

Optimization of a hybrid photovoltaic/grid power source system supplemented by a storage unit: case study

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ABSTRACT

Hybrid power systems have significantly increased in the last decade to supply energy in both industrial and commercial sectors. Because of the abundance of solar radiation, Burkina Faso has the potential to develop solar and or hybrid energy systems to meet its energy demand. In the present case study, solar radiation data have been analysed to optimise and assess a localised hybrid PV-grid system supplemented by a storage unit for CELTIC-BF, a typical small business company. In the proposed hybrid system configuration, the PV system presents a high contribution of about 93.4% of the total power production per day for a solar fraction of 92.9%, whereas the grid contributes about 6.56 %. The investigation also reveals that an excess of 746 kW from PV is obtained and could be re-injected in the network.

1. Introduction

Burkina Faso is a disadvantaged country where energy access remains one of the biggest challenges. Global energy consumption has experienced steady growth and is affected by various factors, including exponential population growth and socio-economic development [1]. Despite the country having made significant efforts to increase its energy generation capacity, there are still difficulties in meeting the electricity. Several options for renewable energy sources, such as solar photovoltaic, wind, biomass, and hydroelectric power plants, have been proposed as alternatives to mitigate the energy problem. According to the literature, the combined contribution of these energy technologies accounted for 39.86% of the total electricity consumption [2] worldwide. These technologies also have significant environmental benefits and contribute to reducing CO₂ emissions [3, 4]. Of all renewable energy

sources, solar and wind are the fastest growing. In this sense, the literature survey indicates that the installation of solar energy technologies (including solar photovoltaic (PV) power and concentrating solar power (CSP)) counts for 31% of the total installed renewable energy capacity in 2022, making it the second largest renewable energy source behind hydropower energy [5]. Despite their multiple advantages, there are certain disadvantages and limitations in using these energy sources [6]. Renewable energy sources are entirely geographical and weather conditions dependent. Blesl et al., 2008 [7] reported that renewable energy sources generally operate for a shorter period of hours in 1 year compared to conventional fossil power plants. They indicate that gas-fired or coal-fired power plants and nuclear power plants can operate for up to 7500 h/year, while wind or solar energy systems operate at only about 2000 h/year over 8760 h of one calendar year [5] have indicated the contribution of solar

sources is about 3.6% of global electricity production remains low. Despite many authors having reported the fact there are diverse technologies for cost-competitive power generation, the general public perceives renewable energy as far more expensive than conventional [8], [9]. There is increasing interest in using renewable energy in a hybrid system to mitigate energy costs and reduce the risk of power shortages during adverse weather conditions. Thus, different models of hybrid systems have been proposed. Luceny et al. (2017) [10] have proposed a new reliable indicator using a probabilistic approach for the wind-solar hybrid system. Fang-Fang et al. (2018) [11] have investigated a multiobjective model of a hydro-photovoltaic hybrid power system by using a Non-dominated Sorting Genetic Algorithms-II (NSGA-II) [12]. In 2019, Ruilin et al. (2019) [13] proposed a hybrid system which combines a chemical heat pump, photovoltaic and solar collector. They analysed the chemical heat influence on the performance and found that the efficiency reaches a maximum of 34.71% at the exothermic chemical heat temperature of 360 °C. Sun et al. (2019) [14] focused on developing a Concentred-PV/T system for electricity supply and simultaneously building heat during winter, while Xu et al. (2011) [15] experimentally tested a low-concentrating PV/T system that could generate electricity with an efficiency of 17.5% and 30–70 °C heating water. Shaahid et al. (2008) [16] have investigated the techno-economic feasibility of hybrid PV–diesel–battery power systems to meet the local energy demand. Since Burkina Faso is one of the sunniest countries, its energy needs may partly be satisfied by solar technologies. Unfortunately, these technologies are still expensive. A combination of hybrid systems which takes into account the environmental aspect seems to be reliable. The present work reports on a case study focusing on a small business company denoted CELTIC-BF. The aim is to simulate and examine a suitable hybrid system integrating PV and grid energy sources supplemented by storage battery units to supply electricity while managing the surplus during peak production. The study exploits the data recorded at solar radiation and meteorological stations. The techno-economic analysis of the hybrid system was carried out using the Hybrid

Optimization Model for Electric Renewable (HOMER) software [18], a sophisticated software used to model and design an appropriate stand-alone electric power system which optimally injects the surplus energy into the network. The study emphasises the impact of the PV contribution in the energy production, the energy cost, the hybrid system cost, the CO₂ emission and the return on investment.

