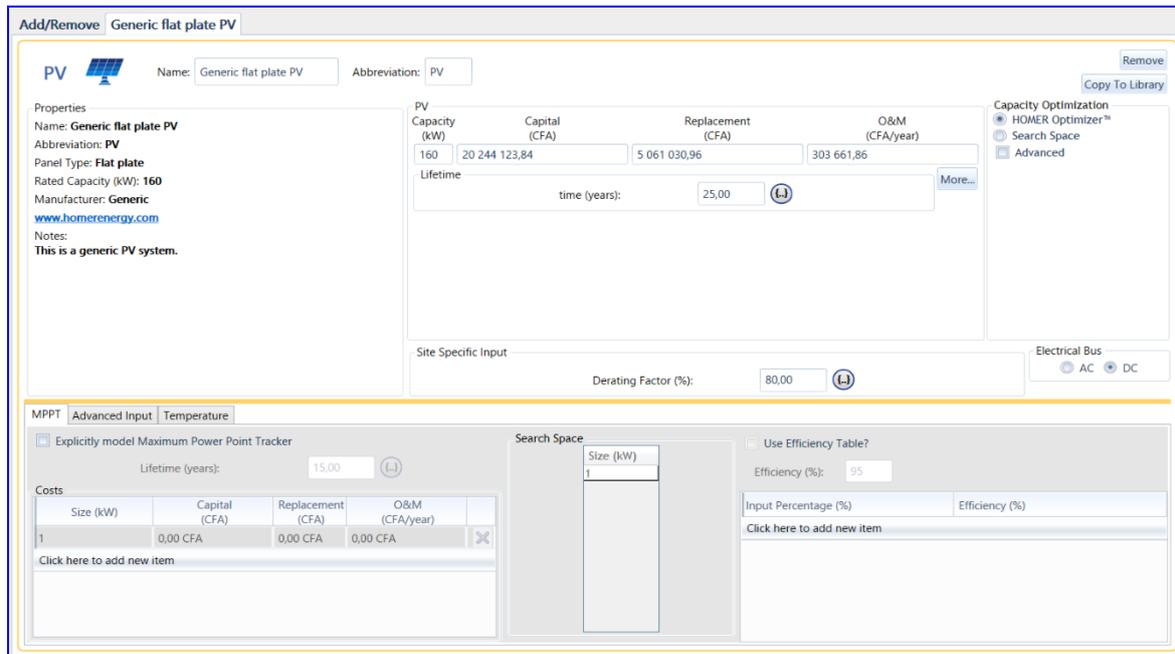


Fig. 6. PV generator settings

The generator set is sized for a power of 100 kVA with a nominal fuel consumption of 5.75 L/hr (Figure 7).

