Analysis of the efficiency of hybrid photovoltaic systems implemented by the IPSE in the non-interconnected zones of the department of Guainía

Análisis de la eficiencia de los sistemas fotovoltaicos híbridos implementados por el IPSE en las zonas no interconectadas del departamento de Guainía

Análise da eficiência dos sistemas fotovoltaicos híbridos implementados pelo IPSE nas áreas não interconectadas do departamento de Guainía

Jairo Alberto Valencia Llanos[1]
Danna Liceth Reyes Viviescas[2]

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1 Institute for the Planning and Promotion of Energy Solutions (IPSE).
Email: jairovalencia@ipse.gov.co
ORCID: https://orcid.org/0000-0002-0400-2615
CvLAC: https://scienti.minciencias.gov.co/cvlac/visualizador/generarCurriculoCv.do?-cod_rh=0001495029

2 Master's Degree in Clean Technologies Santo Tomás University
Email: dannareyes@usantotomas.edu.co
ORCID: https://orcid.org/0000-0001-9392-4170
CvLAC: https://scienti.minciencias.gov.co/cvlac/visualizador/generarCurriculoCv.do?-cod_rh=0001868673

Abstract

Introduction: This article is the product of the research called "Analysis of the efficiency in hybrid photovoltaic systems implemented by the IPSE in the Non-Interconnected Zones of the department of Guainía", a project developed by the Institute for Planning and Promotion of Energy Solutions (IPSE for its abbreviation in Spanish) in the period 2020 to 2021.

Problem: The limited availability of energy service delivery hours and the use of a single CO_2 energy source represented a lack of local energy security, lack of diversification of energy sources, high emissions and energy inefficiency.

Objective: Evaluate the energy conversion efficiency of Hybrid Photovoltaic Solar Systems - implemented by IPSE in the Non-Interconnected Zones of the department of Guainía.

Methodology: The methodologies used for the evaluation of energy efficiency were: 1) Energy conversion method and form factor for solar panels. 2) Graphical analysis method with efficiency curves for grid-tied and bidirectional inverters. 3) Comparative analysis method between theoretical efficiencies and Specific Fuel Consumption (SFC) for diesel generator sets; and finally, the methodology for calculating the carbon footprint for these last components.

Results: For solar panels, the theoretical and actual efficiency were 16.5% and 16.49% with the energy conversion method, and 100% and 78.39% with the form factor method. For inverters linked to the network it was 98.2% and bidirectional 96%; for the generator sets, the efficiency was determined from their fuel consumption with a difference of 2.55 gal/h compared to the current standard and Greenhouse Gas emissions on average were 112,465 $kg_{eq} CO_2/h$ in standby and 98,417 $kg_{eq} CO_2/h$ in prime operating mode.

Conclusion: This research has shown that energy efficiency is a key factor for the good performance of energy systems.

Originality: This research was conducted by using technical data provided by manufacturers and the own work ' own analysis.

Limitations: The evaluation of the efficiency of the Hybrid Photovoltaic Solar System was achieved with the adaptation of technical data sheets and theoretical information, generating a large margin of error in the results.

Keywords: Energy efficiency, emissions of CO_2, Hybrid Solar Photovoltaic Systems and Non-Interconnected Zones.

Resumen

Introducción: El presente artículo es el producto de la investigación denominada "Análisis de la eficiencia en los sistemas fotovoltaicos híbridos implementados por el IPSE en las Zonas No Interconectadas (ZNI) del departamento del Guainía", proyectos desarrollados por el Instituto de Planificación y Promoción de Soluciones Energética (IPSE) en el periodo 2020 a 2021.

Problema: La limitación en la disponibilidad de las horas de prestación del servicio de energía y el uso de una sola fuente de generación representaban falta de seguridad energética local, ausencia de diversificación de fuentes energéticas, emisiones de CO_2 e ineficiencia energética.

Objetivo: Evaluar la eficiencia en la conversión de energía de los Sistemas Solares Fotovoltaicos Híbridos - implementados por IPSE en las ZNI del departamento del Guainía.

Metodología: Las metodologías utilizadas para la evaluación de la eficiencia energética fueron: 1) Método de conversión de energía y factor de forma para los paneles solares. 2) Método de análisis gráfico con curvas de eficiencia para los inversores enlazados a la red y bidireccionales. 3) Método de análisis comparativo entre las eficiencias teóricas y los Consumos Específicos de Combustibles para los grupos electrógeno diésel; y por último la metodología del cálculo de la huella de carbono para estos últimos componentes.