2. Background information

CELTIC-BF is a company located in Ouagadougou (the capital city of Burkina Faso) in the centre of Burkina Faso with the following geographic coordinates 12°21'50" north and 1°31'05" west. The city is subjected to a tropical climate with two distinct seasons: a dry season (mid-September to mid-May) and a rainy season (mid-May to mid-September). The annual mean temperature varies from 37 °C to 42 °C for the hot period and drops by mean temperatures of 18 °C in the cold period. Despite different factors such as scattering, reflection and absorption through the atmosphere depleting the solar radiation, Ouagadougou is abundantly radiated throughout the year with an average insolation of 19.8 MJ/m² per day and direct sunshine over 3000 hours per year [19]

3. Methods and materials

The methodology adopted in this work consists of two main steps: data collection and processing and architectural configuration of the hybrid system. In this study, a multiobjective model was chosen to analyse the feasibility of a hybrid system composed of PV cells, storage batteries and the grid for the daily load power of CELTI-BF.

3.1. Data collection and Optimization criteria

The data were collected from CELTIC-BF and the National Meteorology Centre. The data needed to be pre-processed, as shown in Table 1 are used to generate the quantitative and qualitative information on the hybrid system requirement. The criteria and sizing used to optimize a system depend on the installation site. The parameters of sizing include the determination of the energy consumption [20] and the evaluation of the peak power of the photovoltaic plant [21], the capacity of the energy storage calculations [22], determination of the hybrid inverter.

Table 1 : Data and power consumption estimation

Items	Quantity	Power (W)	cumulative power (W)	Operating time (h)
fan	3	75	225	15
Refrigerator	1	135	135	24
LED lamps of 120	5	22	110	12
Computer	3	75	195	3
Colour printers	1	377	377	1
Photocopiers	1	1300	1 300	1
LED lamps of 60	8	11	88	19
Other charges	1	400	400	12
Total power			2830	

The total power of the electrical installations at CELTIC-BF is calculated through:

$$P_t(\text{kW}) = \sum P_p(\text{kW}) \quad (1)$$

where P_{pi} refers to power associated with the equipment 'i'. The load profile proposed for CELTIC-BF is alternating current (AC), and the estimated daily energy requirement is determined based on the daily operating time expressed by [23]:

$$E_r(\text{Wh}) = \sum (P_{pi} \times T_i) \quad (2)$$

P_{pi} corresponds to the partial total power of devices. T_i represents the usage time. The calculated value is 18.59kWh. The correction coefficient of the PV plant peak power for the daily energy requirement is given by:

$$P_c(\text{Wc}) = \frac{E_r(\text{Wh})}{H_i \times K_p} \quad (3)$$

where H_i corresponds to the irradiation of the most unproductive month of the year (5.15 kWh/m²/Day). K_p represents the product of the yields of the photovoltaic panels and the yield of the energy storage system R_{bat} . The storage capacity is obtained through equation (3) based on the daily needs, the battery characteristics and parameters such as depth of charge, output, and autonomy.

$$C_{bat}(\text{Ah}) = \frac{E_r \times A_{bat}}{V_{bat} \times \eta_{bat} \times DM} \quad (3)$$

where A_{bat} represents the battery autonomy (1 to 5 days, depending on the region), DM (%) is the discharge of the battery (50-80%) for solar batteries, V_{bat} is the operating voltage characteristics (12, 24 or 48 V) and η_{bat} (%) the battery efficiency (70-90%). The inverter power and the PV cells or modules' power must satisfy the following inequation.

