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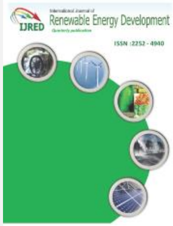

***Research Article***

# Study and Optimization of a Hybrid Power Generation System to Power Kalakala, a Remote Locality in Northern Côte d'Ivoire

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**Abstract**. This work presents the results of a study to optimize the production of electricity, by hybrid system Photovoltaic – Diesel – Batteries, to power the village of Kalakala in the north of Côte d'Ivoire. The study site is an isolated rural community, powered by a diesel generator. It is located in northern Côte d'Ivoire. HOMER software has been used for system simulation and optimization. The result of this study is then compared to those of PV - Batteries and diesel alone systems. From the results of the simulations, it appears that the optimal combination of the hybrid system includes a diesel generator of 50 kW, a photovoltaic field of 46 kW, 10 batteries of 48V and a converter of 100 kW. With a photovoltaic penetration rate of 52.7%, this system, compared to the photovoltaic - batteries system, reduces the photovoltaic field by 56%, the number of batteries by 61.5% and increases battery life by 42.84%. Compared to diesel alone, it reduces fuel consumption and the quantity of $CO_2$ by 60% and improves diesel efficiency by 17%. The cost of generating electricity for the hybrid system is €0.373/kWh compared to €0.466 and €0.608/kWh respectively, for the PV-Batteries and diesel alone systems. The hybrid system with the best technical, economic and environmental performance could be a good alternative for generating electricity in remote communities.

***Keywords:*** Hybrid systems; Photovoltaic; Diesel generator; Batteries, HOMER software.

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## 1. Introduction

Electricity is an essential resource for most human activities and vital to the daily needs of modern man (Vu, 2011). Indeed, since the first high-voltage Alternating Current (AC) coal power station was commissioned in London in 1890, electrification of residential and industrial installations has grown exponentially expanding toe 83% of all urban areas (Pasetti et al., 2018; Chowdhury *et al.*, 2020). However, it remains inaccessible to more than 750 million people worldwide. In Côte d'Ivoire, despite state efforts in recent years to improve the electrification rate, more than 6 million people are without access to electricity in 2019 (IEA, 2020). The situation is worse in rural areas where only 51% of the population has access to electricity. Electricity supply in remote rural areas in Côte d'Ivoire is made using two techniques: rural electrification by extension of the national electricity grid and decentralized rural electrification. The extension of the interconnected national network to rural communities presents shortcomings such as the insufficient production capacity which leads to offloading, limited capacity of the transport network leading to significant voltage drops, and high cost of connection of localities. In addition, the demand for electricity in rural areas is low, which makes extension projects unprofitable.

To get around these difficulties, decentralised power generation systems, via autonomous mini-grids, appear to be a viable alternative. As in many developing countries, mini-grids still rely mainly on fossil fuel-fired diesel generators (DG). However, the combustion of fossil fuels is the biggest contributor to greenhouse gases discharged into the atmosphere. In addition, the consumption of fossil fuels continues to increase at the fastest rate due to population and economic growth. These non-renewable resources are limited and their consumption is at a much higher rate than the available fossil fuel resources

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*Corresponding author: blaise.koua@univ-fhb.edu.ci (depletion of fossil fuels). To overcome the energy challenges with respect to greenhouse gas emissions or air pollution, the depletion of fossil fuel resources, and the high-energy demand, the development, and integration of sustainable and clean energy systems and renewable and alternative fuels are needed (Salas *et al.*, 2015; Ghenai *et al.*, 2020). Sustainable energy systems using renewable resources such as wind, solar, ocean, biomass, geothermal are needed to increase the penetration of renewable power systems in the energy mix.

The development and the integration of clean power systems and renewable and alternative fuels for residential and commercial buildings, transportation, and industrial applications will help to meet the future energy demand due to population growth, reduce the environmental impacts of fossil fuel combustion, and slow down our dependency on fossil fuels. The development and implementation of renewable energy systems such as solar photovoltaic is the key solution for climate change mitigation and energy security (Ghenai *et al.*, 2019). The lower costs associated with photovoltaic energy make its use more and more competitive in highly sunny regions. This is why, recently, the use of photovoltaics in isolated sites is experiencing a resurgence of interest, particularly for large-scale uses (village, industry) (Thibaud, 2014). In Côte d'Ivoire, the government intends to promote the development of renewable energies, including solar photovoltaic energy. But a systematic replacement of DG by solar photovoltaic would have consequences both technically and economically. Indeed, the cost of solar panels and their installation is still high, although the trend is downward. In addition, the energy produced is intermittent in nature and has problems meeting long-term energy demand (Rashidi *et al.*, 2012; Wang *et al.*, 2021) and the cost of battery storage (BAT) is high (Belanger-Gravel, 2011).

To overcome these difficulties in the application of decentralised systems, the option suggested is to use hybrid energy systems, which can also be a combination of renewable and non-renewable sources (Fan *et al.*, 2020; Wang *et al.*, 2021). These hybrid systems can combine GD-based electricity with that produced from solar energy, clean energy (Albadi *et al.*, 2014), renewable and very abundant in tropical countries such as Côte d'Ivoire, can be used. These systems are associated with an electrical energy storage device by the batteries.

