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(Research Article)

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Experimental analysis of a photovoltaic self-consumption system for the offices of a local company

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Abstract

The article analyzes the prospect of a solution for the mutual interaction of a photovoltaic generator and the local electrical grid, within the context of electrifying the offices of a hydrocarbon storage facility. The idea is to examine the operational performance of a system that enables the maximum self-consumption of energy generated by a small-scale photovoltaic system installed on the facility's site. Such a system could prove beneficial for multiple consumers operating in a complex energy environment. The issue is scrutinized based on experimental data from a real case in Dakar, Senegal. An installation with a photovoltaic system of approximately 17 kWp peak power is monitored for a year to assess the reliability of the self-consumption photovoltaic system for a broader application. The data encompasses both the functioning of the photovoltaic system and its interaction with the electrical grid. The potential use of this solution in the context of promoting self-consumption policies to reduce electricity consumption expenses is discussed and analyzed, revealing a relatively high level of interaction with the electrical grid. Despite maintenance costs, the photovoltaic system proves to be cost-effective.

Keywords: Photovoltaic system; Electricity grid; Self-consumption; Self-generation; Expense; Profitability.

1. Introduction

Solar energy is still underutilized in Senegal, considering the significant benefits it can provide. Nevertheless, the country has embarked on an ambitious program by implementing projects aimed at diversifying, increasing, and improving energy production capacity, resulting in positive outcomes and various interesting applications. The Senegalese Government has instituted a policy seeking alternative solutions to its energy supply issues, promoting the development of renewable energy through the diversification of production sources, including the construction of several renewable energy plants (wind, solar, hydroelectricity, etc.). Photovoltaics enable decentralized electricity production, bringing it closer to the end consumer.

With this in mind, many businesses in Senegal are embracing renewable energy, particularly solar photovoltaics, to reduce their electricity bills. This approach, utilized by companies to lower their electricity expenses, is known as a self-consumption system. To better support the successful operation of these projects, we have developed a physical model to assess profitability in terms of financing, aiming to reduce expenditures related to energy consumption.

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1.1. Operating principle of a photovoltaic solar power plant for self-consumption or self-production

Photovoltaic self-consumption refers to the possibility for any type of electricity-consuming producer to connect a photovoltaic installation, sized according to their needs, either solely to their electrical system or in a shared mode between their electrical system and the local grid based on fluctuations in production and consumption [1,2,3]. It plays a significant role in energy transition and the development of renewable energies [4,5,6].

Self-consumption is a regulatory framework aimed at enhancing consumption flexibility by favoring local consumption over exportation [7]. It contributes to the stability of the distribution grid by avoiding voltage increases during peak periods of photovoltaic production and helps achieve higher shares in the electrical mix [8].

1.2. Different types of self-consumption

In the case of self-consumption, individuals with the means often install a photovoltaic system with energy storage batteries to meet their energy needs [9,10,11,12]. These types of systems can be autonomous, independent of the local electrical grid. However, this approach has the drawback that when the batteries are fully charged, the solar panels become idle unless the entire household is connected and can be powered by the photovoltaic system.

On the other hand, in certain local communities, especially in Senegal, where individuals may not have the means to have their own photovoltaic systems, they may come together as a collective to share the production of a communal mini power plant. To avoid the high cost of installation often associated with energy storage batteries, these users may opt for a system that injects surplus energy produced back into the local electrical grid [13,14,15].

Two scenarios are compared below, one with four individual photovoltaic consumers and the other with a collective installation supplying the same four consumers.

1.3. Individual self-consumption

This function is performed by the injection inverter: it converts the direct current from the modules into alternating current that precisely matches the grid current [16,17,18]. The enclosures placed on either side of the inverter ensure the protection of the installation: the DC enclosure on the direct current side and the AC enclosure on the alternating current side [19].

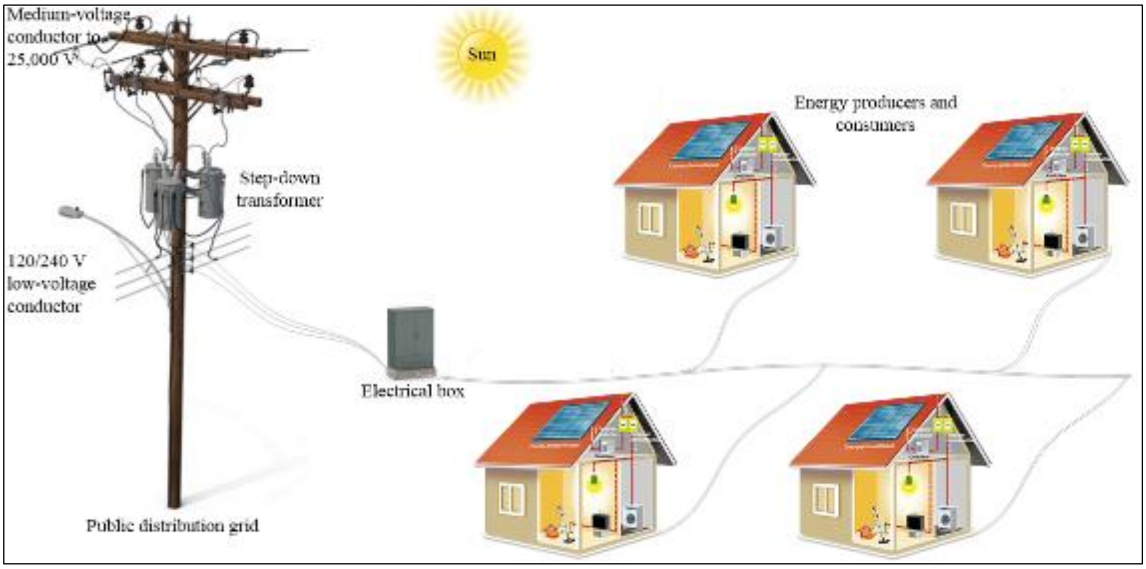

Figure 1 Individual self-consumption

It verifies that the grid is in compliance and injects as soon as it is the case. It then aligns its voltage and frequency with the grid's voltage and frequency. It increases the production current until all that it produces flows into the grid in the case of total injection or until the surplus of the produced energy is injected into the grid in the case of self-consumption [20,21,22]. Note: in the case of standard grid injection, if the grid current is interrupted, the inverter does not produce power.

