EXACTA OPEN ACCESS

Artigos

https://doi.org/10.5585/2025.26050

Check for updates

Comparative analysis between off-grid photovoltaic solar energy, diesel generator and Hybrid system options

Análise comparativa entre energia solar fotovoltaica off-grid, gerador a diesel e sistema híbrido

Recebido: 12 fev. 2024

Aprovado: 01 set. 2025

Versão do autor aceita publicada online: 01 set. 2025

Publicado online: 23 set. 2025

Como citar esse artigo - American Psychological Association (APA)

Villena, J. E. N., Belchior, F. N., Silva, F. C. A., & Moraes, M. P., (out./dez. 2025). Comparative analysis between off-grid photovoltaic solar energy, diesel generator and Hybrid system options. *Exacta, 23*(4), p. 670-990, e26050 https://doi.org/10.5585/2025.26050

Submissões

Processo de Avaliação: *Double Blind Review*

Editor: Dr. Luiz Fernando Rodrigues Pinto

Dados Crossmark

Processo de Avaliação: *Double Blind Review*
Editor: Prof. Dr. Luiz Fernando Rodrigues Pinto
Recebido em: 12 fev. 2024
Aprovado em: 01 set. 2025
Artigos

https://doi.org/10.5585/2025.26050

Comparative analysis between off-grid photovoltaic solar energy, diesel generator and Hybrid system options

Análise comparativa entre energia solar fotovoltaica off-grid, gerador a diesel e sistema híbrido

John Edward Neira Villena[1] Fernando Nunes Belchior[1] Fernando Carvalho Assunção da Silva[2] e Marcela Prudente Moraes[3]

[1]Universidade Federal de Goiás - UFG, Goiás, Brazil
[2]SmartSet - Soluções em energia renovável, Goiânia, Goiás, Brazil
[3] Prudente & Moraes Engenharia, Goiânia, Goiás, Brazil

Authors' notes

The authors have not declared any potential conflicts of interest.
Corresponding author: John Edward Neira Villena johnneirav@ufg.br

Abstract

This study aimed to measure and compare the costs of some energy generation and storage systems that are considered to be more suitable and accessible for use in isolated rural areas, where there is no or limited access to the energy distribution network. In this study, the energy is considered as being produced from a diesel generator set, an off-grid photovoltaic system with a battery and a diesel solar hybrid system. The analysis evaluates the best conditions through a technical and economic comparison presented by these three alternatives. The alternatives were compared, where it was noted that the annual production costs, by obtaining the unit production cost of the diesel generator, reached R$ 1.27/kWh, while for the off-grid photovoltaic generation system using batteries, the value was R$1.64*/kWh and the hybrid system was R$2.37/kWh. *value obtained under specific conditions.

Keywords: off-grid photovoltaic system, diesel generator, hybrid system

Resumo

Análise comparativa entre energia solar fotovoltaica off-grid, gerador a diesel e sistema híbrido

Esse estudo objetivou dimensionar e comparar os custos de alguns sistemas de geração e armazenamento de energia, considerados como sendo mais adequados e acessíveis para serem utilizados em áreas rurais isoladas, sem acesso à rede de distribuição de energia. Neste estudo, considera-se que a energia será produzida a partir de um grupo motor gerador a diesel, um sistema fotovoltaico off grid com bateria e um sistema híbrido solar diesel. A análise observará as melhores condições de comparação técnica e econômica apresentadas pelas três alternativas. As alternativas foram comparadas e foi observado que com a anualização dos custos de produção, a obtenção do custo unitário de produção do gerador a diesel chegou a R$ 1,27/kWh, já para o sistema de geração fotovoltaico off grid com baterias o valor foi de R$ 1,64* /kWh e o sistema híbrido de R$ 2,37/kWh. *valor obtido dentro de condições específicas.

Palavras-chave: sistema fotovoltaico off grid; gerador a diesel; sistema híbrido

1 Introduction

Electric energy is a resource necessary for improving the life quality of human beings, which thus makes it an essential instrument toward socioeconomic development. The obtainment and access to a reliable and stable supply of electricity are modern day challenges, mainly when it comes to rural residents. (Lahimer et al., 2013; Sánchez et al., 2015; Ufa et al., 2022; Yuan, 2015)

Considering the aforementioned, besides non-renewable energies the recent development of technologies in the area of renewables, which need devices to store generated energy for use in periods of system inactivity, can also provide social and economic equity to the population. The economic and environmental aspect are also important in these studies, as these have a direct impact on human life quality. (IEA, 2023; Price, 2015)

In methodological terms, this research adopted a comparative and analytical approach, structured in three stages: (i) sizing of each system (off-grid photovoltaic with batteries, diesel generator, and hybrid solar-diesel) based on standard technical equations consolidated in the specialized literature; (ii) economic evaluation through Life Cycle Cost (LCC) and Levelized Cost of Electricity (LCOE) indicators; and (iii) comparative analysis among the alternatives. The decision to employ the equations presented stems from their widespread acceptance in photovoltaic and energy system sizing studies, ensuring replicability and methodological transparency. Other approaches could be used, such as computational optimization models or simulation software (e.g., HOMER or RETScreen), but this work opted for a deterministic analytical method due to its applicability in contexts where access to such tools is limited. This choice imposes certain limitations: the results are valid for the case study conditions adopted and may vary with different assumptions regarding fuel prices, solar irradiance, or equipment costs. Therefore, the findings should be understood as indicative rather than universally prescriptive, offering a reference framework for similar rural electrification scenarios.