$$P_{inv} > P_{inst} \geq P_c \quad (4)$$

3.2. Loss of load probability

The loss of load probability is criteria reflecting the ratio of unsatisfied energy and total energy consumed over the chosen study period. The determination of these parameters is given by:

$$P_{top} = \frac{\sum_{i=1}^m (E_{load,i} - E_{prod,i})}{\sum_{i=1}^m E_{load,i}} \quad (5)$$

$E_{load,i}$ is the energy requested by the consumer for period i , $E_{prod,i}$ is the energy produced, and m is the number of periods for which the research is carried out [24]. Colle et al. (2001) [24] have expressed the energy generated by the PV plant in the grid as a linear function of the collector area. In their work, Ruther et al. (2000) [25] have replaced the efficiency of PV cells with the monthly average PV plant efficiency g_i for each month considered. The amount of energy supplied to the grid in the month (i) is given

$S_i = \eta_i \bar{H}_{Ti} N_i A_c$, where $\bar{H}_{Ti}$ is the average of the monthly solar radiation on the tilted panels, N_i represents the number of days of the considered month and the total panel area.

3.3. Costs of PV systems and installation

Various approaches to calculating the investment in the system depend on the energy demanded by the consumer. Investments in purchasing solar energy system components and their installation are important factors in solar process economics. The cost of an installed PV system can be summed into two terms. One is proportional to the collector area, and the other is independent. Let's assume C_A to be the investment cost of the PV panels per unit area and C_E to be the cost independent of the total area A_c . The total expense related to the capital investment in the solar energy system plant is given by [26] : $C_s = C_A * A_c + C_E$

where C_s is the total cost of installed PV equipment (US \$), C_A correspond to total area-dependent costs (US \$/m²), A_c corresponds to the collector area (m²)

and C_E refers to the total cost of equipment which is independent of collector area (US \$).

3.4. HOMER simulation

HOMER Pro is a sophisticated software used to simulate a hybrid system combining different energy sources system, whether renewable or fossil, in response to a specific energy demand. In this study, the simulation integrates the meteorological data, electric load, the costs and the components, and their specifications. Table 2 presents the considered parameters. For each combination, HOMER simulates the relevant system and calculates the total and net present cost, the solar fraction as well as the levelized energy cost. From the proposed hybrid system, the configuration presenting the lowest costs is considered the most reliable and optimal

Table 2: Specification of components

Type of cell	Electrical specification	
Monocrystalline	Max power P_{mp}	320 W
	Max Voltage P_{mp}	36,8 V
	Max current P_{mp}	8,7 A
	Open circuit voltage V_{oc}	44,16 V
	Short circuit current I_{sc}	9,22 A
	Module efficiency η	17,8%
	Tolerance	$\pm 3\%$
	Temperature characteristics	
	Temperature coefficient of I_{sc}	-0.07%/°C
	Temperature coefficient of V_{oc}	-0.3%/°C
	Temperature coefficient of P_{mp}	-0.38%/°C
	Normal operating temperature	47°C
Type of batteries	Batteries specification	
GEL	Rated capacity CAP	200 (Ah)
	Voltage	12 V
	Discharge depth DOD %	70%
	Maximum Voltage	13.8
	Number of cells	6
	Efficiency η_{bat}	80%
	Weight	615 KG
Specification of Hybrid inverter		
	Nominal power	5 kW
	Voltage of batteries	48 V
	Current of Batteries	119 A
	Max Power	6 kW
	Current	100 A
	Max Voltage	500 V
	Min Voltage	120 V
	Frequency	50/60 Hz

4. Results and discussions

4.1. Load profile analysis

A key parameter of any power system generator is load. Here, the solar radiation data for this study were extracted from the local solar radiation database and plotted in Fig.1. Clearly, the annual sunshine

radiation reached a maximum of 6.136kWh/m²/day in March and a minimum radiation of 5.098kWh/m²/day in August. However, the relative higher solar radiation is steady from February to May and from September to December.