Individual loads exhibit a very high variability, especially when analyzed at a resolution lower than an hour, further reducing the optimal peak power for self-consumption customers [23].

1.4. Distributed or collective self-consumption

The specific use case studied and addressed by the present solution based on collective self-consumption [24,25,26] is that of an energy community sharing local solar production. Sharing energy produced by one or more common photovoltaic plants or pooling the surplus of photovoltaic consumers helps overcome several obstacles related to individual self-consumption [27,28,29]. This process of mutualizing needs relies on consensus.

There are different types of transformation and distribution centers, each with its own technical characteristics and governance model. These centers can be public, consortium-based, or private, depending on the desired governance and level of accessibility.

The virtual power plant is an increasingly popular smart grid application that aggregates distributed energy resources (e.g., distributed production, controllable loads, and energy storage systems) into a coordinated pool [30]. Aggregating distributed energy resources into a single pool enables the power plant to act as a service provider.

The virtual power plant relies on software systems that coordinate distributed energy resources connected to the main electrical grid [30-33]. These software systems, often referred to as control architectures, are responsible for the coordination and remote control of energy flows from distributed energy resources [34, 35].

Through a virtual power plant, a community could potentially manage how the energy produced by the community is used within it [36] and/or play a role in energy trading, grid support, balancing services, and derive income from these activities [37]. It is increasingly seen as a viable solution to the problems and challenges associated with integrating large amounts of renewable energy sources into the existing electrical grid in a cost-effective manner [30,38-40].

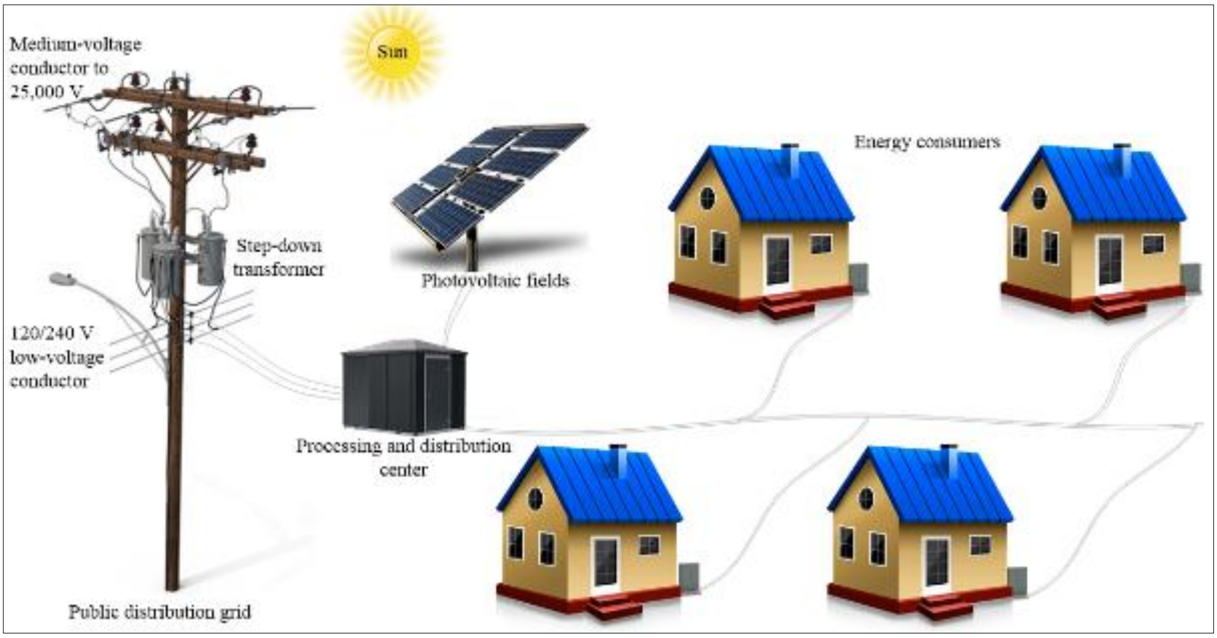

Figure 2 Distributed or collective self-consumption

The aggregation of coordinated and managed distributed energy resources allows virtual power plants to act as a large entity similar to a conventional power plant, enabling better integration of distributed energy resources into the existing centralized energy system [41]. The literature distinguishes three main categories of distributed energy resources:

(1) Distributed production, consisting of controllable or intermittent, renewable or non-renewable energy generators, often of small capacity, connected to the distribution grid.

(2) Controllable loads include various electrical appliances that can be controlled to shift or modify energy demand [42].

(3) Energy storage systems provide flexibility to the grid by supplying backup power, acting either as a load (during charging) or as a generator (during discharge) [42,43].

The primary technical and economic argument in favor of distributed or collective self-consumption is the aggregation of the needs of multiple consumers [44].

1.5. Self-consumption and self-production rates

The energy consumptions and productions are derived from real measured data. The energy performance of these operations is assessed through self-consumption and self-production rates.