This paper therefore has as its objective to evaluate the technical and economic viability of electric power generation systems, including the photovoltaic system (PVS) off-grid with batteries and the use of a diesel generator set (DG). The study will cover the analysis, in a rural residence that works in the area of agriculture, of each one of these systems in a separate manner and then collectively, otherwise known as a hybrid system. The aim here is to verify which is the most advantageous system from the point of view concerning economy, power and viability for agrobusiness.

Studies addressing this topic in the Brazilian context are scarce, and those that do exist were conducted more than 15 years ago. At the same time, it is understood that conducting research in this field is of utmost importance to support public policies, energy planning, and private investments in the sector.

2 Theoretical basis

This section presents the theoretical basis of the study, including the main concepts, technologies, and parameters related to off-grid photovoltaic systems, battery storage, diesel generators, and hybrid configurations, which support the methodological approach adopted.

2.1 Off-grid PVS

The isolated photovoltaic system/autonomous/off-grid is a type of system that possesses generation and energy supply demand without supervision or control from the local energy utility, that is, it does not pay any type of tax and there is no inspection. Its implementation occurs in remote places or regions where the distribution network presents many problems of instability and/or voltage interruptions. (Villalva & Gazoli, 2012). In such places, it is becoming ever more common to see the use of off-grid systems, a technology that gives the option of storing this energy in batteries (*DOE Global Energy Storage Database*, n.d.; Koohi-Fayegh & Rosen, 2020; Krishan & Suhag, 2019), and as such expansion of its use is also seen in the illumination sector, as well as telecommunications and space applications.

The PVS, in general, does not need a great deal of maintenance, only the photovoltaic modules should be cleaned, without the presence of particles that can block solar rays reaching the photovoltaic cells, when such modules are dirty, they may have their generation reduced by up to 25%. It may also be necessary to tighten screws, perform a thermography and check cables (Moreira, 2021; Portal Solar, 2022). Most modules have a 25-year performance guarantee and present a depreciation over time.

2.2 Battery technology

The batteries in question are rechargeable and fixed, and which in photovoltaic systems are designed for shallow to moderate depth daily cycles with reduced discharge rates and should also support sporadic deep discharges due to the absence of generation. The operation of a battery used in an off grid PVS needs to attend to the two types of cycle, daily shallow cycles and deep cycles over various days. (Villalva & Gazoli, 2021; Zhang et al., 2018).

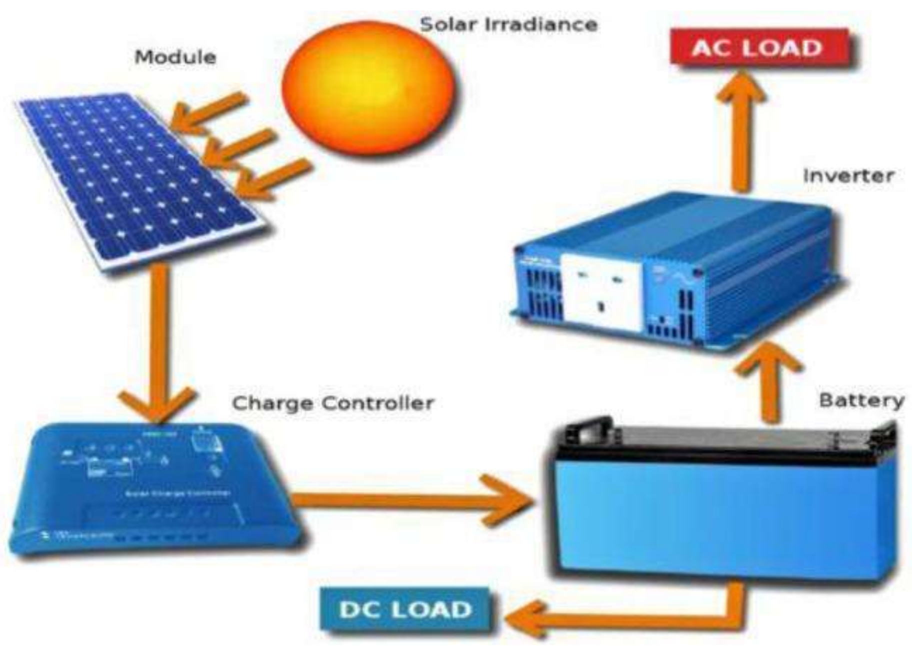
Of the various types of existing electrochemical accumulators that exist, the lead-acid battery (Pb-acid) is still the most widely employed technology. There exist batteries that use more modern technologies, such as nickel cadmium (NiCd), nickel metal hydride (NiMH), lithium ion (Li-ion), among others that are also available on the market (Faessler et al., 2021; Hesse et al., 2017; Portal Solar, 2022, 2023).

2.3 Off grid PVS with batteries

An off grid photovoltaic system with batteries in essence has the following structure, in accordance with Fig 1:

Figure 1

Equipment used in off grid photovoltaic systems with batteries



Source: Olabode et al., 2021

The Fig. 1 shows the equipment used at the off grid photovoltaic systems with batteries in a building terminal (AC and DC load):

- Module - these are made up of a group of electrically connected panels. According to the number of panels that make up the module, it will apply an output voltage and a power to the system (Olabode et al., 2021).
- Charge Controller - the function of the charge controller is to create the connection between the batteries and the solar panel, thus preventing battery discharge or excessive loading (Olabode et al., 2021).