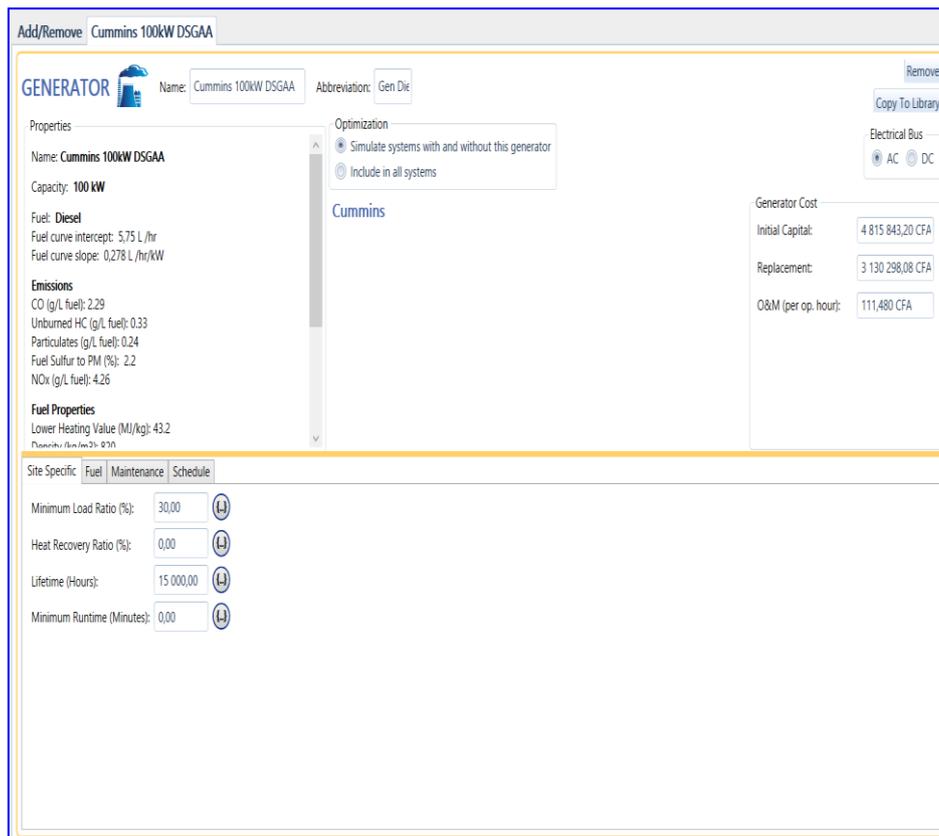


Fig. 7. Diesel generator settings

The fuel chosen is conventional diesel. Its characteristics are defined on the interface in Figure 8.

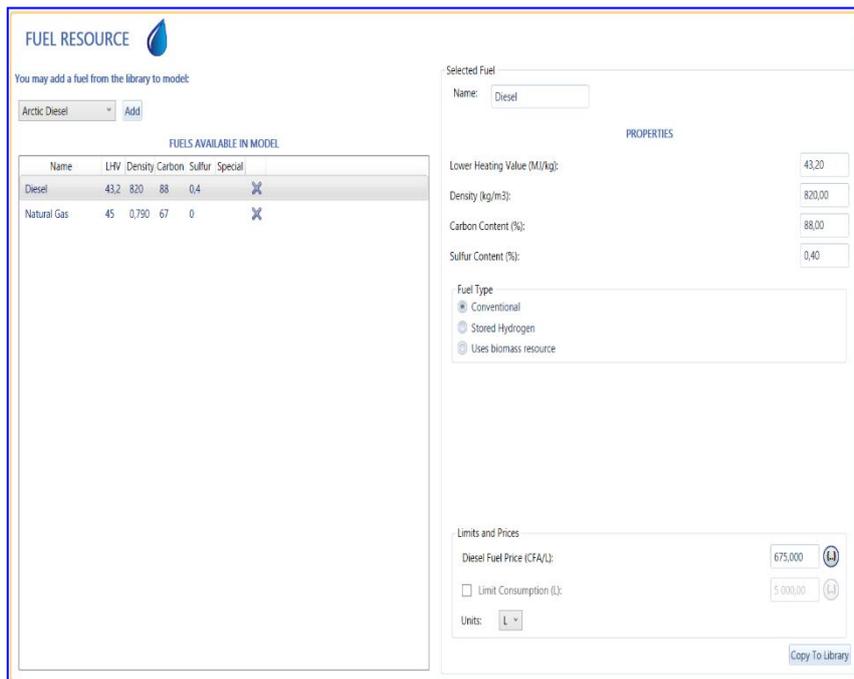


Fig. 8. Diesel generator fuel settings

The sized DC/AC converter has a nominal power of 100 kVA. Its initial cost, other costs related to its maintenance and use, as well as other characteristics, are parameterized in Figure 9.