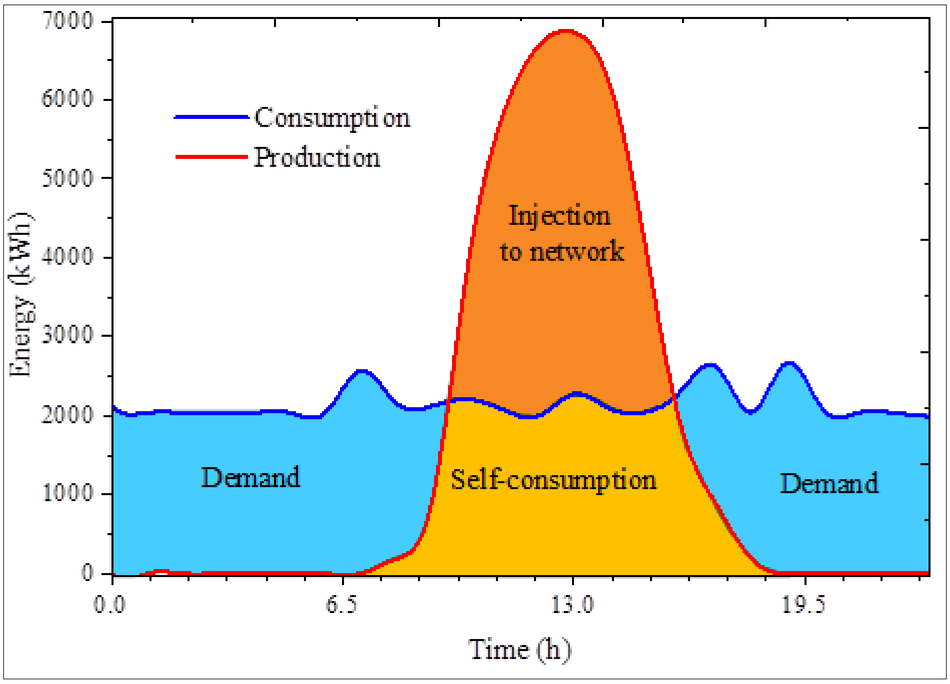

Figure 3 Matching energy needs to electrical production

In the case of self-consumption, it is generally not feasible to cover all the electrical needs of the site, especially during the night or when the photovoltaic installation is not producing. Depending on the power of the photovoltaic generator, the portion covered by solar energy can vary between 10% and 50% [45, 46, 47]. If the electrical production exceeds consumption over a given period, the self-consumed energy will be equal to the consumption. The surplus production will then be consumed by other consumers connected to the grid. If electrical production is lower than consumption over a given period, the self-consumed energy will be equal to the production. Additional electrical supply from the grid will then be necessary.

The self-consumption rate is defined as the amount of electricity produced and consumed locally compared to the total local production [48]:

$$T_{ac} = \frac{QE_{phc}}{QE_{php}} \times 100$$

While the self-consumption rate describes the relationship between electrical needs covered by photovoltaic production and total consumption, it quantifies the user's independence from the grid [49]. A straightforward way to compare the solutions found is to assess the fraction of the total demand provided by the photovoltaic system, namely the self-production rate [50], defined as follows:

$$T_{ap} = \frac{QE_{phc}}{QE_{php} + QE_r} \times 100 = \frac{QE_{phc}}{QE_{tc}} \times 100$$

$$QE_{tc} = QE_{php} + QE_r$$

With T_{ac} and T_{ap} representing the respective rates of self-consumption and self-production, QE_{phc} and QE_{php} denoting the respective quantities of consumed and produced photovoltaic electricity, and QE_r representing the quantity of electricity consumed from the grid. This study focuses on the optimization of self-consumption, as it is a crucial evaluation criterion for these installations [51,52,53]. It is generally considered as a means to reduce electricity bills and lower greenhouse gas emissions.

In this context, self-consumption and self-production are two energy indicators used to quantify the utilization of energy production at the local level [49]. It is, therefore, an indicator of a user's autonomy in relation to the electrical grid. The higher this rate, the less the user relies on electricity from the public grid.

1.6. Exploitation of expérimental data

1.6.1. Daily production in 2020

The figure 1 represents the daily energy production of the photovoltaic system during the months of the year. We observe photovoltaic energy productions below 40 kWh from January to April, followed by productions exceeding 40 kWh and reaching 93 kWh on August 25th. We also notice a minimal energy production of 8 kWh from the photovoltaic system on December 23rd and a few rare exceptions, such as the beginning of June when we have production below 40 kWh. For instance, on August 5th, the photovoltaic energy production was 13 kWh.