Resultados: Para los paneles solares, la eficiencia teórica y real fueron de 16.5% y 16.49% con el método de conversión de la energía, del 100% y 78.39% con el método del factor de forma. Para los inversores enlazado a la red fue del 98.2% y bidireccionales del 96%; para los grupos electrógeno la eficiencia se determinó a partir de su consumo de combustible con una diferencia del 2,55 gal/h en comparación con la norma vigente y emisiones de gases de efecto invernadero en promedio fueron de 112.465 $kg_{eq}\,CO_2/h$ en stand by y 98.417 $kg_{eq}\,CO_2/h$ en modo operativo prime.

Conclusión: Esta investigación evidenció que la eficiencia energética es un factor importante para el buen rendimiento de los sistemas energéticos.

Originalidad: Esta investigación se desarrolló, utilizando datos técnicos proporcionados por fabricantes y análisis propios de los autores.

Limitaciones: La evaluación de la eficiencia de los Sistemas Solares Fotovoltaicos Híbridos se logró con adaptación de fichas técnicas e información teórica generando margen de error en los resultados.

Palabras clave: Eficiencia energética, emisiones de CO_2, Sistemas Solares Fotovoltaicos Híbridos y Zonas No Interconectadas.

Resumo

Introdução: Este artigo é o produto da pesquisa denominada "Análise da eficiência em sistemas fotovoltaicos híbridos implementados pelo IPSE nas Zonas Não Interconectadas (ZNI) do departamento de Guainía", projetos desenvolvidos pelo Instituto de Planejamento e Promoção de Soluções Energéticas (IPSE) no período de 2020 a 2021.

Problema: A limitação na disponibilidade das horas de prestação do serviço de energia e o uso de uma única fonte de geração representaram a falta de segurança energética local, ausência de diversificação de fontes de energia, emissões de CO_2 e ineficiência energética.

Objetivo: Avaliar a eficiência na conversão de energia de Sistemas Solares Fotovoltaicos Híbridos - implementados pelo IPSE no ZNI do departamento de Guainía.

Metodologia: As metodologias utilizadas para a avaliação da eficiência energética foram: 1) Método de conversão de energia e fator de forma para painéis solares. 2) Método de análise gráfica com curvas de eficiência para inversores ligados à grade e bidirecionais. 3) Método de análise comparativa entre eficiência teórica e Consumo Específico de Combustível para conjuntos geradores a diesel; e finalmente, a metodologia de cálculo da pegada de carbono para esses últimos componentes.

Resultados: Para painéis solares, a eficiência teórica e real foi de 16,5% e 16,49% com o método de conversão de energia, 100% e 78,39% com o método do fator de forma. Para investidores vinculados à rede foi de 98,2% e 96%; para os conjuntos geradores, a eficiência foi determinada a partir de seu consumo de combustível com uma diferença de 2,55 gal/h em relação ao padrão atual e as emissões de gases de efeito estufa em média foram de 112.465 $kg_{eq}\,CO_2/h$ em stand by e 98.417 $kg_{eq}\,CO_2/h$ no modo de operação prime.

Conclusão: Esta pesquisa mostrou que a eficiência energética é um fator importante para o bom desempenho dos sistemas de energia.

Originalidade: Esta pesquisa foi desenvolvida, utilizando dados técnicos fornecidos pelos fabricantes e pela própria análise dos autores.

Limitações: A avaliação da eficiência do Sistemas Solares Fotovoltaicos Híbridos foi alcançada com adaptação de fichas técnicas de dados e informações teóricas gerando margem de erro nos resultados.

Palavras-chave: Eficiência energética, emissões de CO_2, Sistemas Solares Fotovoltaicos Híbridos e Zonas Não Interconectadas.

1. Introduction

The participation of renewable energy sources in the formation of a hybrid system, in T. Undurraga [1] represents an increasingly attractive option to reduce dependence on fossil fuels, due to the geographical projection of the systems, offering the potential for an almost uninterrupted power service. Accordingly, the Institute for the Planning and Promotion of Energy Solutions for Non-Interconnected Areas (IPSE), making use of the energy potential in these areas, implemented solutions of this type in four locations in the department of Guainía: Remanso, Caranacoa, Chorro Bocón and Laguna Colorada. These solutions integrate solar resources as a Non-Conventional Source of Renewable Energy (NCSRE) and diesel resources as a Conventional Source of Energy (CSE) in their operational functionalities. In this document, these solutions are identified as Hybrid Photovoltaic Solar Systems (HPSS).