- Battery - this is responsible for storing electric energy, thus allowing its use at any moment, including during night hours. The batteries can be connected in series and/or parallel to obtain the compatible voltage for the output charge controller and the inverter input (Olabode et al., 2021).
- Inverter - this is an electronic device that supplies electric energy in alternating current (AC) from an electric power supply in direct current (DC). The efficiency of inverters varies and may decrease when they are operating below their rated power, as well as when operating at above expected temperatures (Olabode et al., 2021).

2.4 Diesel generator set

DG is used for supplying electric energy on demand, which includes emergency power backup, power conditioning for remote locations, data processing, medical installations or any other mission-critical application be it industrial or commercial that demands independent or remote energy (Babajide & Brito, 2021; El-Hawary & Eckels, 2019; Karakoulidis et al., 2011; López-González et al., 2021).

Depending on the electricity consumers for which they are intended, generator sets are crafted with special features that are appropriate for a number of different applications, classified as (Caterpillar, n.d.):

– *Standby* – the generator operates as a reserve for the main energy source and is not used with frequency. The utilization factor of this type of generator is 1.0;

– *Prime* – the generator is used as the main power source, without limitation in the number of daily hours and with a variable load. The utilization factor is 1.1.

The utilization factor is the factor by which the rated power of the device should be multiplied to obtain its average absorbed power, under its conditions of use (Boylestad & Olivari, 2022).

2.5 Solar-diesel hybrid system

The solar-diesel combination is advantageous as it provides a reliable form of isolated supply, without intensive fossil fuel use. In places that already have a supply through diesel generators, the addition of photovoltaic systems has the effect of reducing the fuel costs, in addition to offering greater reliability and reinforces the autonomy concerning consumer load supply. (Babajide & Brito, 2021).

The diesel and solar sources share the same AC bus, but never operate simultaneously. The diesel generator is activated only occasionally for short periods of time and the loads can be met fully by DG, where photovoltaic generation can be dispensed with during these short periods of time. As an alternative to these hybrid systems, a battery storage system can be used, where the solar modules will charge the batteries and always maintain the system energized. (Iskanderani et al., 2020; Khan & Iqbal, 2005; Paliwal et al., 2014; Salisu et al., 2019)

In light of these considerations, this paper aims to evaluate the technical and economic feasibility of electric power generation systems, including the autonomous photovoltaic system (off-grid) with batteries and the use of a diesel generator set (DG). The study encompasses the analysis, in a rural household engaged in agricultural activities, of each of these systems individually and, subsequently, in an integrated manner, referred to as a hybrid system. The objective is to determine which of these systems proves to be more advantageous from the perspective of cost-effectiveness, energy supply, and overall feasibility for agribusiness. Also, it is important to highlight the potential of the autonomous photovoltaic system (off-grid) with batteries and the use of a diesel generator set (DG) to obtain carbon credits.

3. Methodology

This section describes the methodology adopted in the study, outlining the procedures used for the technical sizing of the photovoltaic system, the diesel generator, and the hybrid configuration. It also details the assumptions, variables, and equations applied, as well as the criteria adopted for the economic evaluation. The objective is to provide a transparent and replicable framework that supports the comparative analysis presented in the following sections.

3.1 PVS calculation

To serve a residence that is isolated from the network, in this case, the only source of energy that will supply its loads is photovoltaic modules. The off-grid PVS is designed to satisfy the total demands of the isolated building, including days with low solar radiation and high cloud. Under such conditions, PVS should make use of storage systems (batteries). According to (Moreira, 2021), one of the options for sizing up photovoltaic modules is the following method.

a) Modules

It is necessary to assess the quantity of modules needed to supply the required consumption. Firstly, it is necessary calculate the energy necessary to produce (E), in accordance with equation (1).

$$E = N \; x \; P°_{mp} \; x \; HSP \; x \; PR \qquad (1)$$

Where,

E = energy for consumption, in kWh,

N = number of modules,

$P°_{mp}$ = maximum rated power under STC*, in Wp,

HSP = hours of full sun, in h,

PR = Performance ratio, 0.7<PR<0.8.

(*STC= standard test condition)

Following on from this, it is necessary to know the configuration, in terms of the quantities allowed for series and shunt connections, in accordance with equations (2) and (3)

$$\frac{V_{MPPT(MIN)}}{V_{mp(TC\ MAX)}} < N_{series} < \frac{V_{MPPT(MAX)}}{V_{mp(TC\ MIN)}} \qquad (2)$$

$$N_{shunt} \le \frac{I_{MPPT}}{I_{SC(STC)}} \qquad (3)$$

Where,

N_{series}= number of photovoltaic modules in series,

$V_{MPPT(MIN)}$= minimum voltage as a function of maximum power point tracking, in V,

$V_{mp(CT\ MAX)}$= maximum power voltage with maximum current transformer (CT), in V,

$V_{MPPT(MAX)}$= maximum voltage as a function of maximum power point tracking, in V,

$V_{mp(CT\ MIN)}$= maximum power voltage with minimum current transformer (CT), in V,

N_{shunt} = number of photovoltaic modules in shunt,

I_{MPPT}= maximum input current as a function of the maximum power point tracking, in A,

$I_{SC(STC)}$= short-circuit current under the STC, in A.

Therefore, to know the generation peak power, Equation (4) is performed, using data from Equation (5):

$$P_{pGFV} = N \; x \; P°_{mp} \qquad (4)$$

$$N = N_{series} \; x \; N_{shunt} \qquad (5)$$

Where,

P_{pGFV} = photovoltaic generator peak power, in kWp,

N = total number of photovoltaic modules.