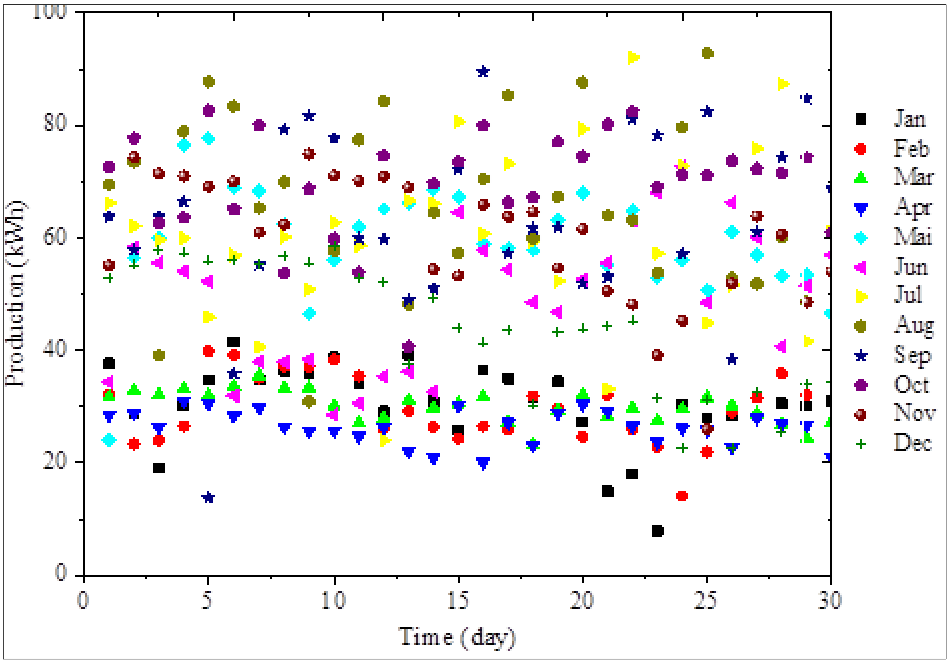

Figure 4 Daily production throughout the year 2020

Photovoltaic energy is generated through a natural energy source (the Sun), whose behavior reflects the different seasons of the year. Consequently, from late December to early February until early June, we experience less intense sunlight due to winter-related weather conditions. Additionally, during winter, winds can lift dust, which settles on the surface of solar panels. Without maintenance, panel production decreases, but with proper upkeep, this issue can be avoided. On the other hand, in summer, from March to September, the sky is clear, radiation is intense, and the panels are cleaned by rains during the wet season, resulting in energy productions exceeding 40 kWh. The noted exceptions arise from the unpredictable nature of weather, leading to sunny days in winter or cloudy days in summer, especially in August, where entirely cloudy days are often observed.

1.6.2. Daily consumption in 2020

In Figure 2, we have the daily electricity consumption of users during the different months of the year. Unlike the daily production of photovoltaic energy, the daily consumption of users is random. In a month, we observe very high consumptions approaching 300 kWh and very low consumptions around 50 kWh. Additionally, we observed a maximum daily consumption on August 22nd (313 kWh) and a minimum on January 22nd (22 kWh).

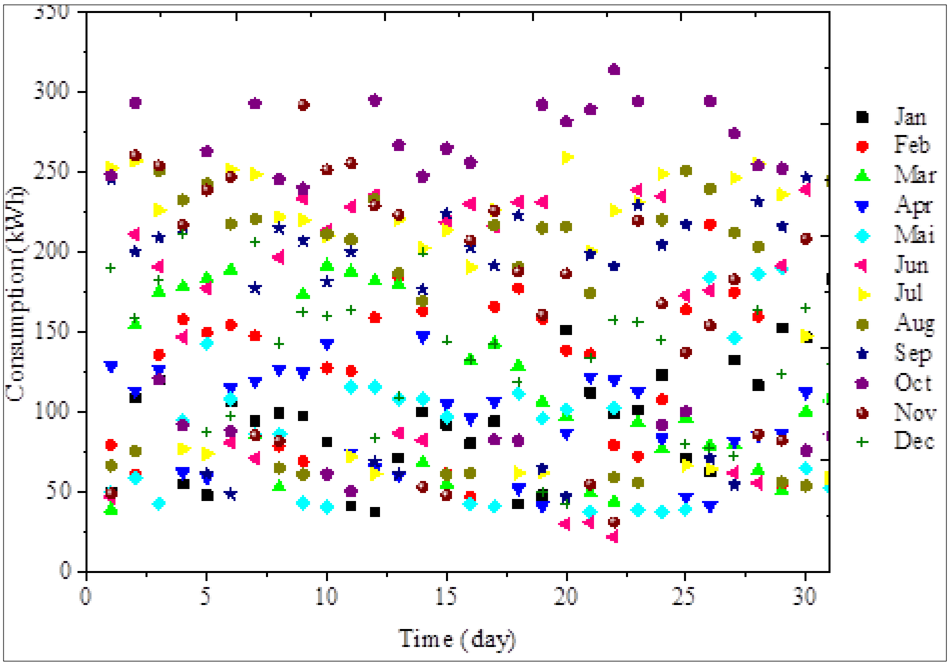

Figure 5 Daily consumption throughout the year 2020

Indeed, user consumption depends on their behaviors towards the spaces but also on meteorological phenomena. Given that the weather is unpredictable, and user behavior is equally unpredictable, hence the random nature of daily consumption. The month of January coincides with winter, where it is cold, and devices such as fans, air conditioners, and refrigerators, known as significant energy consumers, either do not operate or operate less. In contrast, in August, it is very hot, and all the mentioned appliances run at full capacity, consuming the maximum amount of energy.

1.6.3. Daily expenses in 2020

Figure 3 depicts the daily expenses during the months of the year. As in the case of consumption, daily expenses are randomly distributed, ranging from 1500 Fcfa on June 21st to reaching 27000 Fcfa on October 22nd.