A hybrid system is usually configured with a conventional diesel generator and a renewable energy source (photovoltaic, wind or combinatorial) [2]; furthermore, most photovoltaic diesel hybrid systems described in the open literature include battery storage [3]–[7]. The functionality and purpose of an HPSS is centered on increasing hours of service, energy security, and the reduction of fossil fuel consumption and CO_2 emissions.

The Carbon Footprint is a tool used to determine and calculate the total amount of Greenhouse Gas (GHG) emissions, where the principles defined by the Energy Mining Planning Unit (UPME for its abbreviation in Spanish) are: carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and hexafluoride of sulphur (SF_6) [8]; in this regard, the corresponding analysis was carried out regarding the production of energy from the implemented HPSS, in relation to the energy evaluation of the life cycle for the generator sets; this was performed for the generation phase from its energy consumption, in one hour of operation, supported by the technical data sheets provided by the manufacturer [9]–[12].

As a summary, the evaluation of the efficiency of the HPSS was contextualized in the following components: Solar panels, Inverters and Diesel generator sets, describing their characteristics according to technical data sheets. Regarding the methodological stages, the energy conversion and form factor methods for solar panels were applied, initially identifying their technical characteristics. Next, the results of the theoretical efficiency and real efficiency were compared using average solar irradiance data from the city of Inírida, referencing the current-voltage product curve. Regarding the inverters, the efficiency results were analyzed from graphs provided by their manufacturer. Finally, the efficiency of the diesel generator set was analyzed through the specific fuel consumption and the calculation of the carbon footprint considering the emissions generated for each of the locations.

2. Literature Review

In order to guarantee the sustainability of a system and the balance of its resources, the energy sector must be affordable, reliable and modern [13], thus promoting the economic and social development of communities [14], guaranteeing compliance with the Goal of Sustainable Development (SDG) on clean and affordable energy [15].

The implementation of energy systems that incorporate a single generation technology, such as photovoltaic solar energy or wind energy, usually do not fully satisfy the demand, as a consequence of seasonal patterns. For this purpose, hybridization and storage systems are intended to avoid generation intermittency as much as possible, thus increasing energy security, efficiency and performance times [16].

Hybrid configurations have been modeled by various own work ; as stated by X. Qi et al [17], 36.2% of generation is produced with photovoltaic energy and 63.8% with diesel generation, storing energy in a battery system. Additionally, they showed that operating costs are low because fuel consumption decreases by 4.02%, requiring minimal maintenance and reducing CO_2 emissions by 8.55% [18].

On the other hand, a study carried out by H. Rezzouk et al [19] in the north of Algeria, determined through several scenarios that the best result of photovoltaic solar energy penetration in a hybrid system with diesel generator and electric energy storage in batteries was 25%.

Regarding the comprehensive efficiency of hybrid energy systems, F. F. Yanine [20] mentioned that sustainable hybrid energy systems are those that can overcome disturbances and chaos, withstanding adverse and changing conditions despite how complex the environment in which they are immersed may be in a context of energy efficiency.

In Colombia, Non-Interconnected Zones (ZNI for its abbreviation in Spanish) occupy approximately 53% of the national territory and have a high potential for renewable energies, representing a niche opportunity for the implementation of technologies with Non-Conventional Energy Sources (NCES)[21]. The department of Guainía is currently part of the ZNI and has 5 diesel plants with a total installed capacity of 10,090 kW, 2,975.97 kWh of Renewable Energy and 12,945.65 kWh of hybrid systems, benefiting around 7,138 users; by 2021, the IPSE will bring the energy service to 226 homes in seven indigenous communities located nearby along the Inírida River [22].

2.1. Definitions

After reading and assessing the technological literature and the documentation associated with academic articles, definitions were identified regarding the components that make up the HPSS.

2.1.1. Solar panels

A solar panel is a flat plate, composed of materials such as: silicon, cadmium telluride, CIGS (indium, gallium and selenium or sulfur), semiconductor polymers and others [23], which in principle absorbs energy from photons and transforms solar energy by means of the photovoltaic effect into electrical energy [24], [25]; this conversion is carried out through solar cells where a constant electromagnetic field is created [26].

2.1.2. Solar inverters

An inverter is a piece of equipment that takes the direct current (DC) output of the photovoltaic solar panels and then converts it into alternating current (AC), delivering a stable output at the frequency and voltage of the network [27], [28].

Inverter-chargers or bidirectional inverters are defined as those that transform current in both directions: direct current into alternating current from the batteries, as from alternating current to direct current to the batteries. Additionally, they have an AC input to recharge the batteries through a network or a generator [29].