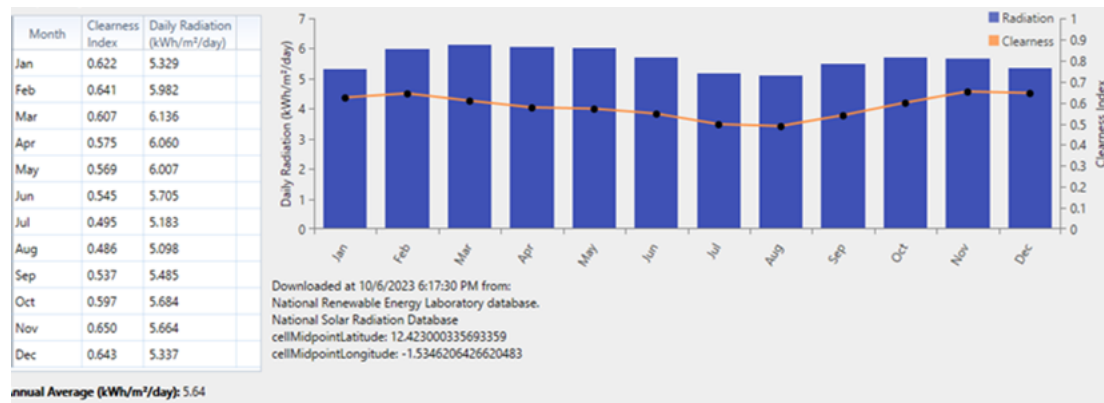


Figure 1: Sunshine profile over a year

The daily and annual load profiles are depicted in Fig. 2a and Fig.2b, respectively. From 8 p.m. to 6 a.m., the load profile plot shows a low load of 0.8 kW due to the inactivity during the night. Between 7 a.m. and 12 p.m., the power demand in this period experiences a load peak, oscillating between 1.53 kW and 2.83 kW. This oscillation is attributed to the switching on of devices. Between 1 p.m. and 7 p.m., we observed a sharp drop in the energy demand up to 0.8 kW. This drop may result from the fact that the equipment such as printers and photocopiers are not in operation during this time slot and the lift of employees around 4 p.m. When we extend the analysis to the annual consumption, the high energy consumption goes from 7 a.m. to 6 p.m. These results were also confirmed by Barry et al. (2022) [27]. As a result, there is a correlation between the working period and the energy demand over the year

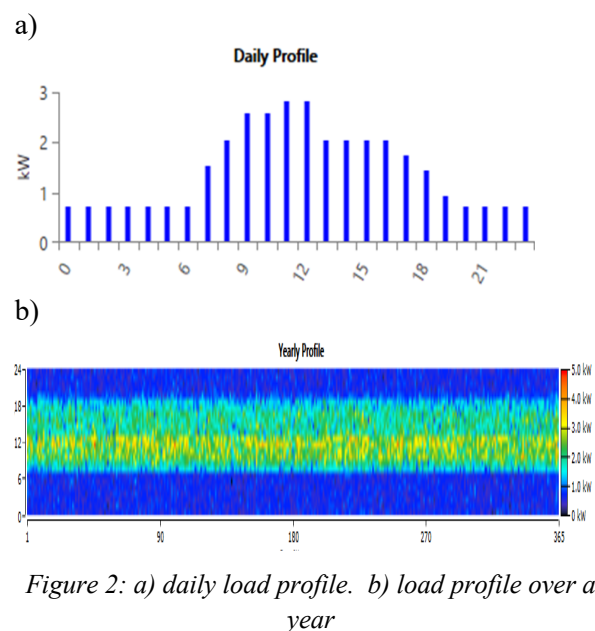


Figure 2: a) daily load profile. b) load profile over a year

4.2. Types of hybrid system configurations

The data simulation has led to four hybrid configurations classified from the most cost-effective to the most expensive, as indicated in Table 3

Table 3: Hybrid system configurations and specification

Case	Renewable power (kW)	Number of battery (201Ah)	Hybrid converter	NPC (US \$)	COE (US \$)	Solar fraction
Case I	5	0	5	13978.49	0.2025	76.8
Case II	5	4	5	14210.09	0.1311	92.9
Case III	0	0	0	15814.72	0.18	0
Case IV	0	4	5	20678.25	0.2350	0.099