In order to verify if the equipment is correctly sized, the equations (6), (7) and (8) are used.

$$\mathrm{V_{OC(MAX)}} = \mathrm{V°_{OC}}\ \mathrm{x}\ (1 + (\gamma_{sc}\ \mathrm{x}\ (\mathrm{T_C} - \mathrm{T°_C})) \quad (6)$$

Where,

$V_{OC(MAX)}$ = maximum open circuit voltage, in V,

$V°_{OC}$ = open circuit voltage under STC, in V,

γ_{sc} = temperature coefficient Isc, in $°C^{-1}$.

Considering,

$$Tc = T_a\ x\ \frac{G_T}{800}\ x\ (T_c^* - 20)\ x\ 0.9 \quad (7)$$

Where,

Tc = photovoltaic cell temperature, in °C,

T_a = ambient air temperature, in °C,

G_T = in-plane irradiation of photovoltaic panel, in W/m^2,

T_c^* = photovoltaic cell temperature at **NOCT, 25°C, in °C.

(**NOCT= nominal operating cell temperature.)

Therefore,

$$Voc\ system = N_{series}\ x\ VocPanels \quad (8)$$

b) Inverter

Inverter sizing must allow for a clearance from 43% to 100% greater than the rated load, while considering an efficiency of approximately 93%.

c) Load Controller

As previously mentioned, a load controller is essential to an off-grid photovoltaic system. This should be situated between the photovoltaic modules and the batteries, and always respecting the connection polarities.

d) Battery

In order to calculate the size of the battery bank, it is necessary to know the energy consumption of the property. The objective is not to have breaks in electric energy. In this way, all calculations will be overestimated, thus opening the possibility of the property owner to increase the load slightly, should the need arise, in addition to factoring in the degradation in system generation over time.

Considering a global efficiency value for batteries between 87% and 91%, as most batteries sit at 89%, one has equation (9). Therefore,

$$C_{real} = \frac{C_{daily}}{0.89} \tag{9}$$

Where,
C_{real} = actual consumption to be used, in kWh,
C_{daily} = calculated daily consumption, in kWh.

With knowledge of the battery bank voltage, the quantity of batteries in series to be used, and which batteries will be used, one can calculate the capacity of the battery bank (equation (10)). Considering a battery depth of 20%.

$$C_{bank} = \frac{C_{real}}{V_{bank} * 0.2} \tag{10}$$

C_{bank} = battery bank capacity, in Ah,
V_{bank}= battery bank voltage, in V.

Considering the use of 220Ah batteries (equation (11)):

$$N_{batteries} = \frac{C_{bank}}{220} \tag{11}$$

Where,
$N_{batteries}$ = number of batteries in series

3.2 DG set calculation

A diesel generator will be used, in prime power, meeting all the requirements of frequency 60Hz and electrical voltage of 220 V. The generators are classified in apparent power (VA), as such it is necessary to transform the demand (W), using the power factor 0.8. Therefore, in accordance with equation (12):

$$Papparent = \frac{demand}{power\ factor} \tag{12}$$

As a generator in prime power will be used, which is where a generator is used as the main supply of energy, without limitation in the number of daily hours and operates with the utilization factor 1.1. Consequently, the power of the generator will be calculated according to equation (13).

$$Pgenerator = demandx\ utilization\ factor \tag{13}$$

3.3 Solar-diesel hybrid system

The hybrid system considered herein will have as its supply, during the day, the photovoltaic system along with batteries, while during the night period only batteries will be considered. Therefore, in the absence of sun, the diesel generator will enter into action to supply the loads.

a) PVS calculation

The same method used for sizing the off-grid PVS with batteries will also be used in the part pertaining to the hybrid system. Considering here all the constants that remain the same, such as irradiance, temperature, data from the modules and batteries used.

For the calculation of batteries and modules, only the load of a single day will be considered, since the DG set will be the backup of the system, without the need to oversize generation and storage, while still employing equations (1) to (11).

b) DG set calculation

To perform this calculation, we will consider a diesel generator, in standby, which will supply the demand, thus fulfilling all the battery requirements. Using the adopted utilization factor (1.00), the adopted power factor is 0.8. the same method used for sizing the DG set will also be used in this part of the hybrid system, that is, equations (12) and (13).

3.4 Economic viability

The initial costs of a system are the global cost with the system installed correctly and operating, which is known as CAPEX, Capital Expenditure. Initial costs include the acquisition of main and secondary equipment.

The Life Cycle Cost, the cost over the working life of a system is related to the sum of the initial costs (CAPEX) and the operational and maintenance costs, with planned preventative and corrective maintenance. The annual cost of preventative maintenance for PVS normally represent between 0.5% and 1% of the initial cost of the (*CAPEX*), which will be considered as 0.5% (Walker et al., 2020).

The cost analysis for corrective maintenance of the main equipment is performed by bringing the "present value" the investment cost (at the time of installation), converted through a "recurrence reduction factor", while taking into consideration the substitution period. In this case, there is no real financial return, but a comparison will be made with the energy supplied by the utilities just to facilitate the analysis. The analysis of mutually exclusive investment alternatives with equivalent periods needs to be performed through the NPV (net present value) analysis. In order to find the most realistic reduction rate, the average rate over the last 25 years was performed (Higgins et al., 2023).

Equation (14) presents the LCC (Life Cycle Cost) calculation for photovoltaic electricity generators.

$$LCC = Ccapex + CMP\ (current\ market\ price) \tag{14}$$

LCC – Life cycle cost, in R$,

Ccapex – Initial cost of the system installed and operational, in R$,

CMP – Annual cost of preventative maintenance, in R$.

a) PVS

With all the information presented for elaborating the projects of the PVS for each locality in the study, the present value associated with the expected 25-year cash flow was used as a financial viability criterion. This represents the average life cycle of the photovoltaic generator provided by the manufacturers.