Extensive research has been conducted on the performance of hybrid power systems in several countries around the world and for various applications. Adaramola *et al.* (2014) presented an economic analysis of the feasibility of utilizing a hybrid energy system consisting of solar, wind, and diesel generators for application in remote areas of southern Ghana. Chowdhury *et al.* (2015) provided critical insides into the case of Bangladesh for a cost-effective route to sustainable energy access for all goals by applying practical and resource-efficient mini-grid design principles. Planning and operation techniques have been elaborated on in detail and concluded with financial analysis for a hybrid solar-PV-Diesel mini-grid that provides enhanced energy access in particular for productive use. Peerapong and Limmeechokchai (2017) analyzed the viability to increase solar photovoltaic (PV) resources in the existing diesel-based systems. The hybrid PV/diesel system is not only reducing the cost of electricity generation but also decreasing the harmful emissions from fossil fuels. Maleki and Rosen (2017) examined the performance of a hybrid energy system composed of fuel cells and wind turbines for a residential building in Iran and showed that the use of fuel cell waste heat improves system operation and increases its economic justification and reliability. Arnaoutakis *et al.* (2018) presented the energy modeling and the life cycle analysis of a generic hybrid power system installed on the island of Crete, Greece. Their studied system comprises a cogeneration system, photovoltaics, and wind turbines. Fan *et al.* (2021) proposed a system including wind, hydropower, and photovoltaic systems. To estimate the maximum power generation and reduce fluctuations in electricity generation, three algorithms have been used and three common solutions have been applied to solve the optimization problem. Kanti De and Ganguly (2021) proposed a solar-hydrogen-based hybrid power system to run a remotely located cold storage facility for developing countries on a sustainable basis. The proposed system includes an array of parabolic trough collectors with short-term thermal storage, an array of solar photovoltaic modules, an electrolyzer bank, compressed hydrogen storage, and a proton exchange membrane fuel cell stack to satisfy the thermal and electrical demands of a standalone multi-commodity cold storage. De Campos *et al.* (2021) assessed the influence of adding floating photovoltaic power in the large-scale reservoir of hydropower plants of Sobradinho, located in the Sao Francisco River, in Brazil, from 2009 to 2018. The simulated scenarios varied the installed PV power capacity from 50 to 1000 MW. Several of these studies have been conducted using software for the design, sizing, optimization, and functional control of hybrid systems.

Excessive consumption of fossil fuels has led to the depletion of reserves and environmental crises. Therefore, turning to clean energy sources is essential. However, these energy sources are intermittent in nature and have problems meeting long-term energy demand. The option suggested by the researchers is to use hybrid energy systems. The purpose of this study is to determine the optimal combination of the components of a hybrid PV-DG-BAT system, which will produce electricity at the lowest price, to supply Kalakala, a remote locality in northern Côte d'Ivoire. This study estimated the operating characteristics of the system, such as the power of the PV panels, the number of batteries, the specific cost of generating electricity, the penetration rate of the PV, the amount of CO2 emitted. The HOMER Pro software has been used for simulation and installation optimization. The proposed system has then been compared to other systems such as the DG alone and the PV-BAT system.

## 2. Hybrid Energy System Study

Hybrid systems are emerging energy generation technologies that integrate two or more production sources from both renewable and conventional sources (typically Diesel Generators). A hybrid energy system is distinguished in two ways:

- It combines and exploits several available and easily mobilizable energy generation sources and technologies (Belhamel *et al.*, 2002);

- Its specific complexity in the management of contributions is in many ways identical to that of a traditional electricity grid (Ashari *et al.*, 2001).

The hybrid electric power generation system studied is a hybrid photovoltaic – diesel – battery system. This hybrid electric power generation system includes a photovoltaic generator (PV), a diesel generator (DG), storage batteries (BAT), and a multifunctional converter.

### *2.1. Diesel Generator*

Diesel generator operates as a continuous source of electricity in various hybrid energy systems and is distinguished by its fuel intake and efficiency (Oladigbolu *et al.*, 2019). Diesel generators are often used as a backup in a system with renewable energy sources since these sources heavily depend on weather conditions, which significantly affect their power generation levels.

Diesel generators are generally sized to meet peak consumption. The nominal power of the diesel generator to be installed is directly related to the load to be supplied. It takes into account the peak power consumption ($P_p$), the factor on the in-line losses (transport) ($f_t$) and the factor on the peak consumption ($f_p$). Thus, the nominal power ($P^{max}$) of the diesel generator can be determined by the formula (1) (Contreras, 2006):

$$P^{max} = \frac{P_p}{f_p \times f_t} \tag{1}$$

### *2.2. Photovoltaic Generator (PV)*

The PV panels are used to generate electrical energy for meeting the power requirement of different loads. Two types of models of PV systems are often encountered in studies of hybrid systems: the electrical model and the energy model.

The electrical model is used to calculate the current and voltage supplied to the module terminals from the received solar light, and the ambient temperature (Nfah *et al.*, 2007). The energy model calculates the output power delivered by the solar panel at a given moment. The power generation level of a PV system is often impacted by the level of solar irradiation, cell temperature, and the geographical features of the experimental place (Maleki and Askarzadeh, 2014). The PV output power is calculated using Eq. (2) (Lambert *et al.*, 2006; Ismail *et al.*, 2013; Nacer *et al.*, 2016; Oladigbolu *et al.*, 2021):

$$P_{S-PV} = P_{R-PV} \times f_{PV} \times \left(\frac{G}{G_R}\right) \times [1 + K_T \times (T_C - T_R)] \tag{2}$$