- Case I: The configuration consists of a grid source, a solar plant and an intelligent hybrid converter. The net present cost (NPC) is 13978.49 US \$, the energy price (COE) given by HOMER is 0.2025 and a solar fraction of 76.8%.
- Case II: The proposed second cost-effective system configuration includes a grid source, a solar plant, a bank of four (04) 201 Ah batteries, and intelligent hybrid inverters with a net present cost estimated at 14210.09 \$, an average energy cost of 92.9 and a solar fraction of 92.3%.
- Case III: The third cost-effective system proposed by the software relies on the grid source only, for which the net discounted cost is 15814.72 \$ and an energy price of 0.18 US \$.
- Case IV: The optimised hybrid system's last option is a backup system composed of a grid source, a bank of four (04) 201 Ah batteries and a hybrid inverter. The estimated net present cost is 20678.25 US \$, and the energy cost is about 0.2350 US \$, with no solar fraction. Although the most cost-effective hybrid system proposed by the HOMER software is the Case I configuration, the most reliable seems to be the Case II configuration. Also, the configuration has a higher solar fraction, and the system remains usable all the time in the advent of outages or load shedding because of the batteries. Overall, investment in this configuration is also reasonable compared to the first configuration.

4.3. Architecture of the chosen hybrid photovoltaic-grid-storage system

Of the four hybrid system configurations given by HOMER, the combined photovoltaic system configuration connected to the grid source with an energy storage unit and a converter system is the most reliable for CELTIC-BF. The architectural profile of this configuration and its characteristics are shown in Fig.3

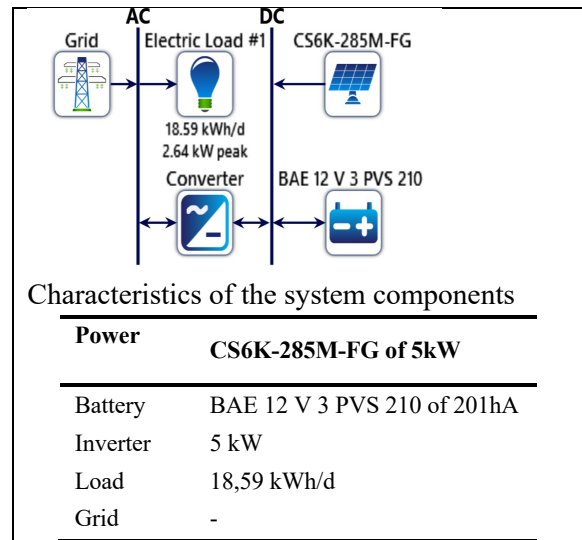


Figure 3: Hybrid PV/grid system architecture

4.4. Evaluation of PV plant performance

Table 4 shows the performance parameters of the proposed configuration. The daily production of energy power over a year is presented in Fig. 4.

Table 4: Evaluation of the propose PV plant performance

Specification	
The power to be installed	5.00 kW
Average output power	0.974 A
Average daily energy	23.4 V
Capacity factor Total	19.5 %
Total production	8,531 kW