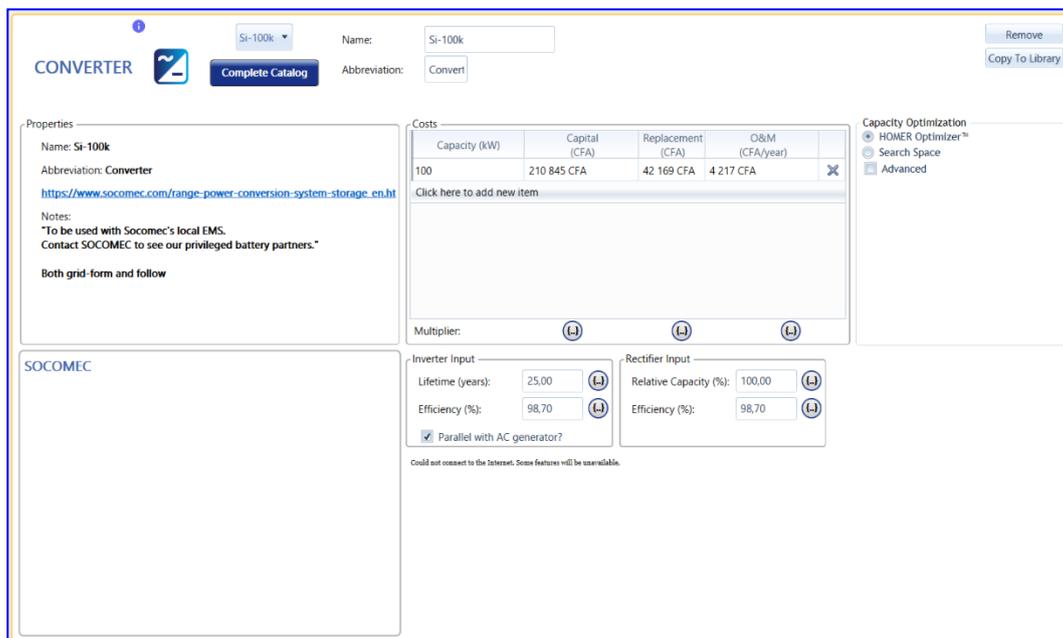


Fig. 9. Inverter settings

Figure 10 shows the parameterization of the storage system consisting of 120 batteries with a voltage of 2 V and a capacity of 7.15 kWh.

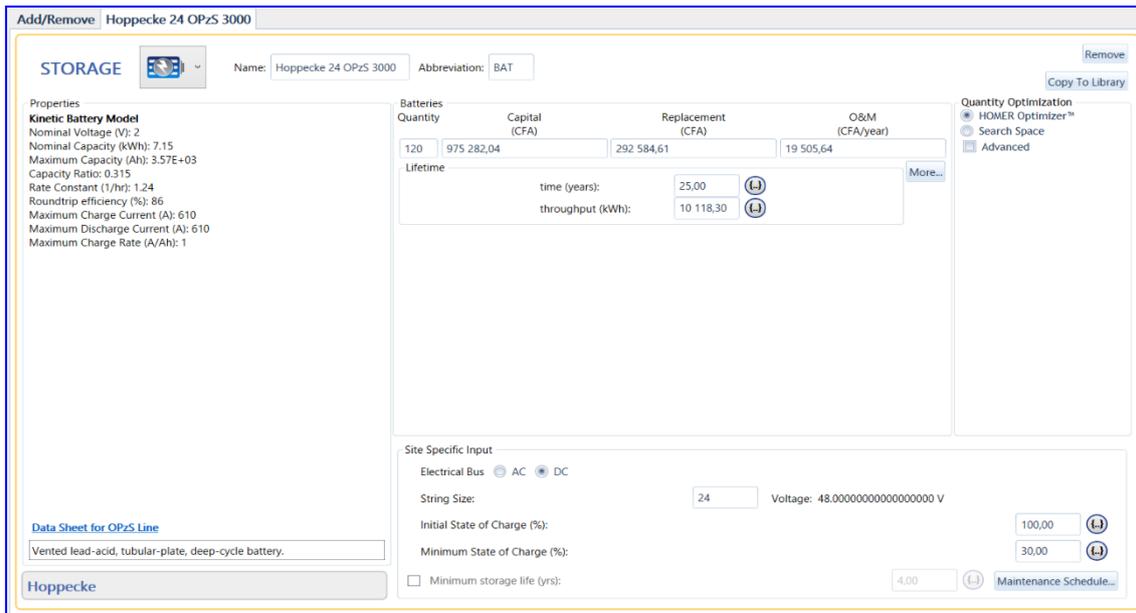


Fig. 10. Storage System Configuration

2.2.1 CLIMATE DATA GENERATION

Climate data such as solar radiation and temperature are generated directly by the software using the entered geographic coordinates. Figures 11 and 12 show the annual solar radiation and temperature data for the Koumnéré area, respectively.

- Solar radiation:

Figure 11 provides an estimate of the site’s solar radiation at different times of the year.