The planning horizon of 25 years was chosen based on the guarantee of the photovoltaic modules and the inverter. It is considered that the inverter will be replaced in the thirteenth year and that the modules will have a useful life of 25 years, with a decrease in production of 1% per year, with maintenance every year.

b) DG set

One can estimate, proportionally, the number of daily hours of equivalent operation, as well as the total DG consumption and diesel costs, according to equation (15):

$$Cost = dieselprice * consumptionDG\ set * \frac{Cmax\ x\ 30\ days}{Pgenerator * 0.8} \tag{15}$$

Where,

$dieselprice$ = The actual price of diesel, in R$,

$consumptionDGset$ = the consumption of the DG set, in L/h,

$Pgenerator$ = Total power of the generator, in kVA,

$Cmax$ = Maximum consumption of the property over the month, in kWh.

In order to ensure the replicability of this study, the selection of the main variables used in the calculations was guided by three criteria: (i) consolidated references in the specialized literature; (ii) manufacturer data sheets and technical recommendations; and (iii) contextual adjustments to the case study conditions. For example, the inverter efficiency was fixed at 93%, a value consistent with the efficiency range reported by current market equipment. The depth of discharge of the batteries was limited to 20%, following recommendations to extend their operational lifespan. The useful life of the photovoltaic modules was assumed as 25 years, in line with the warranty period provided by manufacturers, while the degradation rate of 1% per year corresponds to values commonly adopted in techno-economic analyses of PV systems. In the case of the diesel generator, a utilization factor of 1.1 was applied for prime power operation, according to Caterpillar (n.d.) and Boylestad & Olivari (2022). These parameters, together with the equations already presented, form a methodological framework that can be adapted to other geographic and socioeconomic contexts, thus making the study reproducible and comparable in future works.

4. Case Study

This section presents the case study developed to apply the proposed methodology. The systems under analysis — off-grid photovoltaic with batteries, diesel generator, and hybrid solar-diesel — are dimensioned and evaluated according to the established parameters. The results obtained for each configuration are discussed in order to highlight their technical and economic performance, serving as a basis for the comparative analysis.

4.1 Off grid PVS with batteries

a) PVS

The total consumption (3 days) is 70 kWh/cycle. Considering here that there are no space restrictions, and the modules will be directed north, the photovoltaic modules and inverters are chosen. In addition, with knowledge of data such as local irradiance, maximum and minimum temperatures, it is possible to survey all the necessary calculations, from the use of equations (1) to (7).

Thus, encountering an N≅ 44 modules. Then: Tc_{max} = 60.13°C and Tc_{min} = 47.13°C. Now, it is possible to discover $V_{mp(CT\ MAX)} = 41.21\ V$ and $V_{mp(CT\ MIN)} = 42.90\ V$. One finds, $3 < N_{series} < 10$ and $N_{shunt} \leq 9$.

However, for module configuration reasons, this number is increased to 48, being $N_{series} = 8$ and $N_{shunt} = 6$. Through equation (4), one finds P_{pGFV} = 21.6 kWp.

b) Inverter

Following on, it is necessary to size the frequency inverters. Due to lack of option in the current market, four solar off-grid inverters will be used - SPF 5000 ESG of 5000W. In this case, 20W is within the possible values of 43% to 100% greater than the residential load of 12.97 kW, an efficiency of 93% was also considered. The inverter chosen already has an integrated load controller.

In order to verify if the equipment is sized correctly, it is necessary to find the maximum open circuit voltage of the modules ($V_{oc(MAX)}$), for which the value is 401.84V, which is lower than the limit of the inverter which is 450V_{DC}, encountered through equation (6).

c) Batteries

As discussed previously, consumption will be rounded to 700 kWh/month. Using a battery bank with a voltage of 48V (4 x 12V batteries connected in series) and considering a battery depth of 20% of the charge depth, equation (10) is employed, $C_{bank} = \frac{78630}{48\ x\ 0.2} = 8190.6Ah$.

In this scenario, it is considered the use of 220Ah batteries and through use of equation (11), $N_{batteries} \cong 37$. In other words, the battery bank consists of 148 batteries of the lead-acid type with a voltage of 12V and capacity of 220Ah (C100), which is ideal for PVS. Additionally, there are 4 batteries connected in series and 37 batteries in shunt connection.

4.2 DG set

It was established through the calculations, a 23.33 kWh of electric energy consumption per day, at a voltage of 220V, the residence has a maximum power demand of 23.33 kW. Assuming a power factor equal to 0.8 and a prime power generator, the DG is used as the main source of energy, with no limitation on the number of hours per day and with a variable load. By using a 1.1 utilization factor and equation (13), $Pgenerator = 32.07kVA$.

4.3 Solar-diesel hybrid system

a) PVS

By encountering an N≅ 14 modules. Then $Tc_{max} = 60.13°C$ and $Tc_{min} = 47.13°C$. Now, it is possible to discover $V_{mp(CT\ MAX)} = 41.21\ V$ and $V_{mp(CT\ MIN)} = 42.90\ V$. One encounters $3 < N_{series} < 10$ and $N_{shunt} \leq 9$. However, by reason of module configuration, this number goes to 16, being $N_{series} = 4$ and $N_{shunt} = 4$.

b) Inverter

At the off-grid system, the sizing of the inverter depends entirely on the load, which in this case does not change. Therefore, all the sizing performed for the photovoltaic solar system will be maintained the same, that is, 4 solar off-grid inverters will be used SPF 5000 ESG of 5000W, with a P_{pGFV} = 7.2 kWp. As such, one has 50.23 x 6, as there are 6 modules in series, 301.38V is lower than the inverter limit, which is 450V_{DC}.

c) Batteries

Using the same consumption, that is rounded to 700 kWh/month, the battery bank at a voltage of 24V (2 batteries of 12V connected in series) and considering a battery depth of 20%, along with equation (10), $C_{bank} = \frac{26210}{24\ x\ 0.2} = 5460{,}41Ah$. Considering 220Ah each battery and using equation (11), $N_{batteries} \cong 25$.