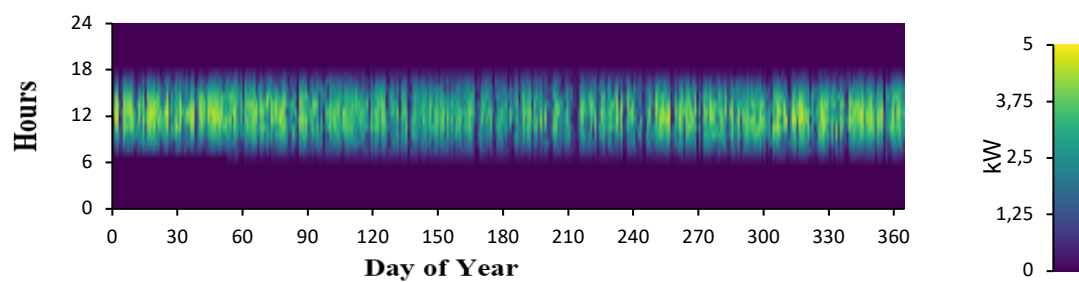


Figure 4: Profile of energy production at CELCTIC

The evolution of the daily production of energy power over a year is presented in Fig. 5. The energy production is optimal from 7 a.m. to 10 a.m. and from 11 a.m. to 3 p.m. A decrease in the energy production is observed from 4 p.m. to 5 p.m. From 6 p.m. to 6 a.m., there is no record of energy production. This phenomenon is explained by the absence of the sun and, therefore, no power production from the PVs. A carefully examining the figure indicates e that the energy production does not reach the maximum power due to the intermittency of the sun. Another explanation can be associated with the fact that days are often cloudy in the rainy season, resulting in the reduction of sunlight intensity reaching the installed PV system for conversion into electrical energy. The coverage of the sky by dust clouds may also affect

the system's performance. The simulated results obtained from the PV system are in agreement with those found in a study carried out by BARRY et al. (2022) [27]

4.5. Energy storage

In a PV system installation, storage remains the most prominent challenge. To take into consideration this aspect, the HOMER software proposed for the system, four (04) batteries connected in series with a single string in parallel to obtain a voltage of 48V. The battery's autonomy is about 9.96 hours, with a nominal capacity of 9.65 kWh and a usable capacity of 7.72 kWh. The total capacity during the life of the batteries is 11.320 kWh, with a lifespan of 5.38 years. Figure 5 depicts the charging and discharging profile of the annual storage

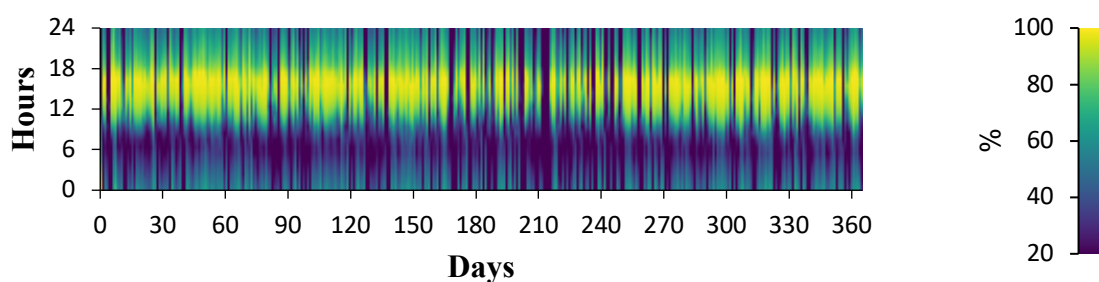


Figure 5: Charge and discharge profile of storage batteries

From the profile, the batteries are discharged overnight at a rate ranging between 20 and 60%. From 6 a.m. to 9 a.m., the PV system has a weak

contribution because of the absence of intense sun radiation. The charging process begins around 10 a.m. However, the maximum charge recorder between 12 p.m. and 3 p.m. resulted from the best harness of sun radiation. Similarly to the PV energy production profile, the maximum charge of the

batteries is discontinuous due to the intermittency during the rainy season

4.6. Specification and performance of the hybrid inverter

The intended intelligent hybrid inverter for the storage unit of the hybrid PV and the grid source management is presented in Table 5. The estimated capacity of the inverter is an average power of 0.889kW with a capacity factor of 17.8%.

Table 5:: Characteristics of the hybrid inverter

Specifications	
Capacity	5.00 (kW)
Average power	0.889 (kW)
Minimum output power	0 (kW)
Maximum outpower	4.06 (kW)
Capacity factor	17.8 %