Fig. 11. Solar radiation at the Koumnéré site

- Temperature:

The temperature evolution at the site is shown in Figure 12.



Fig. 12. Average monthly and annual site temperature

2.2.2 SYSTEM DIAGRAM PROPOSED BY HOMER PRO SOFTWARE

HOMER Pro generates a diagram once the system components have been selected and characterized.

Figure 13 provides details of the system diagram proposed by HOMER Pro software.

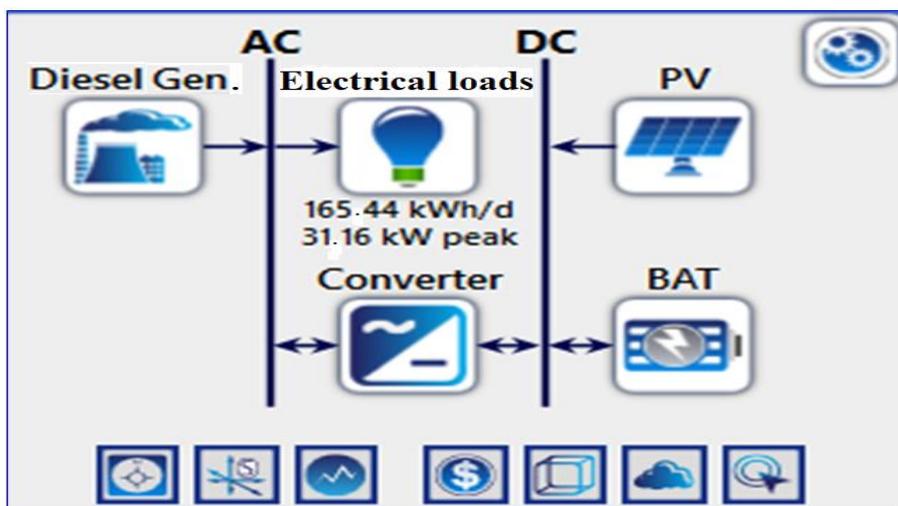


Fig. 13. Diagram of the system proposed by the HOMER Pro Software

After entering this data and launching the calculation (simulation), HOMER Pro provides us with results, which we will present below.

3 RESULTS AND DISCUSSION

3.1 SIMULATION RESULTS FOR DIFFERENT SCENARIOS

The simulation results are summarized in Tables 1.1 and 1.2. These tables present the financial details and system performance. Five scenarios were considered in the calculation of the results. These scenarios were obtained by automatically removing one or more system components before the simulation. They are:

- **Scenario 1:** Complete system (PV generator + Diesel generator + Storage + DC/AC converter);
- **Scenario 2:** Removal of the PV generator (Diesel generator + Storage + DC/AC converter);
- **Scenario 3:** Removal of the Diesel generator (PV generator + Storage + DC/AC converter);
- **Scenario 4:** Removal of the PV system, storage, and inverter (Diesel generator);
- **Scenario 5:** Removal of the storage system (PV generator + Diesel generator + DC/AC converter);

Tables 1.1 and 1.2 present the results of the HomerPro simulation, which ranks the different scenarios in order of best performance.

Table 1.1. Summary of simulation results

Configuration				Costs				Systems		Diesel generator					PV generator					
				PV generator (kW)	Diesel generator (kW)	Batteries	DC/AC converter (kW)	Energy cost (COE) in F cfa	Net updated cost (NPC) in F cfa	Operating cost in F cfa	Initial capital in F cfa	Renewable energy fraction (Ren Frac) in %	Total quantity of fuel (in Litres/year)	Operating time in (hours)	Production (in kWh)	Fuel consumed (in litre)	Operating and de maintenance Cost (O&M cost) (in F cf/an)	Fuel cost in (F cfa)	Capital (in F cfa)	Production (in kWh/year)
				43.4		144	35.8	10,4	8.12 Millions	107 215	6,73 Millions	100	0						5 486 468	74 822
				43.5	100	144	30.8	15,63	12.2 Millions	50 621	11.5 Millions	100	0	0	0	0	0	0	5 498 180	74 982
					100	1824	96.9	262,41	205 Millions	14.3 Millions	19.8 Millions	0	20 648	616	61 444	20 648	68 672	13 937 476		
				221	100		38.4	798,77	624 Millions	45.7 Millions	32.9 Millions	0	65 053	4 613	138 390	65 053	514 257	43 910 456	27 985 484	381 655
					100			1432	1.12 Milliard	86.1 Millions	4.82 Millions	0	123 534	8760	262 802	123 534	976 565	83 385 488		