Where $P_{S\text{-}PV}$ is the output power generated by the PV panel (in W); $P_{R\text{-}PV}$ is the nominal power of the PV panel under reference conditions (in W). The nominal power, also called peak power, takes into account both the surface and the efficiency of the PV module. $f_{PV}$ is called PV panel depreciation factor (%). $f_{PV}$ takes into account the reduced power under actual operating conditions compared to the conditions under which the photovoltaic panel was evaluated and takes into account factors such as clogging of panels, loss of wiring, the shade, the aging. G is the solar energy illumination in W/m$^2$, taking into account the tilt of the panel. $G_R$ is the solar energy illumination under reference conditions and equal to 1000 W/m$^2$. $T_R$ is the temperature of the cells under reference conditions and is equal to 25°C; $K_T$ is the temperature coefficient of the maximum power of the PV panel, taken equal to -3.7x10$^{-3}$(1/°C) for mono- and polycrystalline silicon. The temperature of the cells, $T_C$, is determined using the Eq. (3):

$$T_C = T_A + \left(\frac{NOCT - 20}{800}\right) \times G \tag{3}$$

$T_A$ is the ambient air temperature in °C; NOCT is the nominal operating temperature of the cells in °C; this is one of the specifications of the PV module provided by the manufacturer.

### *2.3. Storage battery*

Battery storage is a device for storing and supplying energy for the reliable and effective operation of a renewable energy-based hybrid system. The battery storage's main target in this analysis is to store the excess electricity from the electricity-generating components and supply the stored energy to the load in the event of any shortage in capacity. For technical-economic modelling, the three most important aspects of battery performance are efficiency (or losses), charging and discharging capacity, and service life (Lilienthal *et al.*, 2004).

The charging and discharging capacities of a battery are a measure of how quickly the battery can absorb or release energy. To calculate the load and discharge capacity, performance models should take into account that most batteries do not tolerate being discharged below a certain critical load state. The state of charge of the battery is expressed by the formula (4):

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{4}$$

where $SOC_{min}$ is the minimum battery charge level;and $SOC_{max}$ as the maximum value of SOC assumed equal to 1.

At any time *t*, the condition of the battery is related to the previous state of charge and the system's production and energy consumption situation during the period t – 1 to t (Ani, 2016; Suresh and Kiranmayi, 2020).

During the charging process, when the total energy produced by all generators exceeds the requirements of the loads, the capacity of the battery fleet, available at time t, may be described by the formula (5):

$$E_{BAT}(t) = E_{BAT}(t-1) + E_{CC-OUT}(t) \times \eta_{CH} \tag{5}$$

On the other hand, when the demand for charges exceeds the energy produced, the battery park is in a state of discharge. Therefore, the battery park capacity, available at time t, can be expressed by the formula (6):

$$E_{BAT}(t) = E_{BAT}(t-1) - E_{Needed}(t) \tag{6}$$

$E_{BAT}(t)$ is the energy stored in the battery at time t (kWh); $E_{BAT}(t\text{-}1)$ is the energy stored in the battery at time t-1 (kWh); $E_{CC\text{-}OUT}(t)$ is the load controller's hourly energy production (kWh); $E_{Needed}(t)$ is the energy (kWh) necessary to satisfy the load at time t; the hourly requirements of the load; $\eta_{CH}$ is the charging efficiency of the battery.

The battery storage capacity ($C_{kwh}$) can be calculated by the formula (7) (Daud and Ismail, 2012; Oladigbolu *et al.*, 2019):

$$C_{kWh} = \frac{(E_{dL} \times N_d)}{(\eta_{inv} \times \eta_{bd} \times DOD)} \tag{7}$$

where $N_d$ is the number of days of battery life, $E_{dL}$ denotes the mean daily load energy (kWh/day), DOD denotes the depth of discharge (80%), $\eta_{bd}$ represents the efficiency of battery storage (80%) and $\eta_{inv}$represents the inverter efficiency (90%).

The battery capacity [in Ah] is using the formula (8) Bhandari *et al.*, 2015):

$$C_{Ah} = \frac{C_{kWh} \times 1000}{U} = \frac{(E_{dL} \times N_d) \times 1000}{U \times (\eta_{inv} \times \eta_{bd} \times DOD)} \tag{8}$$

U is the battery voltage (in V).

### *2.4. Multifunctional converter*

The power converter is expected to operate in two directions, i.e. as an inverter (DC-AC) or as a rectifier (AC-DC). It keeps the flow of electricity between the components of the AC bus and the DC bus. It incorporates a controller that oversees the operation of the system by selecting the most appropriate model of operation to supply the load without interruption (Halim *et al.*, 2018). For technical-economic modelling, the important characteristics of the performance of a conversion device are its maximum power and efficiency. The efficiency of the bidirectional converter is important because it appears in both the formula of calculation of the power supplied by the PV panel and the capacity of the battery. The power of the converter shall be at least equal to the peak power of consumption.

## 3. Analysis Methodology

### *3.1. The study site*

The site considered for analysis in this study is the locality of Kalakala in northern Côte d'Ivoire. Located in the department of Ferkessédougou, Kalakala is one of the communities supplied with electricity by Diesel Generator. Figure 1 shows the geographical location of Kalakala.

**Fig.1** Geographical situation of the village of Kalakala in Côte d'Ivoire

The geographical coordinates of this site were provided by Google Maps. The 2014 General Population and Habitat Census provided the number of residents of the locality. Energy consumption and peak consumption were determined using the method of establishing the load profile of rural communities in Côte d'Ivoire. We note that the average daily consumption of this locality is 332.72 kWh and a peak consumption of 40 kW is observed from 7 p.m. to 10 p.m. The load profile of this site obtained from the standard load profile of rural localities in Côte d'Ivoire is presented in figure 2. The solar potential of the locality, presented in figure 3, was obtained from the solar field assessment site, PVGIS, for an optimal 12° panel tilt and a southerly orientation. Some characteristics of this locality are given in Table 1.