The usage profile of the hybrid inverter along the year is presented in Fig 6

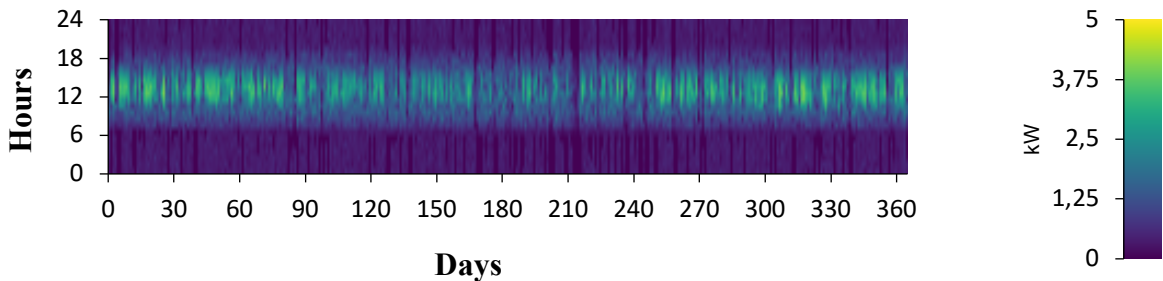


Figure 6:Hybrid inverter usage profile

From the figure, it can be observed that the hybrid inverter operates continuously over 24 hours throughout the year with a variable power in the range of 0kW to 5kW. From 6 p.m. to 6 a.m., the power supplied by the inverter is less than 1kW due to inactivity and the absence of sunlight during the night. From 7 a.m. to 5 p.m., the inverter power varies between 1.25 kW to 5 kW due to the activities carried out during the day and the charging of the batteries due to the excess daily production of the photovoltaic panels.

4.7. Evaluation of energy contribution per source

Table 6 summarises the energy production, consumption and the different prices applied to the

installed hybrid system the estimated production will exceed consumption for ten (10) months in the year while the consumption will exceed production during the during July and August. The observation can be explained by the heavy rainfall during this period in the country. The contribution profile of the grid to the hybrid system production over the year is presented in figure 7a.