Table 1.2. Summary of simulation results

Configuration				Batteries				DC/AC converter					
				PV generator (kW)	Diesel generator (kW)	Batteries	DC/AC converter (kW)	Autonomy (heure)	Total quantity of energy that passes through the batteries (charge-discharge) pro year	Nominal capacity (kWh)	Usable capacity (en kWh)	Average power of rectifier (kW)	Average power of DC/AC converter(kW)
				43.4		144	35.8	105	25 360	1029	721	0	6.89
				43.5	100	144	30.8	105	25 335	1029	721	0	6.89
					100	1824	96.9	1324	61 228	13 040	9128	6.43	6.40
				221	100		38.4					0	5.26
					100								

- : PV Generator
- : Diesel Generator
- : Batteries
- : DC/AC Converter

3.2 ECONOMIC AND ENVIRONMENTAL ANALYSIS OF THE RESULTS

Table 1 summarizes the results of the five (5) scenarios; however, each scenario contains more detailed system results. For the analysis, we will present the results of the different scenarios in tables to simplify the process.

3.2.1 ECONOMIC ANALYSIS

This analysis will primarily consider four costs:

- Initial capital in CFA francs (FCFA);
- Operating cost in CFA francs per year (FCFA/year);
- Life cycle cost (LCC) or Net present cost (NPC) in FCFA;
- Cost of energy (COE) in CFA francs (FCFA).

The results in Table 1 allow us to create Table 2 (comparative table):

Table 2. Different Costs of the 5 Scenarios

Scenarios	Initial capital (FCFA)	Operating cost (FCFA/year)	Initial capital + operating cost for 20 years (FCFA)	Life cycle cost (FCFA)	Energy cost (FCFA)
Scenario 1	11.5 Millions	50 621	12.513 Millions	12.2 Millions	15.63
Scenario 2	19. 8 Millions	14.3 Millions	306.813 Millions	205 Millions	262.41
Scenario 3	6.73 Millions	107 215	8.875 Millions	8.12 Millions	10.4
Scenario 4	4.82 Millions	86.1 Millions	1.727 Billiards	1.12 Millions	1432
Scenario 5	32.9 Millions	45.7 Millions	946.9 Millions	624 Millions	798.77

In terms of initial capital and operating costs, we observe that:

- Scenario 4 has the lowest initial capital of all, but the highest operating costs compared to the other scenarios; projecting over 20 years, this scenario becomes the most expensive on the list.

Therefore, financially speaking, this scenario is not feasible for our system.

- Scenario 5 has a very high cost compared to the other three (scenarios 1, 2, and 3), both for initial investment and operating costs.

Therefore, scenario 5 is also not feasible for our system because it is very expensive [6], [7].

- Scenario 2 is also unsuitable for our system, because when compared to scenarios 1 and 3, we find that it has higher investment and operating costs.
- Between scenarios 1 and 3, the 20-year projection shows that scenario 3 is the most financially suitable, followed by scenario 1.

Indeed, the best economic indicators for choosing the best scenario for our system are the life-cycle cost and the energy cost [8], [9]. The best system is the one with the lowest life-cycle and energy costs.

Thus, we note in Table 2 that the best scenario in terms of economics is scenario 3, ahead of scenario 1. This confirms the results of the analysis on initial capital and operating costs.