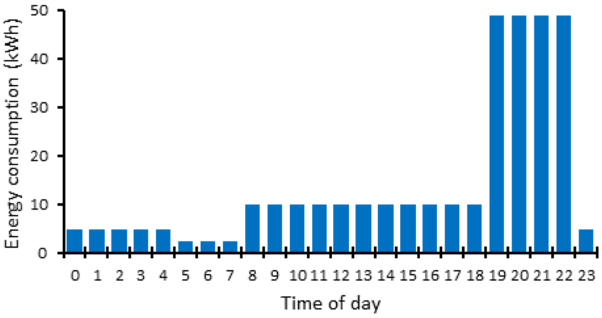


**Fig. 2** Daily hourly load profile of Kalakala

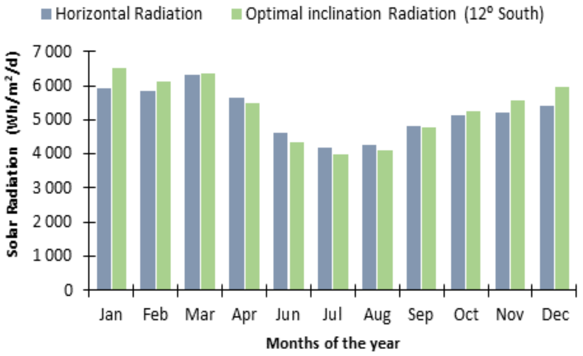


**Fig. 3** Average monthly solar irradiation from the locality of Kalakala

**Table 1**
Characteristics of the locality of Kalakala

| Geographical location in C.I. | Geographical coordinates (°) | Number of inhabitants (in 2014) | Energy consumption (kWh/year) | Peak consumption (kW) | Mean temperature (°C) | Horizontal solar irradiation (kWh/m²/d) |
|---|---|---|---|---|---|---|
| NORD | 9.46 N / 4.91 W | 2 269 | 121 442 | 40.00 | 26.90 | 5.47 |

### 3.2. *Homer software and simulation data*

The design of hybrid systems requires the correct selection and sizing of components and an adequate energy management strategy. The design and operation management of the system is not a linear problem due to the non-linear characteristics of the components, with a large number of variables (Ashari and Nayar, 1999). Thereby, HOMER simulation software was utilized to conduct the techno-economic viability assessment of different system models including the proposed system to obtain the best combination of the hybrid energy system for the selected locality.

HOMER simulates and optimizes the system (Anayochukwu, 2013). It is widely used for the design and analysis of hybrid systems. It balances demand with production and optimizes the cost of electricity generated by the system. The optimal solution is that which satisfies the physical and technical constraints at the lowest possible total net present cost (NPC). Several studies have used HOMER software to simulate and optimize hybrid systems (Ani, 2016; Halim *et al.*, 2018; Sen and Bhattacharyya, 2014). Table 2 presents the data used for input costs of the components. The investment cost of the components varies according to their power or nominal capacity. Analysis of component costs by some manufacturers allowed us to establish the relationship (9) between these costs (Ci) and the power or capacity (P) of the component:

$$C_i = a \times P^b \tag{9}$$

where a and b are constants that are functions of the component type.

This model for calculating the investment cost of components has been adopted in several research projects (Nguewo, 2012; Koucï, 2017). The cost of maintenance of the components is taken as a percentage of the investment cost. The maintenance cost of the PV generator and batteries is taken equal to 1% of the investment cost (Pueyo *et al.*, 2016). In addition to equipment cost data, Homer requires economic data values. Table 3 provides the economic data and their values used. The fixed initial cost is fixed at 15% of the total investment cost.

**Table 2**
Component cost data

| Equipment | Capacity | Initial cost | Maintenance cost |
|---|---|---|---|
| Diesel Generator | 50 kW | 22 646 € | 0.75 €/h |
| PV Generator | 1 kW | 1 800 € | 18 €/year |
| Batteries | 20.2 kWh | 4 332.46 € | 43.32 €/year |
| Converter | 100 kW | 10 310 € | 103.1 €/year |