In other words, the battery bank consists of 50 lead-acid batteries with a voltage of 12V and a capacity of 220Ah (C100), which is ideal for PVS. Accordingly, there are 2 batteries connected in series and a 25-battery series in shunt.

d) DG set

For the diesel generator, it was considering a consumption of 23.33 kWh of electric energy per day, with a voltage of 220V between phase and neutral. As mentioned, the residence has a maximum power demand of 23.33 kW, the power factor equal to 0.8 and the generator in standby, that is applying the main power supply, without any limit in the quantity of daily hours and with a variable load, according equation (13), $Pgenerator = 29.16kVA$.

4.4 Economic viability

The analysis across all the LCCs and the levelized cost of electricity, thus leads us to which project is the cheapest financially. As seen on Table 1 and Table 2.

Table 1.

Values to LCC - Life Cycle Cost for cases

Case	LCC
Off grid PVS with batteries (Alternative I)	R$ 722.191.97
DG set (Alternative II)	R$ 199.224.59
Solar-diesel hybrid system (Alternative III)	R$ 387.581.27

Source: Author.

Noteworthy here is that the LCC for alternative I is the most expensive, which is due to the size of the generation system, However, the cost of alternative II is the lowest. Alternative III is more expensive than alternative II, since it merges the two systems, and as such is not as expensive as alternative I, as it is a smaller system that does not need 3 days of storage.

Table 2

Values to LCOE - Levelized cost of electricity for cases

Case	LCOE
Off grid PVS with batteries (Alternative I)	1.64
DG set (Alternative II)	1.27
Solar-diesel hybrid system (Alternative III)	2.37

Source: Author.

Some observations need to be made about the levelized cost of energy. The price of alternative I is only valid when the generation and daily consumption is 70kWh, when it is lower than this, the price will rise. By forecasting that most situations will not occur within this consumption range, it can be assumed that the cost R$/kWh will almost always be more expensive than expected.

By analyzing the cash flow of alternative I, one notes that there are years that the system gives a profit, as its cost is low. However, the moment equipment changes are necessary, an additional cost is incurred, thus making the system financially impracticable.

By analyzing the cash flow of alternative II, one notes that across all years there are greater out goings than incomings of cash, as the investment with diesel is a considerable value and is made every year. Therefore, the system is financially impractical.

By analyzing the cash flow of alternative III, one notes that there are years that the system gives only a low profit, lower than that of alternative I, as there are still costs with diesel. The cost is still less than that of alternative II, but when equipment changes are necessary, cash outgoings increase greatly, in addition to the cost of diesel. This fact makes this system the most impractical of the three.

It is important to highlight that the results obtained in this case study are subject to certain limitations. The analyses were based on specific assumptions regarding fuel prices, solar irradiance, equipment costs, and component lifetimes, which may vary significantly depending on geographical location and market conditions. Moreover, the deterministic approach adopted for system sizing and cost estimation, although methodologically transparent, does not account for uncertainties or dynamic variations that could be better addressed by simulation tools or optimization models. Therefore, the findings should be interpreted as indicative rather than universally prescriptive, serving as a reference framework for similar rural electrification scenarios but not as absolute guidelines.

4.5 Environmental Impacts and Reliability

This section discusses the environmental impacts and long-term reliability of the three energy supply alternatives under analysis, highlighting how different storage technologies and generation sources influence sustainability and system performance.

a) Off-grid Photovoltaic System with NiCd, NiMH, and Li-ion Batteries

From an environmental standpoint, the off-grid photovoltaic system remains advantageous due to its absence of greenhouse gas emissions during operation. The environmental impact, however, varies according to the battery technology employed. Nickel-cadmium (NiCd) batteries present challenges due to the high toxicity of cadmium, which requires strict recycling and disposal processes to avoid soil and water contamination. Nickel-metal hydride (NiMH) batteries are less toxic and more environmentally friendly but still rely on rare earth elements, whose extraction has considerable ecological impacts. Lithium-ion (Li-ion) batteries, increasingly adopted in photovoltaic systems, have a lower environmental footprint during operation and higher recyclability potential, although issues related to lithium and cobalt mining remain a concern. In all cases, the use of advanced batteries significantly reduces fossil fuel dependence compared to diesel generation.

In terms of reliability, battery technology plays a decisive role. NiCd batteries are known for their robustness and tolerance to deep discharge, offering long operational lifespans even under harsh conditions, although they suffer from the "memory effect" if not properly managed. NiMH batteries have improved energy density and reduced memory effect but generally shorter lifespans than NiCd or Li-ion. Li-ion batteries stand out for their high efficiency, longer cycle life, and reduced maintenance needs, making them the most reliable option in long-term applications. Nevertheless, their higher acquisition cost and sensitivity to extreme temperatures must be considered. Overall, the adoption of Li-ion batteries enhances system reliability significantly, while NiCd and NiMH provide more limited but still consistent alternatives depending on the context.

b) Diesel Generator

When compared to battery-based photovoltaic systems, diesel generators remain the most environmentally burdensome option. They emit significant quantities of CO_2, NO_x, and particulate matter during operation, in addition to risks of leakage and contamination associated with fuel logistics. Even when supported by cleaner battery technologies such as NiMH or Li-ion, reliance on diesel as the primary source of energy imposes unavoidable negative impacts on the environment, making it the least sustainable alternative in long-term scenarios.