3.2.2 ENVIRONMENTAL ANALYSIS

We summarize the results with an environmental impact in Table 3:

Table 3. Simulation Results on Environmental Impact

Scenarios	Energy production (%)		Fuel consumption (litre/day)	Emissions (kg/year)					
	PV	Diesel		Carbon dioxide (CO ₂)	Carbon monoxide (CO)	Unburned hydrocarbon	Fine particles	Sulfur dioxide	Nitrogen oxide
Scenario 1	97	03	02.7	2607	2.26	0.326	0.237	6.33	4.21
Scenario 2	00	100	56.6	54536	47.3	6.81	4.94	132	88
Scenario 3	100	00	00	00	00	00	00	00	00
Scenario 4	00	100	338	326279	283	40.8	29.6	792	526
Scenario 5	23.3	78.7	178	171817	149	21.5	15.6	417	277

- We note that scenario 3 has no emissions because it does not contain a diesel generator.
- For the other scenarios, the more the diesel generator is used (high fuel consumption), the greater the emissions (gaseous and particulate).
- Since the emissions of scenarios 4 and 5 are too high, they are not suitable for our system.

Therefore, we will choose the first three scenarios (1, 2, and 3).

- Of these three scenarios, scenario 3 is the most environmentally friendly because it emits no harmful gases or particles.
- Scenario 1 has very low emissions; it is not perfectly environmentally friendly, but is quite acceptable for our system.
- Scenario 2 does not emit as much as scenarios 4 and 5, but it does produce a significant amount of gaseous and particulate emissions.

3.3 COMPARISON OF ECONOMIC AND ENVIRONMENTAL ANALYSES

Even before performing the comparison, we note that scenario 3 is not only more economically advantageous but also emits no polluting particles. Thus, scenario 3 (PV Generator – Storage System – DC/AC converter) is ideal for our Mini Smart Grid system in terms of both economic and environmental benefits [11]. With proper sizing of the storage system, we can reduce the intermittency of energy production.

However, in the medium to long term, with population growth and technological advancements (increasing energy needs) as well as climate variations (long periods of low sunlight), energy intermittency may develop in this system. Therefore, the study is extended by selecting scenario 1 (Diesel Generator – PV Generator – Storage System – DC/AC converter) as the best scenario, as this system better manages energy intermittency while offering significant economic and environmental advantages (close to those of scenario 3) [5], [12], [13].

As for scenarios 2, 4 and 5, they cannot be adopted for our Mini Smart Grid because they are not only very expensive but also emit large quantities of gases and particles harmful to the environment.

3.4 INTEGRATION OF ABATEMENT COSTS FOR SCENARIOS 1 AND 2

Abatement costs primarily concern taxes related to pollutant emissions.

Integrating these costs will not affect the results determined above (in either the long or short term), as the scenarios defined as best are also the least polluting. Table 4 provides an overview of abatement costs for different types of pollutants.

Table 4. Table of abatement costs by pollutant emission type [14]

Pollution elements	Carbon dioxide (CO ₂)	Carbon monoxide (CO)	Unburned hydrocarbon	Fine particles	Sulfur dioxide	Nitrogen oxide
Cost of abatement (\$/kg)	0.27	0.27	0.1566	0.3	0.1566	0.189

4 CONCLUSION

In our study, we designed and analyzed a Mini Smart Grid system for the electrification of the locality of Koumnéré in Burkina Faso. Our main objective was to develop a reliable and sustainable electrification solution using a hybrid power plant composed of a photovoltaic (PV) solar array, an energy storage system, and a diesel generator to compensate for energy intermittency [15], [16].

The results obtained were evaluated across five (5) different scenarios, focusing on economic and environmental aspects. Initially, the PV-storage- DC/AC converter combination (scenario 3) showed significant potential for meeting Koumnéré’s energy needs. However, this system presented limitations due to the intermittency of solar production and the variability of electricity demand.

To address these shortcomings, we integrated a diesel generator into the initial system. This configuration, including a PV generator, a diesel generator, a storage system, and an DC/AC converter (scenario 1), proved to be the most efficient. It ensures a continuous and reliable power supply while optimizing costs and reducing the carbon footprint compared to a solution entirely dependent on fossil fuels [16], [17], [18].

In conclusion, the best system proposed for the electrification of the Koumnéré community relies on a synergy between renewable and conventional energy sources. This hybrid system combines the sustainability and environmental benefits of solar PV with the operational reliability of a diesel generator. This approach guarantees a stable and continuous power supply, tailored to the community’s needs, while contributing to the energy transition and the reduction of greenhouse gas emissions.

This work highlights the importance of an integrated approach to the development of energy infrastructure in rural areas, reconciling technological innovation, environmental sustainability and economic viability [19], [20].

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