2.1.3. Stationary batteries

Stationary tubular plate batteries of type Ortsfeste Panzerplatten Verschlossen OPzV, according to Deutsche Dgs et al [30], are defined as those that have a standard gel electrolyte, which circulates through permeable tubes in energy systems, ensuring that there is a high resistance to the cycle. They are designed for non-moving applications, with medium-high consumption, continuous use, and moderate current peaks [2], [31]; therefore, they can reduce stability problems induced by variables in the generation of photovoltaic energy [32].

2.1.4. Diesel generator set

A generator set has an internal combustion engine which has a constant axis rotation frequency, regardless of the load. It converts mechanical energy into electrical energy through an alternator; It has also been considered that its efficiency improves when working in parallel with other generators and for extended periods [33], [34].

3. Materials and Methods

3.1. Research providers and regulatory context

The areas under study have had an electricity service between 4 and 8 hours a day supplied by diesel generators. Since the implementation of the new HPSS, it was possible to expand the provision of the energy service of the 624 users up to 24 hours. Figure 1 shows the geographical location of the HPSS, users benefited, type of locality as established by Resolution 182138 2007 of the Ministry of Mines and Energy (MinEnergía for its abbreviation in Spanish). The total installed capacity of the HPSS is 935.6 kW, of which 559 kWe are diesel capacity and 376,6 kWp are photovoltaic solar capacity [35].

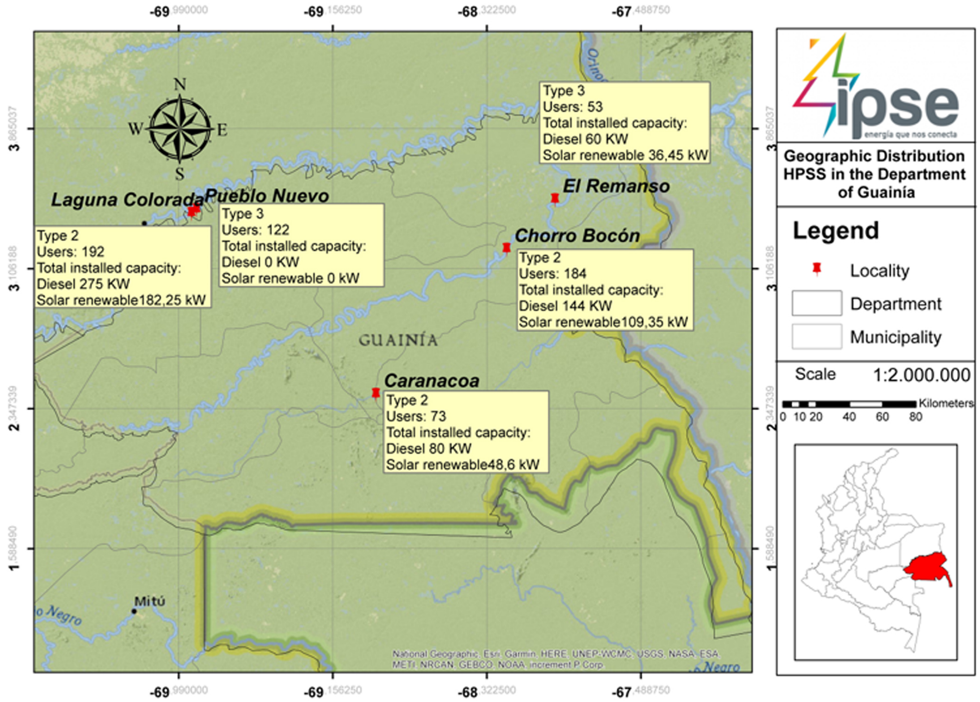

Figure 1. Geographical distribution in the Department of Guainía
Source: own work using software ArcGIS

3.2. Hybrid Photovoltaic Solar System Components

Table 1 shows the capabilities by component of HPSS.

Table 1. HPSS Components by Locality

Locality	Remanso	Chorro Bocón	Laguna colorada and Pueblo Nuevo	Caranacoa
Description	**Installed capacity**			
Polycrystalline photovoltaic solar subsystem (Wp)	36450	109350	182250	48600
OPzV Type Energy Storage Subsystem (Ah.)	57600	172800	12000	86400
Inverter Subsystem injection to network (kW)	30	90	150	42
Bidirectional Inverter Subsystem (kW)	30	90	150	45
Diesel generator set (kW)	60	144	275.2	80

Source: IPSE

3.2.1. Evaluation of Solar panel efficiency

Initially, we proceeded to identify the main characteristics of the solar panels; relating these variables in Table 2. For the calculation of energy efficiency, the following methods were used: Energy conversion and Form factor [36].