From a reliability perspective, diesel generators are capable of providing continuous energy as long as fuel is available. However, their dependence on external fuel supply makes them vulnerable to price fluctuations and logistical constraints in remote areas. While battery integration (e.g., NiCd, NiMH, or Li-ion) could theoretically improve operational stability by storing excess diesel-generated electricity, this is rarely applied in practice due to cost and efficiency concerns. Consequently, diesel-only systems tend to be less reliable in the long run compared to photovoltaic or hybrid solutions, as their operation is tied to resource availability and intensive maintenance schedules.

c) Solar-Diesel Hybrid System with NiCd, NiMH, and Li-ion Batteries

The hybrid solar-diesel system combines the reduction of emissions from photovoltaic generation with the dispatchable reliability of diesel generators. The choice of battery technology influences its environmental balance: NiCd batteries may reduce diesel dependence but pose disposal challenges due to cadmium toxicity; NiMH batteries improve sustainability but still involve resource extraction concerns; while Li-ion batteries allow for higher efficiency and lower long-term environmental impact, provided recycling chains are adequately implemented. Overall, hybrid systems with Li-ion storage represent a more environmentally favorable pathway compared to diesel-only configurations.

In terms of reliability, hybrid systems are the most resilient of the three alternatives, as they ensure continuous supply through the complementarity of solar energy, battery storage, and diesel backup. NiCd batteries enhance durability in harsh conditions, NiMH batteries offer moderate performance but lower lifespan, while Li-ion batteries maximize efficiency, depth of discharge, and cycle life, making them the most suitable choice for ensuring long-term reliability. Despite higher initial costs and the need to maintain both diesel and photovoltaic subsystems, hybrid systems supported by Li-ion technology provide the best balance between robustness, flexibility, and operational continuity in remote applications.

5. Conclusion

As a matter of course, due to the high price of equipment and maintenance, all alternatives are impractical compared to the tariff set by distributed electricity local company for rural properties. Through an addendum, this rate has a benefit, which as of the 2023, according to the decree 9.642/2018, will end. Case in point, as of 2023 these proposed alternatives can become more viable to consumers with access to the power grid.

There currently exists a large increase in the quantity of research and studies concerning technology for clean and sustainable energy, which in part encompasses solar energy. However, this study shows that such research needs more support, as all alternatives that involve a renewable energy are economically impractical, due to the high costs and low durability of some equipment.

The diffusion of this technology is necessary to create a culture that disseminates around this source and as such increase the power of influence over those who manage, decide and finance the resources necessary for its implementation. The fact that the price of diesel is so high reaffirms that in a few years non-renewable energy sources will no longer be an option.

The high initial investment of capital makes the dissemination of the use of these systems very difficult, mainly for low-income users in isolated regions, where the use of this alternative would be most adequate. The unit cost of electric energy obtained from PVS calculated by the systematic proposals is still quite high in relation to the cost of electricity supplied, for example, to users of energy utilities.

Noteworthy here is that the financial analysis can easily deviate, as there exist numerous parameters that can consider which of the alternatives is best for the rural consumer. The losses incurred through the absence of energy that are placed upon the rural producer, as well as its incumbent discomfort, need to be considered. Additionally, consideration should be given to the carbon emissions that the DG generates, as well as the waste generated after 25 years of such equipment in use and if this has any type of resale value.

References

Babajide, A., & Brito, M. C. (2021). Solar PV systems to eliminate or reduce the use of diesel generators at no additional cost: A case study of Lagos, Nigeria. *Renewable Energy*, *172*, 209–218. https://doi.org/10.1016/j.renene.2021.02.088

Boylestad, R. L., & Olivari, B. A. (2022). *Introductory circuit analysis* (Pearson, Vol. 14th).

Caterpillar. (n.d.). *Understanding generator set ratings*. Retrieved December 17, 2023, from https://www.cat.com/en_US/by-industry/electric-power/Articles/White-papers/understanding-generator-set-ratings.html

DOE global energy storage database. (n.d.). Retrieved July 23, 2023, from https://www.energystorageexchange.org/projects/

El-Hawary, M. E., & Eckels, A. R. (2019). Motor-generator set. *Access Science*. https://doi.org/10.1036/1097-8542.436110

Faessler, B., Caballero, A., & Aziz, M. (2021). Stationary, Second Use Battery Energy Storage Systems and Their Applications: A Research Review. *Energies 2021, Vol. 14, Page 2335*, *14*(8), 2335. https://doi.org/10.3390/EN14082335

Hesse, H. C., Schimpe, M., Kucevic, D., & Jossen, A. (2017). Lithium-ion battery storage for the grid - A review of stationary battery storage system design tailored for applications in modern power grids. *Energies*, *10*(12). https://doi.org/10.3390/EN10122107

Higgins, R. C., Koski, J. L., & Mitton, T. (2023). *Analysis for financial management* (13th ed.). McGrawHill.