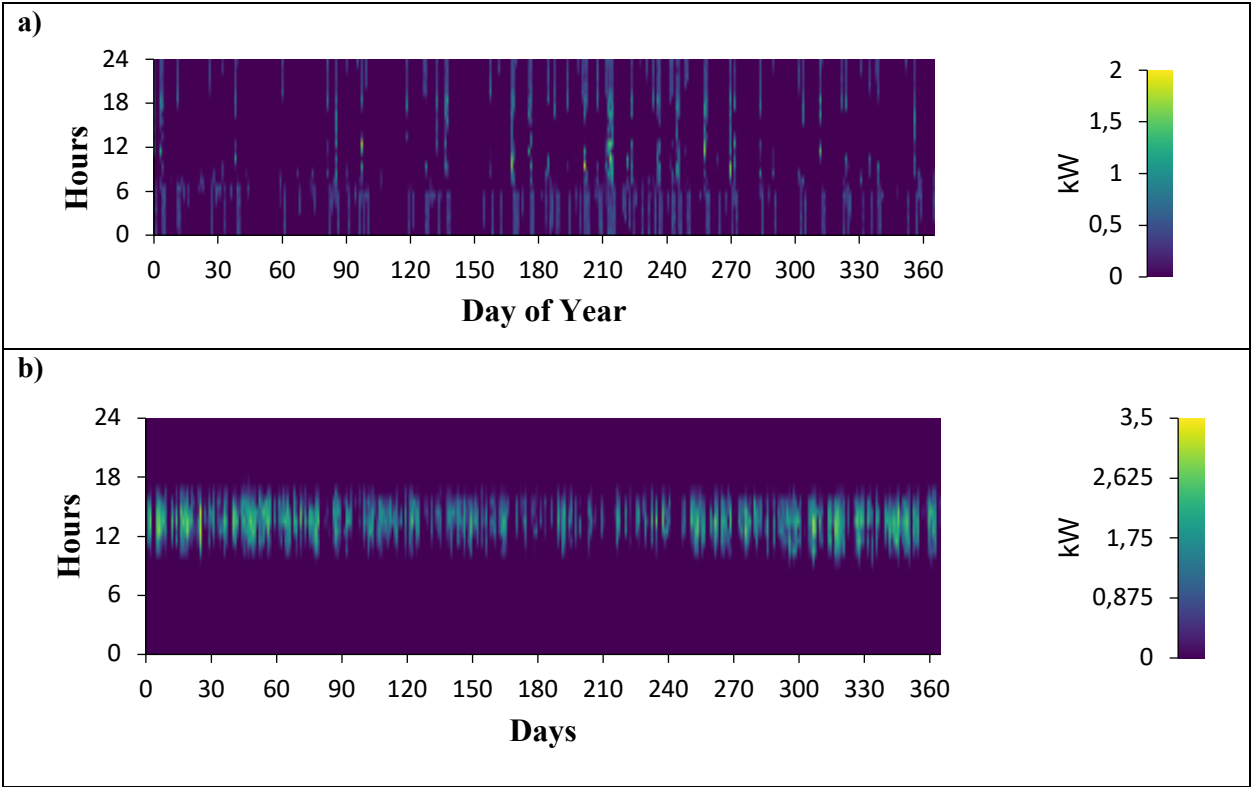


Figure 7: a) Behavior of the grid system source; b) Energy sold to the network

Figure 7a reveals that the grid source is in less demand in the system. Its usage mainly occurs at night when the batteries are discharged or when the energy demand is unsatisfied but at a low power proportion (1kW). During the daytime, the energy produced by PV is sufficient to meet the demand of CELTIC-BF. Therefore, grid exploitation occurs during intermittent periods and the rainy season with a maximum power of around 2kW. From Figure 7b, there exists a possibility of reselling while injecting

the excess (up to 3.5 kW) energy produced from 11 a.m. to 3 p.m. In comparison to other hybrid models, which often consider multistage investment plans, our model has a lower level of detail, but it offers rational exploitation of the renewable energy source a reasonable return on investment for lifecycle period of 25 year. This evaluation takes into account the main factors such as long-term energy storage management, seasonal variations, and uncertainties in loads.

Production	kWh/yr	%
CanadianSolar Dymond CS6K-285M-FG	8,531	93.4
Grid Purchases	599	6.56
Total	9,130	100

Consumption	kWh/yr	%
AC Primary Load	6,786	80.9
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	1,597	19.1
Total	8,384	100

Quantity	kWh/yr	%
Excess Electricity	0	0
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	92.9	%
Max. Renew. Penetration	481	%

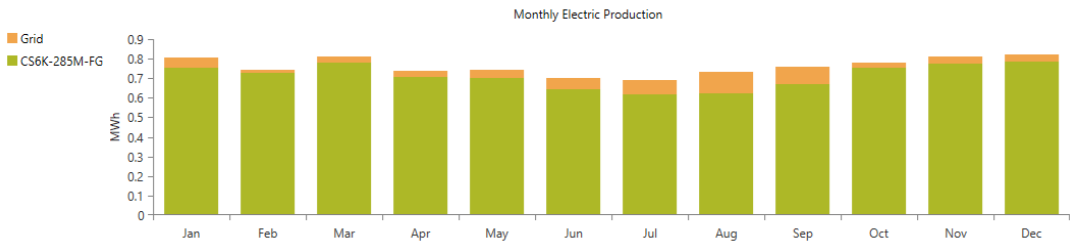


Figure 8: Comparison of the power produced by the two sources

As shown in Fig 8., the annual PV energy production dominates with about 8531kWh, i.e. a contribution of 93.4% to the total energy production. The grid contribution is 599kWh per year, which represents 6.56%. For a total annual energy production estimated at 9130kWh, the total consumption is 8,384kWh.

This analysis indicates that the proposed hybrid system could be advantageous in supplying energy to CELTIC-BF. Furthermore, the model identifies the optimal investment and operation strategies to meet the demand and minimize the total annual expenditure of the energy system.

5. Conclusion

A hybrid photovoltaic-grid source supplemented by a storage unit has been simulated and optimized to meet the energy of a typical small business CELTIC-BF company. The results demonstrate that the optimized hybrid can supply sufficient energy to meet the demand. During the daytime and sunny periods, the PV system supplies the necessary power with more than 93.4% of the total energy production, and the grid system source contributes during intermittent periods and the rainy season with a maximum power of approximately 2kW. For a total energy production estimated at 9,130 kWh per year, for total consumption is about 8,384 kWh per year, i.e. the system generates an excess of 746 kWh. This suggests that the optimized hybrid system is reliable for supplying power to CELTIC-BF and could be a promising model for a large-scale building.

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