Table 2. Characteristics of polycrystalline solar panels

Description	
Number of Cells	60
Power (Wp)	270
Efficiency (%)	16.50
Operating temperature (°C)	-40 to 85
Voltage at maximum point power (V)	31.20
Maximum power current (A)	8.66
Open circuit voltage (V)	35.5
Short circuit current (A)	7.44

Source: Taken from [37].

- Energy Conversion Method

For the current-voltage product structure of Table 2, the Maximum Power Point (Mpp) in Equation 1 is obtained by multiplying the values of the maximum voltage and maximum current in appropriate radiation conditions [36], [38]–[40]:

$$Mpp = Vmp \, x \, Imp \quad (1)$$

Where:
Mpp: Maximum power point
Vmp: Maximum power voltage
Imp: Maximum power current

Conversion efficiency is related to the ratio between the useful energy delivered by the solar panel and the light energy received directly from the sun when the panel is connected to an electrical circuit [36], [41]. In this case, the efficiency was determined via Equation 2 [42].

$$\eta = \frac{Mpp}{E \, x \, Ac} \quad (2)$$

Where:
E: Radiation level on the surface of the panel (W/m^2).
Ac: Surface of the photovoltaic panel (m^2)
η: Theoretical or real efficiency, according to technical sheet values.

- Efficiency method according to Form Factor

The efficiency according to Form Factor was obtained through Equation 3; dividing the *Mpp* obtained by Equation 1, between the multiplication of the open circuit voltage and the short circuit current described in Table 2.

$$\eta = \frac{Mpp}{Voc \, x \, Isc} \quad (3)$$

Where:
Voc: Open circuit voltage
Isc: Short circuit current
η: Theoretical or real efficiency

3.3. Grid Tied Inverter

For this device, the efficiency analysis was carried out from the revision of its performance curves according to the technical sheet from the manufacturer [43]; its characteristics are shown in Table 3.

Table 3. Characteristics of the inverter

Description	
Sunny Tripower (TL)	5000-12000
Network-Linked SMA (kW)	10
MPPT Control (VDC/VAC)	300 – 480/ 208
Frequency (Hz)	60
Voltage at maximum point power (V)	31.20

Source: Taken from [43]

3.4. Bidirectional Inverter

Like the analysis carried out for the inverter linked to the network, the efficiency was reviewed based on its yield curve according to a manufacturer technical sheet [44], its most relevant characteristics are shown in the Table 4.

Table 4. Characteristics of the bidirectional inverter

Description	
Rated power (W)	5000
Wave input type	Sinusoidal
Nominal input voltage (VAC)	120
Frequency (Hz)	60
PV Range	120 VDC para 48 V
Maximun PV open circuit voltage	48 V para 120 VAC
Charger mode	MPPT
Nominal battery voltage	48 V

Source: Taken from [44]

3.5. Batteries

Regarding the storage subsystem, Table 5 identifies the main characteristics of this component; the respective calculation of efficiency employed the relationship between the Depth of Discharge (DoD) and the number of charge/discharge cycles.

Table 5. Battery characteristics

Description	
Voltage per unit (V)	2
Capacity (Ah)	1200
Rated capacity (Ah)	1200

Source: Taken from [45]

3.6. Efficiency calculation for diesel generator

The theoretical efficiency was calculated using Equation 4 [46]:

$$\eta_T = \frac{P_{out}}{P_{in}} = \frac{P * \cos\theta}{P} \tag{4}$$

Where:
P_{out}: Output power
P_{in}: Input power
η_T: Theoretical efficiency, according to technical sheet values

Next, the Specific Fuel Consumption Efficiency (SFC) at different output powers was calculated using Equation 5 [47]:

$$SFC = \frac{FCi}{Ei} \tag{5}$$

Where:
FC: fuel consumption
E: Power generated

3.7. Carbon footprint calculation

The carbon footprint was calculated for each of the internal combustion generators, specifically, in their hourly operation phase.

The *Emissions Calculator*, developed by the Mining-Energy Planning Unit (UPME for its abbreviation in Spanish) [48], and the tool *Memory of calculation of emissions of Compounds and Greenhouse Gasses* [49] were used to investigate the emissions from liquid diesel-biodiesel mixture using the following parameters:

Fuel consumption: This was obtained from technical data sheets for the localities, except Remanso, as the load in standby was calculated theoretically with the *Atlas Copco Fuel Consumption Calculator* tool [50].