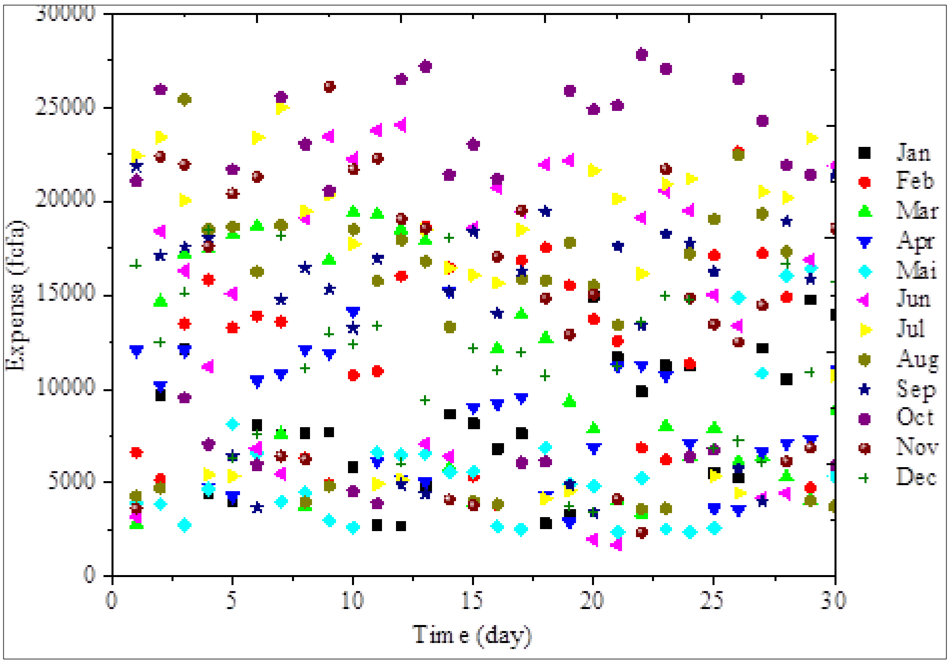

Figure 6 Daily expenses of the self-consumption system throughout the year 2020

In addition to the random phenomena of weather and user consumption patterns, expenses, which also depend on the maintenance of the photovoltaic installation and grid electricity consumption, become even more unpredictable. We cannot control expenses as we can with production or consumption, although they are related to both. Simply through the maintenance of the photovoltaic system and the electrical usage from the grid, which varies from time to time or from day to day. This results in expenses that differ by 20000 Fcfa within just two days.

1.6.4. Daily profitability in 2020

Figure 7 illustrates the daily profitability of the self-consumption system over the course of a year. The self-consumption system is more profitable when productions are at their maximum and less profitable with minimal productions. We also observed that the system was less profitable on January 12th and more profitable on August 25th.

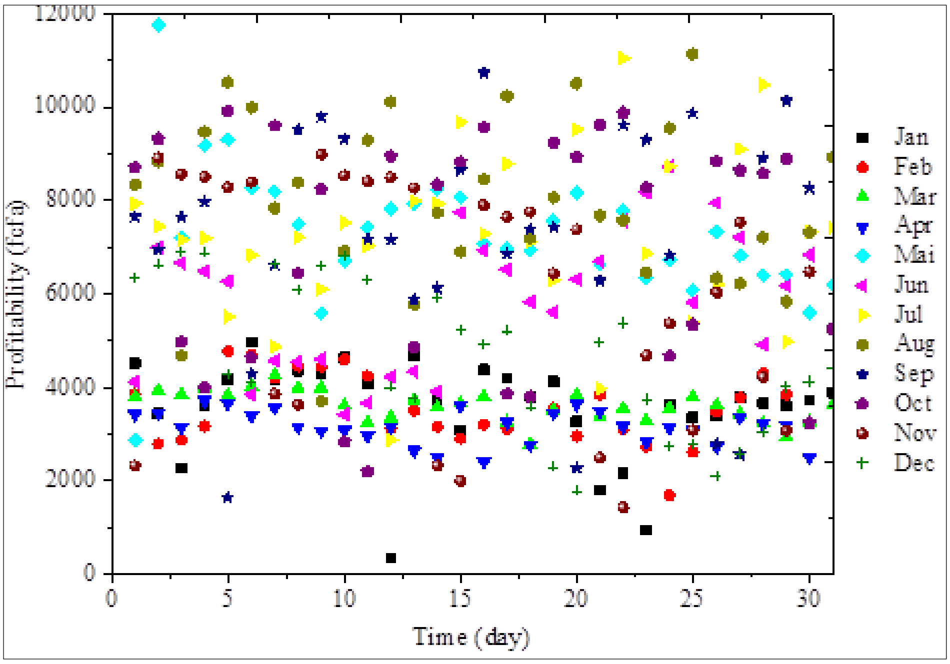

Figure 7 Daily profitability throughout the year 2020

Unlike expenses, the profitability of the system depends on the energy production of the panels. The system is more profitable in summer than in winter due to weather conditions. Unpredictable expenses do not have significant effects, allowing us to recover the investments in the photovoltaic system installation within a few years, despite unpredictable expenses post-installation.

1.7. Monthly production and cconsumption in 2020

Figures 5 and 6 depict the bar chart and histograms of the production and consumption of the self-consumption system. We observe energy consumption higher than the energy produced by the photovoltaic system, with minimum photovoltaic energy productions of 782.38 kWh in April, a production reaching a value of 2174.76 kWh in October, and a minimum consumption of 2799.67 kWh in May, which increases to 6421.5 kWh in October.

The annual production and consumption increase proportionally until October before decreasing. In May, we observe an increase in production and a decrease in consumption, which will contribute to reducing expenses, the self-consumption or self-production rate.

As we have already explained, the production of photovoltaic energy and the electrical consumption of users depend on weather conditions.

1.8. Bar chart and histogram of monthly expenses and profitability of the self-consumption system in 2020

Figures 7 and 8 represent the bar charts and histograms of the profitability and expenses of the system. We observe that expenses are higher than profitability, except in May, where the profitability of the self-consumption system

(821,000 Fcfa) exceeds expenses (177,590 Fcfa). Similar to consumption, expenses are more costly in October and less costly in May. The hybrid system is most profitable in August (247,640 Fcfa) and least profitable in April (96,688 Fcfa).