IEA. (2023, July). *Tracking clean energy progress 2023*. Paris. https://www.iea.org/reports/tracking-clean-energy-progress-2023

Iskanderani, A. I. M., Mehedi, I. M., Ramli, M. A. M., & Islam, M. R. (2020). Analyzing the Off-Grid Performance of the Hybrid Photovoltaic/Diesel Energy System for a Peripheral Village. *International Journal of Photoenergy*, *2020*. https://doi.org/10.1155/2020/7673937

Karakoulidis, K., Mavridis, K., Bandekas, D. V., Adoniadis, P., Potolias, C., & Vordos, N. (2011). Techno-economic analysis of a stand-alone hybrid photovoltaic-diesel-battery-fuel cell power system. *Renewable Energy*, *36*(8), 2238–2244. https://doi.org/10.1016/J.RENENE.2010.12.003

Khan, M. J., & Iqbal, M. T. (2005). Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland. *Renewable Energy*, *30*(6), 835–854. https://doi.org/10.1016/J.RENENE.2004.09.001

Koohi-Fayegh, S., & Rosen, M. A. (2020). A review of energy storage types, applications and recent developments. *Journal of Energy Storage*, *27*. https://doi.org/10.1016/j.est.2019.101047

Krishan, O., & Suhag, S. (2019). An updated review of energy storage systems: Classification and applications in distributed generation power systems incorporating renewable energy resources. *International Journal of Energy Research*, *43*(12), 6171–6210. https://doi.org/10.1002/ER.4285

Lahimer, A. A., Alghoul, M. A., Yousif, F., Razykov, T. M., Amin, N., & Sopian, K. (2013). Research and development aspects on decentralized electrification options for rural household. *Renewable and Sustainable Energy Reviews*, *24*, 314–324. https://doi.org/10.1016/J.RSER.2013.03.057

López-González, A., Domenech, B., & Ferrer-Martí, L. (2021). Sustainability Evaluation of Rural Electrification in Cuba: From Fossil Fuels to Modular Photovoltaic Systems: Case Studies from Sancti Spiritus Province. *Energies 2021, Vol. 14, Page 2480*, *14*(9), 2480. https://doi.org/10.3390/EN14092480

Moreira, J. R. S. (2021). *Energias renováveis, geração distribuída e eficiência energética* (Vol. 2). LTC.

Olabode, O.E., Ajewole, T.O., Okakwu, I.K., Alayande, A.S., Akinyele, D.O., (2021). Hybrid power systems for off-grid locations: A cmprehensive review of design technologies, applications and future trends. *Scientific African*, *13*, 2468-2276. https://doi.org/10.1016/j.sciaf.2021.e00884

Paliwal, P., Patidar, N. P., & Nema, R. K. (2014). Planning of grid integrated distributed generators: A review of technology, objectives and techniques. *Renewable and Sustainable Energy Reviews*, *40*, 557–570. https://doi.org/10.1016/J.RSER.2014.07.200

Portal Solar. (2022, January 10). *Tudo sobre a manutenção do painel solar e do sistema fotovoltaico*. https://www.portalsolar.com.br/tudo-sobre-a-manutencao-do-painel-solar

Portal Solar. (2023, April 14). *Painel solar: o que é, como funciona e tipos*. https://www.portalsolar.com.br/painel-solar

Price, A. (2015). The exploitation of renewable sources of energy for power generation. In *Electrochemical Energy Storage for Renewable Sources and Grid Balancing* (pp. 3–12). Elsevier Inc. https://doi.org/10.1016/B978-0-444-62616-5.00001-2

Salisu, S., Mustafa, M. W., Olatomiwa, L., & Mohammed, O. O. (2019). Assessment of technical and economic feasibility for a hybrid PV-wind-diesel-battery energy system in a remote community of north central Nigeria. *Alexandria Engineering Journal*, *58*(4), 1103–1118. https://doi.org/10.1016/J.AEJ.2019.09.013

Sánchez, A. S., Torres, E. A., & Kalid, R. A. (2015). Renewable energy generation for the rural electrification of isolated communities in the Amazon Region. *Renewable and Sustainable Energy Reviews*, *49*, 278–290.

https://doi.org/10.1016/J.RSER.2015.04.075

Ufa, R. A., Rudnik, V. E., Malkova, Y. Y., Bay, Y. D., & Kosmynina, N. M. (2022). Impact of renewable generation unit on stability of power systems. *International Journal of Hydrogen Energy*, *47*(46), 19947–19954. https://doi.org/10.1016/j.ijhydene.2022.04.141

Villalva, M. G., & Gazoli, J. R. (2012). *Energia solar fotovoltaica - conceitos e aplicações* (1a ed., Vol. 1). Editora Érica.

Villalva, M. G., & Gazoli, J. R. (2021, February 22). *Armazenamento de energia: tecnologias de baterias elétricas*. https://canalsolar.com.br/armazenamento-de-energia-tecnologias-de-baterias-eletricas/

Walker, A., Lockhart, E., Desai, J., Ardani, K., Klise, G., Lavrova, O., Tansy, T., Deot, J., Fox, B., & Pochiraju, A. (2020). *Model of operation-and-maintenance costs for photovoltaic systems*. https://www.nrel.gov/docs/fy20osti/74840.pdf.

Yuan, G. (2015). Rural Electrification Goes Local: Recent innovations in renewable generation, energy efficiency, and grid modernization. *IEEE Electrification Magazine*, *3*(1), 16–24. https://doi.org/10.1109/MELE.2014.2380193

Zhang, C., Wei, Y.-L., Cao, P.-F., & Lin, M.-C. (2018). Energy storage system: Current studies on batteries and power condition system. *Renewable and Sustainable Energy Reviews*, *82*, 3091–3106. https://doi.org/10.1016/j.rser.2017.10.030