**Table 3**
Economic data

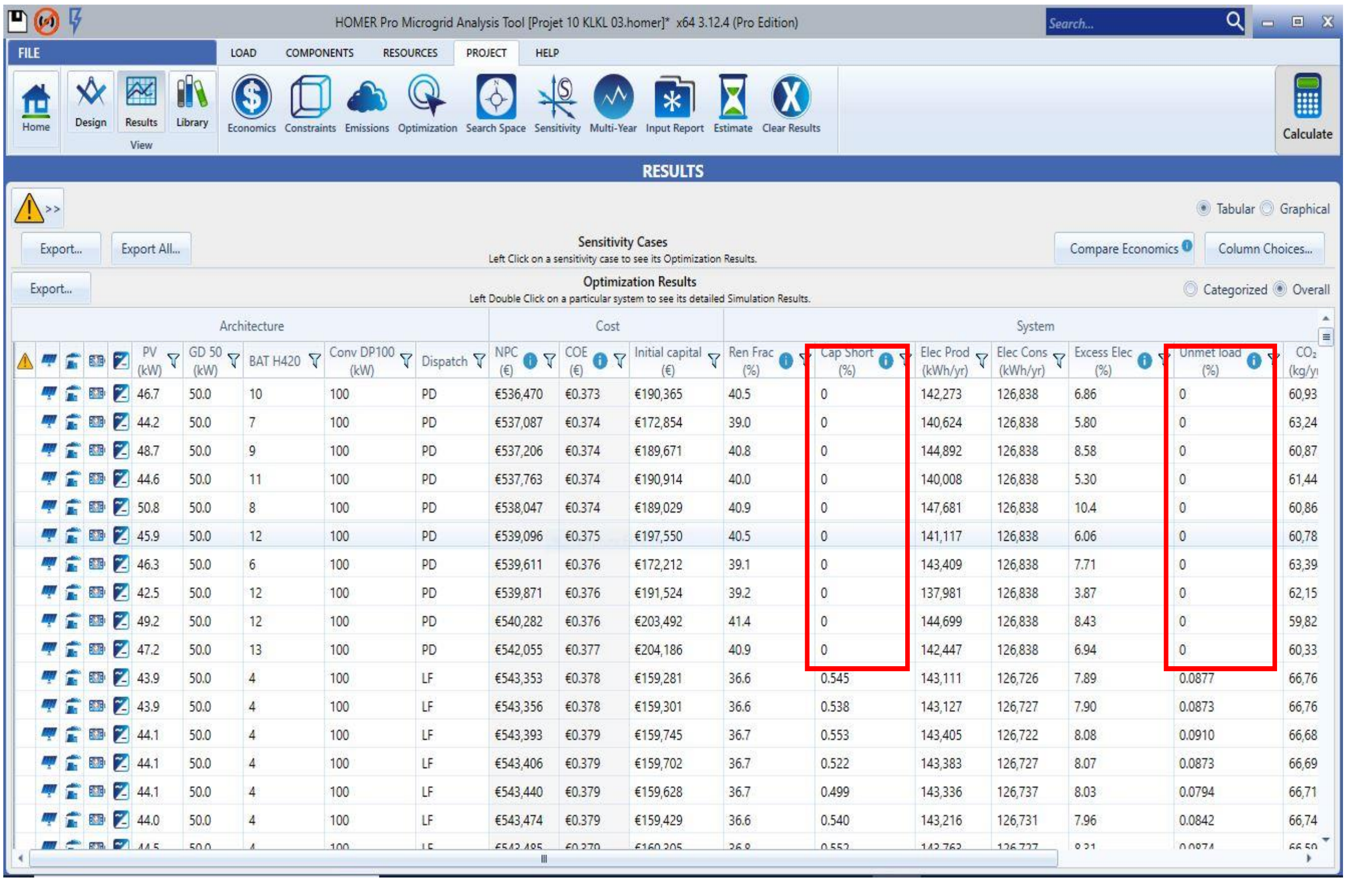
| Economic data | Value | Unit |
|---|---|---|
| Discount rate | 10 | % |
| Inflation rate | 2.5 | % |
| Project life | 25 | year |
| Initial fixed cost | 30 000 | € |
| Gas oil cost | 0.93 | €/L |

## 4. Results and Discussions

The results of the HOMER software simulation demonstrate the feasibility of hybrid PV–GD–BAT systems. For the Kalakala locality, more than 200 configurations of this system, which can produce electricity and power the village, have been modelled. Figure 4 shows the screenshot for some of the possible configurations. It is observed that the first 10 configurations of the system operate without interruption and without load shedding.

While the simulation process models a particular system configuration, the optimization process determines the best possible system configuration. The optimal configuration is that for which the combination of system components, the size or quantity of the components and the operational strategy used, presents the Net Present Cost (NPC) and the specific energy cost (COE: Cost of Energy) as low as possible. The modelled architecture of the optimal configuration of the PV–GD–BAT system to power the Kalakala locality is shown in Table 4.

The system includes a diesel generator with 50 kW of power, a PV generator with a total power of 46.7 kW, a bench of 10 parallel-mounted of 48 V batteries, and a 100-kW power converter. The optimization strategy used for energy flow management is HOMER's predictive strategy. The PV generator and battery are connected to the DC bus while the diesel generator and charge are connected to the AC bus, the converter managing the energy flows between these two buses. This optimal configuration gives, in economic terms, an NPC of 536,470.10 € as well as a COE of 0.3734 €/kWh, over the life of the project which is 25 years. It should be noted that for this configuration, the system operation is without interruption and without load shedding. The contribution of the PV system to energy production is estimated at 66,854 kWh/year for a total load of 126,825 kWh/year. This contribution corresponds to a penetration rate of 52.7% of the PV.



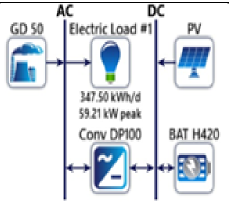
Sensitivity Cases
Left Click on a sensitivity case to see its Optimization Results.