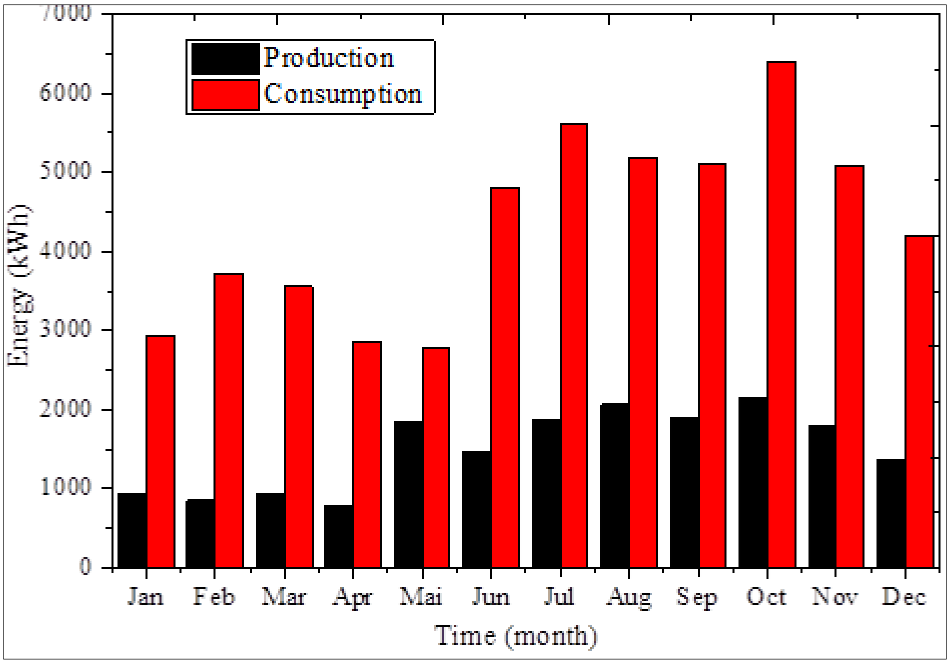

Figure 8 The bar chart of monthly production and consumption throughout the year 2020

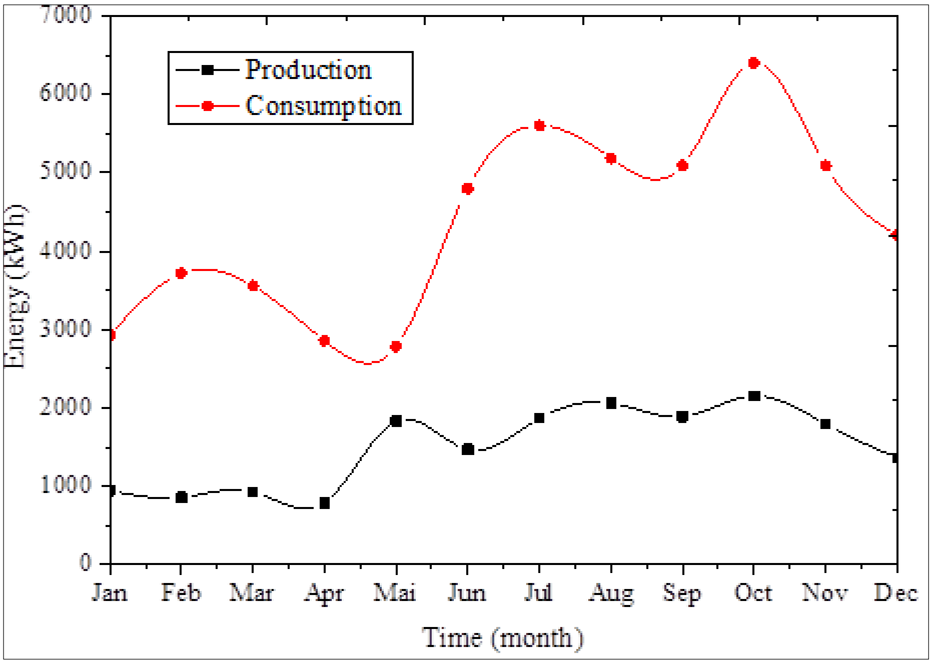

Figure 9 Monthly production and consumption curves throughout the year 2020

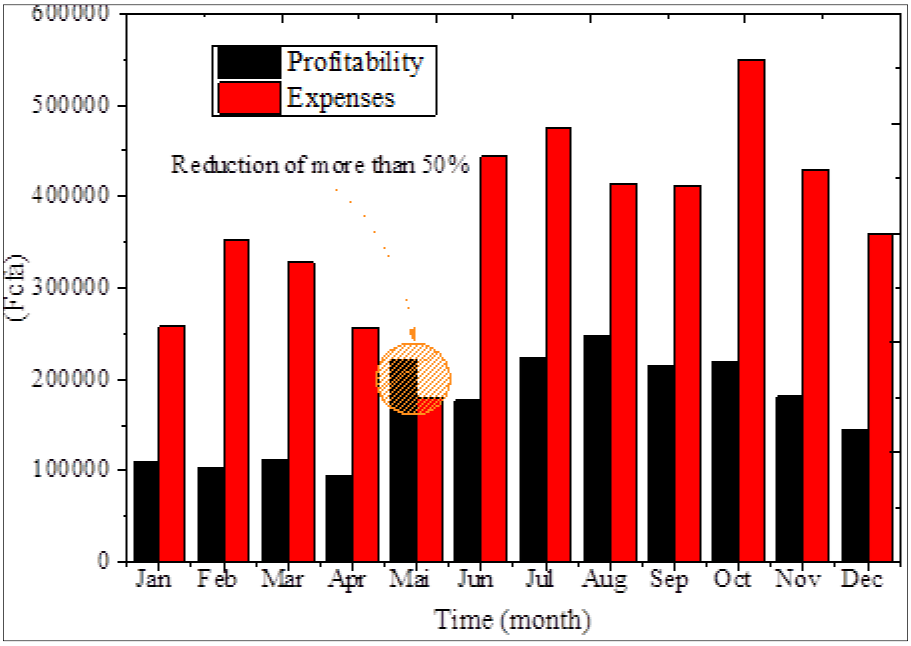

Figure 10 The bar chart of monthly profitability and expenses throughout the year 2020.

Overall, annual profitability and expenses increase over the estimated time in months until October before decreasing, except for expenses, where there is a significant drop and a peak in maximum production.