Excess air: This was calculated with the air consumption, obtaining the parameter of the technical sheet, or by means of the compression ratio (air: fuel), and the stoichiometric amount of air was calculated by the ratio (stoichiometric air: fuel) as shown in Equation 6.

$$\%Excess\ of\ air\ = \frac{Air\ consumption}{Stoichiometric\ \ amount\ in\ air} * 100 - 100 \qquad (6)$$

Where:

Stoichiometric factor is 14.5:1[51]

Percentage of biodiesel: According to Resolution 40666 of August 20, 2019 *"By which a maximum biofuel content is established for use in diesel engines of 12% in the mixture with fossil fuel in some areas of the country and other provisions are dictated"* in Colombia; for this reason 12% is taken as a calculation basis [52].

Figure 2 shows a schematic representation of an energy generator, where diesel B12 is supplied as fuel for the generation of electric energy, and as a result of this combustion, various quantified emissions are generated in ($kg_{eq}\ CO_2$).

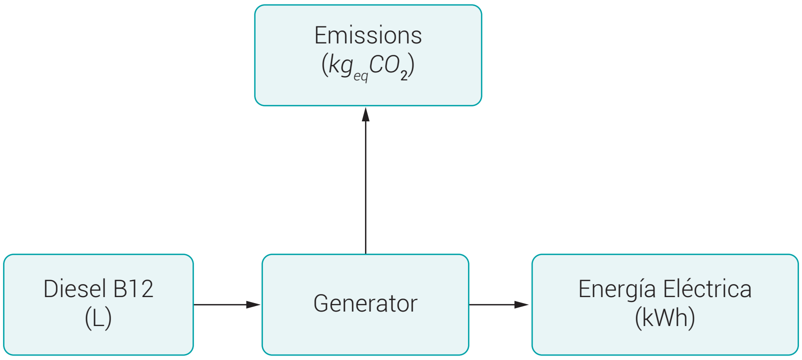

Figure 2. Schematic representation of an internal combustion system.
Source: Own work

4. Results

4.1. Hybrid Photovoltaic Solar System Components

4.1.1. Evaluation of efficiency Solar panel

Then show the calculation with the following methods:

- Energy Conversion Method

The results for the calculation of Mpp is shown in Equation 7.

$$Mpp = 31.20V * 8.66\ A = 270.192\ W \tag{7}$$

Substituting, the result of the theoretical efficiency is shown in Equation 8.

$$\eta_T = \frac{270.192\ W}{1000\ \left(\frac{\mathrm{W}}{\mathrm{m}^2}\right) * (1.65m * 0.992\ m)} = 16.50\% \tag{8}$$

Where:

η_T: Theoretical efficiency, according to data sheet values.

Now, to calculate the real efficiency, the Mpp was determined from Figure 3 with a monthly average solar irradiance of 198 W/m^2 (Data for the municipality of Inírida in the geographic coordinates (3.8653 N, 67.9239 W), determined with the help of the PVsyst software); its result is indicated in Equation 9. Then, this value was substituted into Equation 10 obtaining the real efficiency [36], [39]:

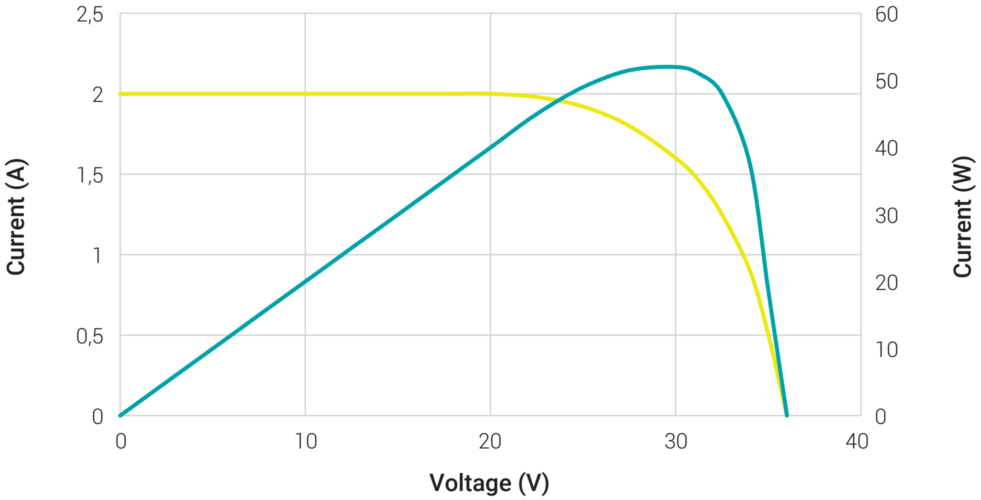

Figure 3. Curve I-V for irradiation values 200 W/m[2].
Source: Adapted from [37].