Optimization Results
Left Double Click on a particular system to see its detailed Simulation Results.

| Architecture | | | | | | Cost | | | System | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PV (kW) | GD 50 (kW) | BAT H420 | Conv DP100 (kW) | Dispatch | NPC (€) | COE (€) | Initial capital (€) | Ren Frac (%) | Cap Short (%) | Elec Prod (kWh/yr) | Elec Cons (kWh/yr) | Excess Elec (%) | Unmet load (%) | $CO_2$ (kg/yı |
| 46.7 | 50.0 | 10 | 100 | PD | €536,470 | €0.373 | €190,365 | 40.5 | 0 | 142,273 | 126,838 | 6.86 | 0 | 60,93 |
| 44.2 | 50.0 | 7 | 100 | PD | €537,087 | €0.374 | €172,854 | 39.0 | 0 | 140,624 | 126,838 | 5.80 | 0 | 63,24 |
| 48.7 | 50.0 | 9 | 100 | PD | €537,206 | €0.374 | €189,671 | 40.8 | 0 | 144,892 | 126,838 | 8.58 | 0 | 60,87 |
| 44.6 | 50.0 | 11 | 100 | PD | €537,763 | €0.374 | €190,914 | 40.0 | 0 | 140,008 | 126,838 | 5.30 | 0 | 61,44 |
| 50.8 | 50.0 | 8 | 100 | PD | €538,047 | €0.374 | €189,029 | 40.9 | 0 | 147,681 | 126,838 | 10.4 | 0 | 60,86 |
| 45.9 | 50.0 | 12 | 100 | PD | €539,096 | €0.375 | €197,550 | 40.5 | 0 | 141,117 | 126,838 | 6.06 | 0 | 60,78 |
| 46.3 | 50.0 | 6 | 100 | PD | €539,611 | €0.376 | €172,212 | 39.1 | 0 | 143,409 | 126,838 | 7.71 | 0 | 63,39 |
| 42.5 | 50.0 | 12 | 100 | PD | €539,871 | €0.376 | €191,524 | 39.2 | 0 | 137,981 | 126,838 | 3.87 | 0 | 62,15 |
| 49.2 | 50.0 | 12 | 100 | PD | €540,282 | €0.376 | €203,492 | 41.4 | 0 | 144,699 | 126,838 | 8.43 | 0 | 59,82 |
| 47.2 | 50.0 | 13 | 100 | PD | €542,055 | €0.377 | €204,186 | 40.9 | 0 | 142,447 | 126,838 | 6.94 | 0 | 60,33 |
| 43.9 | 50.0 | 4 | 100 | LF | €543,353 | €0.378 | €159,281 | 36.6 | 0.545 | 143,111 | 126,726 | 7.89 | 0.0877 | 66,76 |
| 43.9 | 50.0 | 4 | 100 | LF | €543,356 | €0.378 | €159,301 | 36.6 | 0.538 | 143,127 | 126,727 | 7.90 | 0.0873 | 66,76 |
| 44.1 | 50.0 | 4 | 100 | LF | €543,393 | €0.379 | €159,745 | 36.7 | 0.553 | 143,405 | 126,722 | 8.08 | 0.0910 | 66,68 |
| 44.1 | 50.0 | 4 | 100 | LF | €543,406 | €0.379 | €159,702 | 36.7 | 0.522 | 143,383 | 126,727 | 8.07 | 0.0873 | 66,69 |
| 44.1 | 50.0 | 4 | 100 | LF | €543,440 | €0.379 | €159,628 | 36.7 | 0.499 | 143,336 | 126,737 | 8.03 | 0.0794 | 66,71 |
| 44.0 | 50.0 | 4 | 100 | LF | €543,474 | €0.379 | €159,429 | 36.6 | 0.540 | 143,216 | 126,731 | 7.96 | 0.0842 | 66,74 |

**Fig. 4.** Screenshot of the HOMER software, showing the configurations of the PV-GD-BAT systems modelled by the simulation

**Table 4**
Modelled optimal system configuration for the locality of Kalakala



| Component | Name | Size | Unit |
|---|---|---|---|
| Diesel Generator | Generic 50kW Fixed Capacity Genset | 50 | kW |
| PV | Generic flat plate PV | 46.7 | kW |
| Storage | Hoppecke 6 OPzS 420 48V | 10 | Strings |
| System converter | Dynapower SPS-100 | 100 | kW |
| Dispatch strategy | Homer Predictive | | |

Figure 5 shows the monthly evolution of energy, produced and consumed. As shown in Figure 6, the DG is in higher demand in the period from June to September. This is a period of low sunshine. The contribution of the PV system is therefore low. However, production is still higher than consumption, which shows that the loads are fed without interruption and without load shedding.

Figure 6 shows how the hybrid system works on a sunny day (a) and a day with little sun (b): On a sunny day, the loads are powered by the batteries at night (11 p.m. to 6 a.m.). During the day (6 a.m. to 5 p.m.), the PV system powers the loads and the excess energy from this system is used to charge the batteries. After 5 p.m., the batteries are used, first to support the PV system, whose production has fallen sharply, and then on their own to supply the loads. From 6 p.m. to 10 p.m., peak consumption period, the diesel generator is used. For a weakly sunny day, the scenario of the night is identical to that of the sunny day, as long as the batteries are not discharged. During the day, the production of the PV system being insufficient, the batteries also come into play, to supply the loads. During peak consumption periods and even beyond, the Diesel Generator is used to supply the loads and charge the batteries. It should be noted that the PV system is used first, then the batteries for low loads. The GD is solicited during the peak period or when the batteries are discharged. Thus, it powers the charges and charges the batteries, which allows it to operate at high load.

The modelled optimal configuration is compared with the GD system alone and the PV system with batteries (PV-BAT), with the meteorological conditions and of the loads to be supplied, identical, over the lifetime. Table 5 shows some comparative technical characteristics of each of the systems.