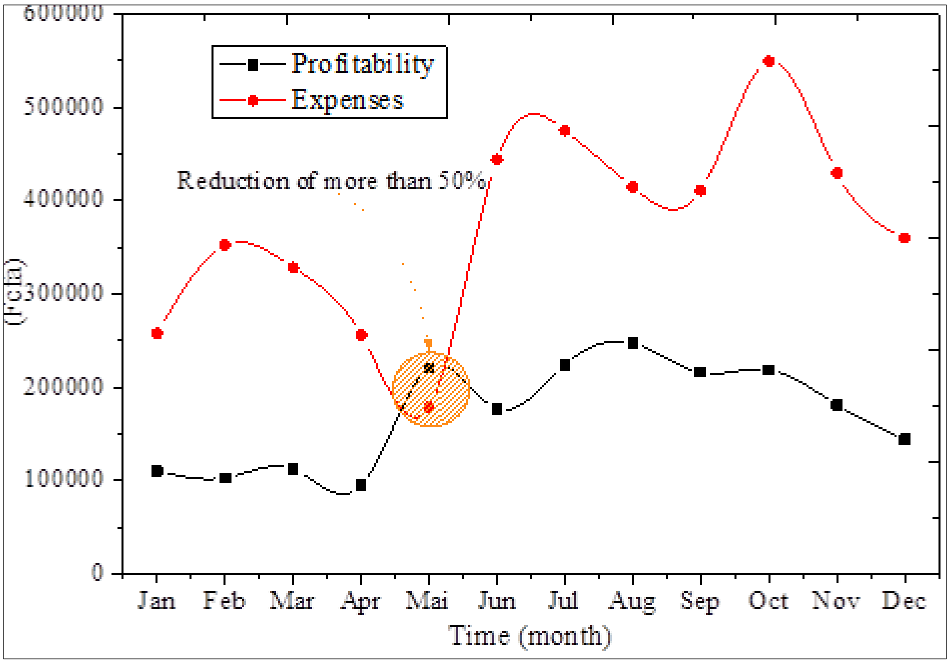

Figure 11 The histogram of monthly profitability and expenses throughout the year 2020

The photovoltaic installation reduces expenses related to energy consumption. This expense reduction can go up to more than 50% in May, caused by low expenses and high production, which in turn contributes to profitability.

1.9. Bar chart and histogram of monthly direct, grid, and self-consumption system consumption in 2020

Figures 9 and 10 represent the bar charts and histograms of direct, grid, and total consumptions of the hybrid system (grid-connected system). We observe that the total consumption is higher than both grid and direct consumption throughout the year. Users consume less energy directly (from solar panels) than indirectly (from the grid), except in May, where grid consumption is reduced by less than 50%.

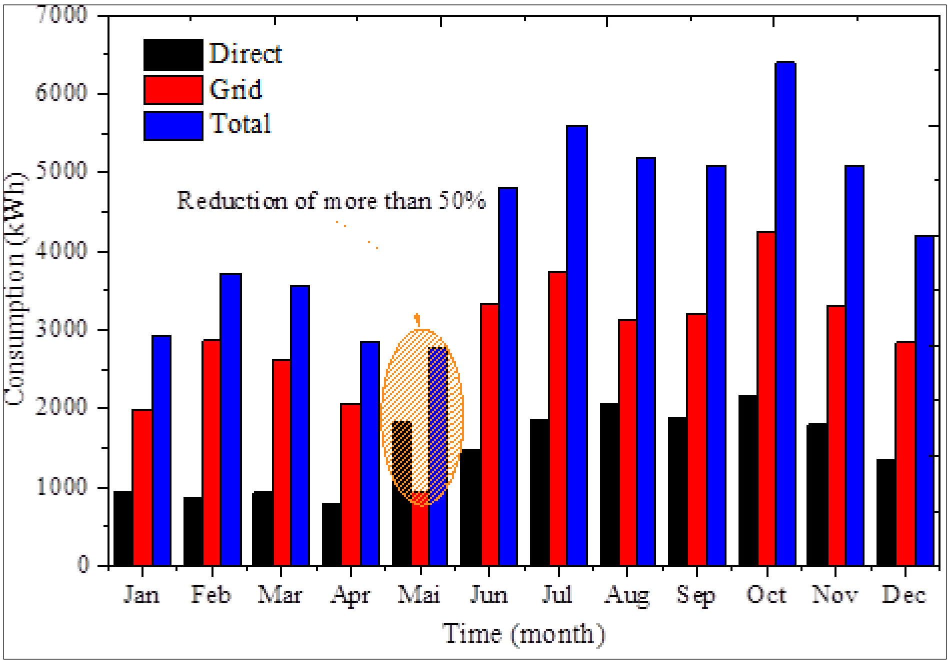

Figure 12 The bar charts of monthly direct, grid, and total consumptions throughout the year 2020.

Direct and indirect consumptions are respectively proportional to profitability and expenses. Since the energy consumed by users mainly comes from the grid, the total consumption varies in the same way as that of the grid, with an additional consumption coming from the photovoltaic cells (direct consumption).