$$Mpp = 32.2\ V * 1.66\ A = 53.47\ W \qquad (9)$$

$$\eta_R = \frac{53.47\ W}{198\left(\frac{\mathrm{W}}{\mathrm{m}^2}\right) * (1.65m * 0.992\ m)} = 16.49\% \qquad (10)$$

Where:

η_R: Real efficiency, according to real irradiation values in the department of Guainía

- Efficiency method according to Form Factor

The result of the theoretical efficiency is presented in Equation 11 [53]. Now, taking as a reference the current-voltage product curve for different irradiation values of Figure 3, the actual efficiency was calculated; the result is indicated in Equation 12 with data at the installation site[54]:

$$\eta_T = \frac{270.192\ W}{35.5\ V * 7.44\ A} = 1.023 \approx 100\% \qquad (11)$$

Where:

η_T: Theoretical efficiency, according to technical sheet values

$$\eta_R = \frac{53.47\ W}{35.9\ V * 1.9\ A} = 0.78 \approx 78.39\% \tag{12}$$

Where:

η_R: Real efficiency, according to real irradiation values in the department of Guainía.

4.2. Grid Tied Inverter

Figure 4 shows that the inverter can achieve a maximum efficiency of up to 98.2% over an output power range of 20% to 100% of its capacity at a voltage level of 440V. Other efficiency values of 97% and 97.5% are observed for voltage values of 580V and 800V, respectively.

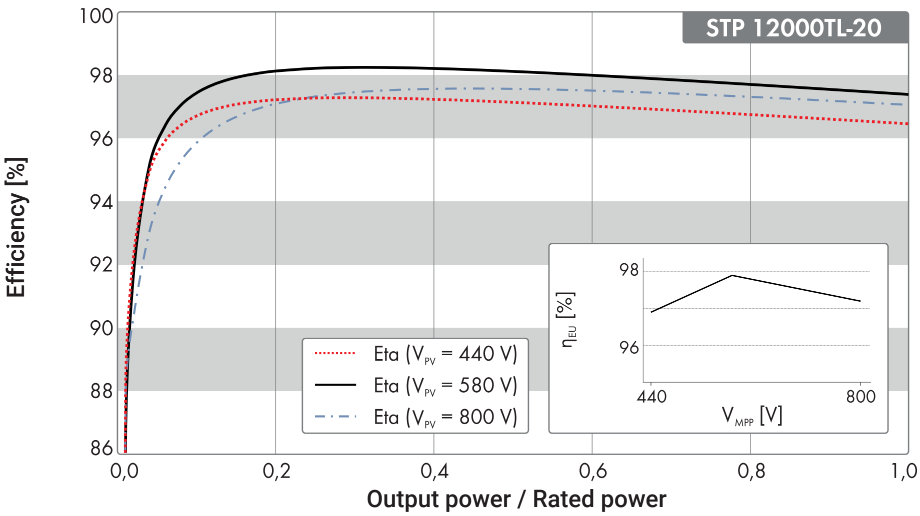

Figure 4. Efficiency curve for a Sunny Tripower 5000TL – 12000TL inverter.
Source: Taken from [43]

4.3. Bidirectional Inverter

In Figure 5, it is observed that the bidirectional inverter achieves an efficiency between 92% and 96% for a wide range of output power between 20% and 100% of its capacity.