Compared to the PV-BAT system alone, the PV-DG-BAT hybrid system reduces the power and energy output of the PV by 56%, reducing the field area and the number of PV panels. This system also reduces the number of batteries by 61.54% and increases their service life by 42.84%, thus limiting their impact on the environment. The hybrid system, compared to DG alone, reduces fuel consumption by 60.46% and increases the average DG efficiency by 17%, which contributes to the reliability of the DG and increases its lifetime.

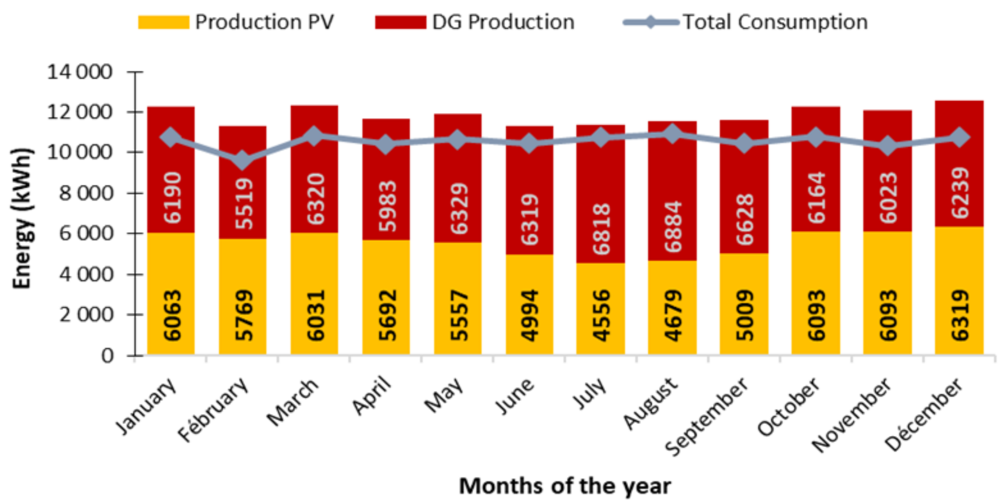


**Fig. 5** Monthly energy production and consumption

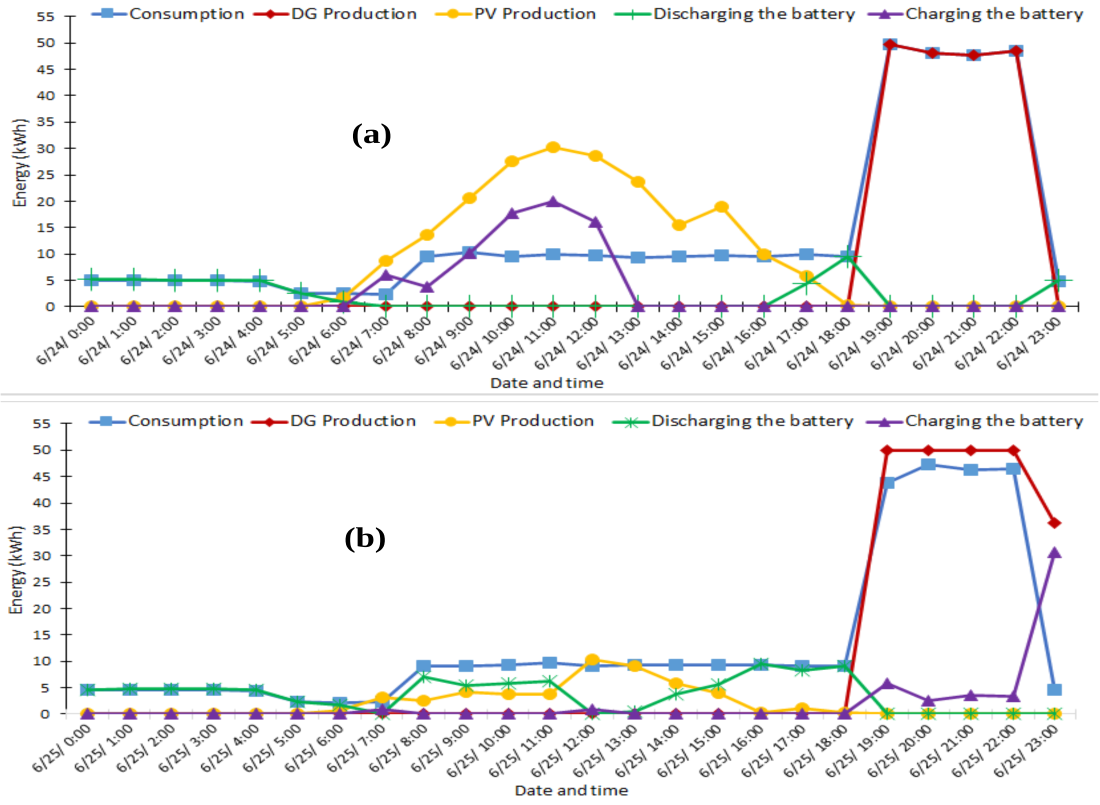


**Fig. 6** Hourly energy consumption and production during a sunny (a) and little sunny day (b)

Figure 7 shows a comparison of the quantities of pollutants produced by the GD and the hybrid PV – GD – BAT system. We note a decrease in the quantity of pollutants produced by the hybrid system. Compared to DG, this hybrid system results in a 60% reduction in $CO_2$ and other pollutants. The environmental impact of electricity generation is therefore greatly reduced by the use of the hybrid PV –DG – BAT system.