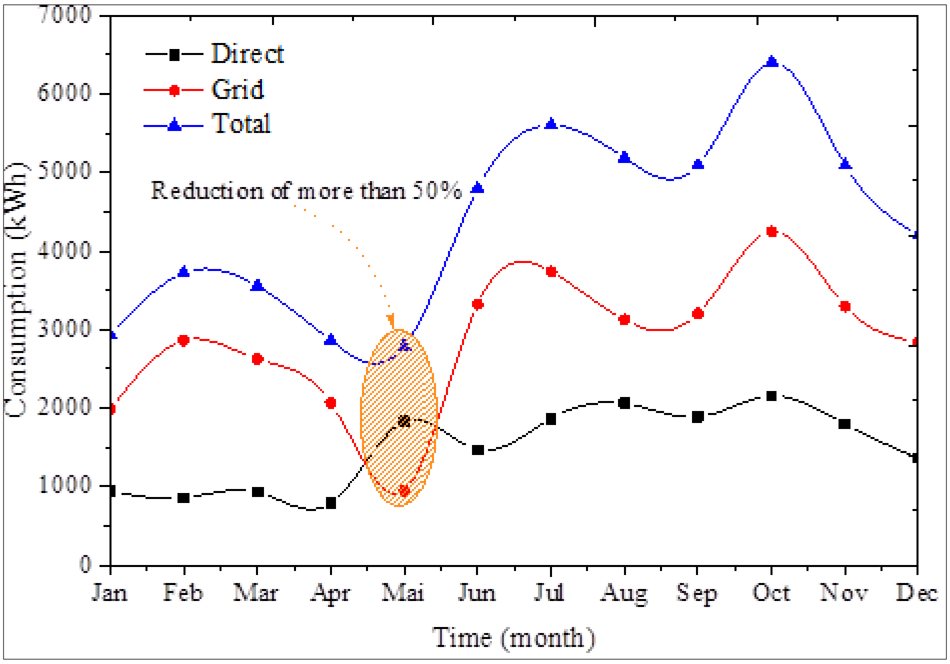

Figure 13 Les The histograms of monthly direct, grid, and total consumptions throughout the year 2020

The self-consumption system helps to reduce user consumption costs, although it can cut down consumption costs from the distribution grid by 50% in May. However, the self-consumption system is not fully autonomous as it depends on the grid to operate and is never sufficient to cover the energy needs of users.

1.10. Pie charts of the profitability of the self-consumption system in 2020

Figures 11 and 12 depict the pie charts of monthly and seasonal profitability of the system. The system is more profitable (over 10%) during the summer months and in May, then less profitable during the winter months (below 8%) and equals 4.63% in April. Specifically, in summer, we observe a profitability of 63.04%, and in winter, a profitability of 36.96%.

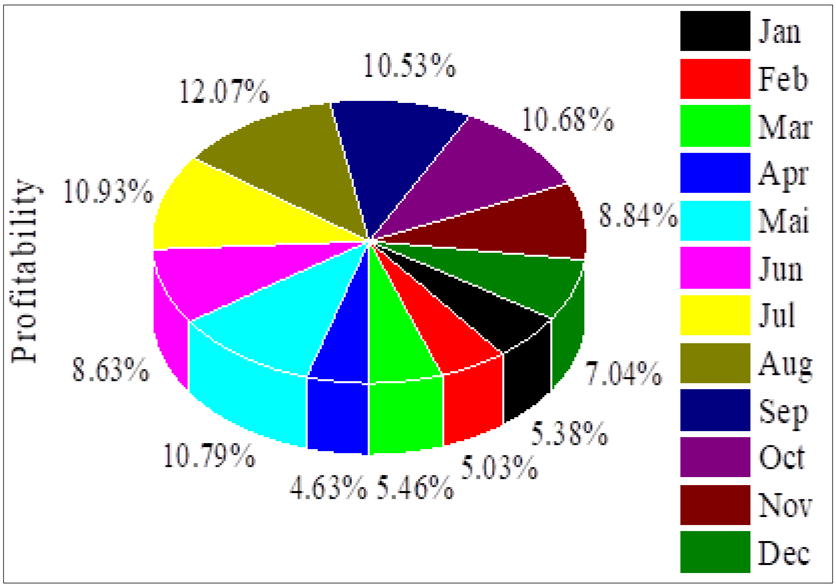

Figure 14 The monthly profitability of the photovoltaic system throughout the year 2020

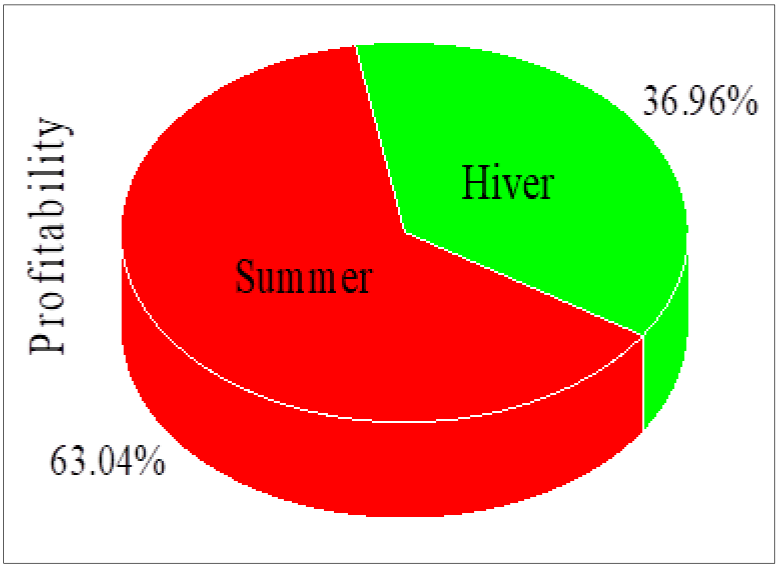

Figure 15 The profitability of the photovoltaic system during the different seasons of the year 2020

The weather conditions associated with winter and summer result in higher solar energy production in summer than in winter. Given that the profitability of the self-consumption system is primarily linked to photovoltaic energy production, we can therefore conclude that the system is more profitable in summer than in winter.

2. Conclusion

The installed self-consumption system helps reduce energy consumption from the grid, leading to a decrease in expenses incurred to provide electricity to users. Even though the photovoltaic system feeds its energy into the grid when panel energy production exceeds user consumption, this does not eliminate the dependence of user consumption on grid energy.

The studied self-consumption system is not autonomous and does not allow us to sell electricity to the grid, but it helps to reduce expenses related to electricity consumption by users during sunny hours. Thus, we achieved a maximum daily photovoltaic production (around 7000 kWh) when the sun is at its zenith and a maximum annual photovoltaic production in summer, resulting in a profitability of 63.04% in summer compared to 36.96% in winter.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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