From an economic and financial point of view, the comparison of the three systems shows that the PV-GD-BAT system is economically more viable. Indeed, as shown in the graphs in Figure 8, this hybrid system shows the lowest Cost of Energy Production (COE) and total net present cost (NPC), followed by the PV-BAT system. However, the GD alone system is the cheapest in capital investment, followed by the PV-GD-BAT system. The operating cost of the PV-BAT system is the lowest followed by the PV-BAT system.

In addition to the economic aspects, the autonomy factor is one of the important criteria that must be taken into account in any design optimization study.

**Table 5**
Comparison of the technical characteristics of the three systems

| Technical characteristics | DG alone | Hybrid PV-DG-BAT | PV - BAT | Increase or Decrease rate / Other Systems (DG, PV-BAT) |
|---|---|---|---|---|
| PV power (kW) | - | 46.7 | 106 | -55.94 % |
| PV energy production (kWh/year) | - | 66 857 | 152065 | -56 % |
| Number of batteries | - | 10 | 26 | -61.54 % |
| Battery life (year) | - | 6.67 | 4.67 | +42.84 % |
| DG energy production (kWh/year) | 162 704 | 75 416 | - | -53.64% |
| Fuel consumption (L/year) | 58 872 | 23 276 | - | -60.46 % |
| DG Specific consumption (L/kWh) | 0.362 | 0.309 | - | -14.67 % |
| DG Average efficiency (%) | 28.1 | 32.9 | - | +17.1% |

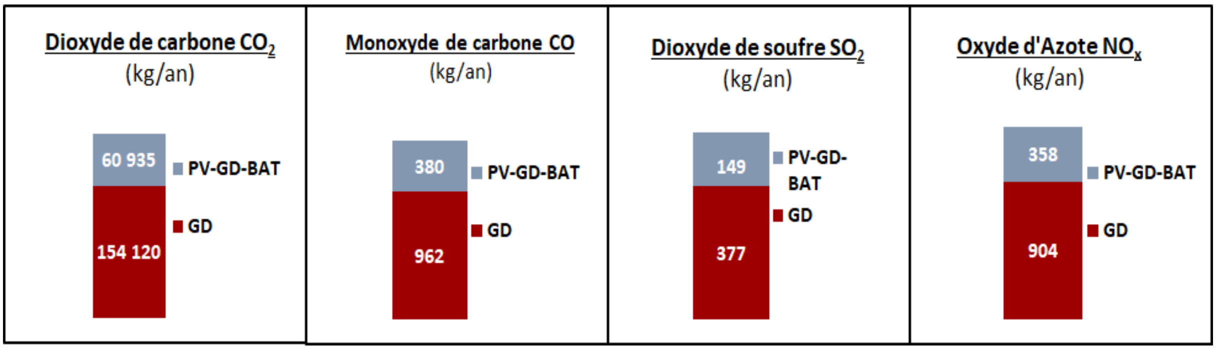


**Fig. 7** Comparison of quantities of pollutants produced by DG and PV-DG-BAT

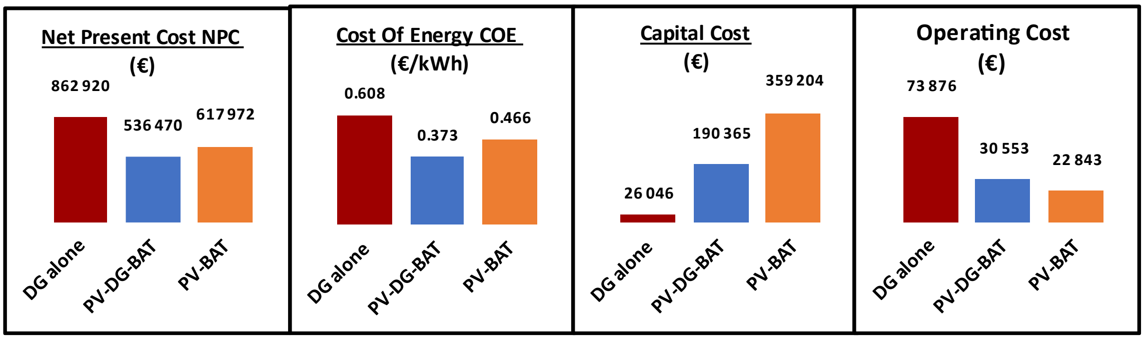


**Fig. 8** Comparison of the economic performance of the three systems

## 5. Conclusion

The simulation and optimization software, HOMER, was used to obtain a combination of components of a hybrid PV-GD-BAT system that minimizes the cost of energy production, in order to power an isolated locality like Kalakala. As a result, the optimal technical configuration includes a 50 kW GD, a 46.7 kW PV system, a fleet of 10 48 V batteries and a 100 kW converter, with a 52.7% PV penetration rate. It produces electricity without interruption and without load shedding, at a cost of €0.373/kWh. The comparison of this hybrid system with the DG alone and the PV-BAT system shows that the hybrid system has the best performance from a technical, economic and environmental point of view. It reduces the amount of $CO_2$ by 60% compared to DG alone and the number of batteries by 61.5% compared to the PV-BAT system. This study could be extended to several other isolated locations to confirm or not the viability of hybrid PV-GD-BAT systems in Côte d'Ivoire and create standards for the design of these systems.

## Acronyms

| | |
|---|---|
| AC | Alternating Current |
| BAT | Battery |
| COE | Cost Of Energy |
| $CO_2$ | Carbon Dioxide |
| DC | Direct Current |
| DG | Diesel Generator |
| NPC | Net Present Cost |
| PV | Photovoltaic |

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