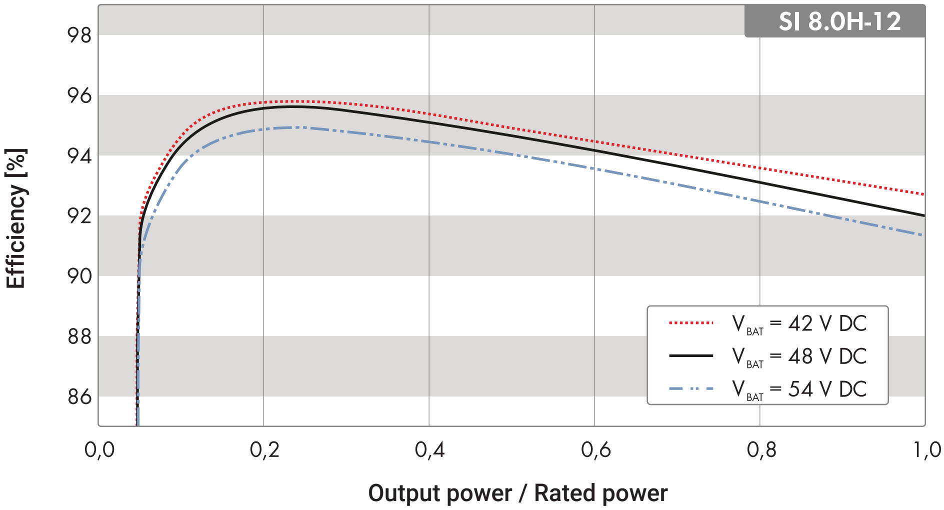

Figure 5. Efficiency curve.
Source: Taken from [44]

4.4. Batteries

Table 6 shows the relationship between the DoD and the number of charge/discharge cycles, indicating that the higher the DoD, the shorter the battery life. This takes into account an operating regime between 60% and 100% of its capacity.

Table 6. Number of life cycles

Capacity (%)	DoD (%)	Number of cycles
60 -100	100	0-1500
	80	900 -2200
	50	1800-3500
	40	2600-4500
	30	3700-5500
	20	4900-6200

Source: Taken from.[45]

4.5. Efficiency calculation for diesel generator

The characteristics and results of the theoretical efficiency are indicated in Table 7 [46]:

Table 7. Efficiency of diesel generator sets by location

Locality	Characteristics	Source	Efficiency a	
Remanso	75kVA	[55]	$\eta = \frac{75\ kVA * 0.8}{75\ kVA} = 80\%$	(13)
Chorro Bocón	180 kVA	[56]	$\eta = \frac{180\ kVA * 0.8}{180\ kVA} = 80\%$	(14)
Pueblo Nuevo and Laguna Colorada	344VA	[57]	$\eta = \frac{344\ kVA * 0.8}{344\ kVA} = 80\%$	(15)
Caranacoa	100kVA	[58]	$\eta = \frac{100\ kVA * 0.8}{100\ kVA} = 80\%$	(16)

Source: Own work.

In Tables 8, 9, 10 and 11 and in Figures 6, 7, 8 and 9 it was observed that SFC depended on the load; technical data sheets of Perkins generation units of the same characteristics were referenced.

Table 8. Specific consumption as a function of load for Remanso

Rated Power (*kW*)	Load (%)	Output power (*kW*)	SFC (*gal/kWh*)
60	100	60	0.0705
	88	52.5	0.0716
	75	45	0.0724
	63	37.5	0.0745
	50	30	0.0762
	25	15	0.0787

Source: Own work using [59]

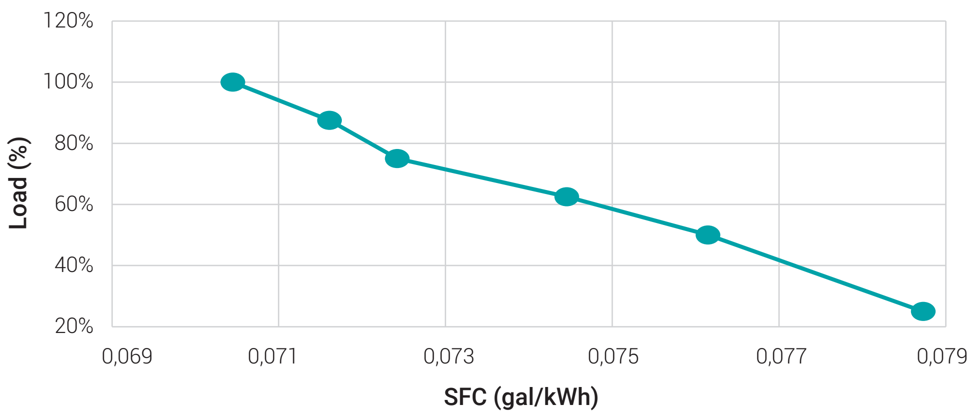

Figure 6. Fuel efficiency diesel generator set 60 kW.
Source: Own work .

Table 9. Specific consumption as a function of load for Caranacoa

Rated Power (*kW*)	Load (%)	Output power (*kW*)	SFC (gal/*kWh*)
80	100	80	0.0693
	88	70	0.0703
	75	60	0.0712
	63	50	0.0725
	50	40	0.0737
	25	20	0.0758

Source: Own work using [59]

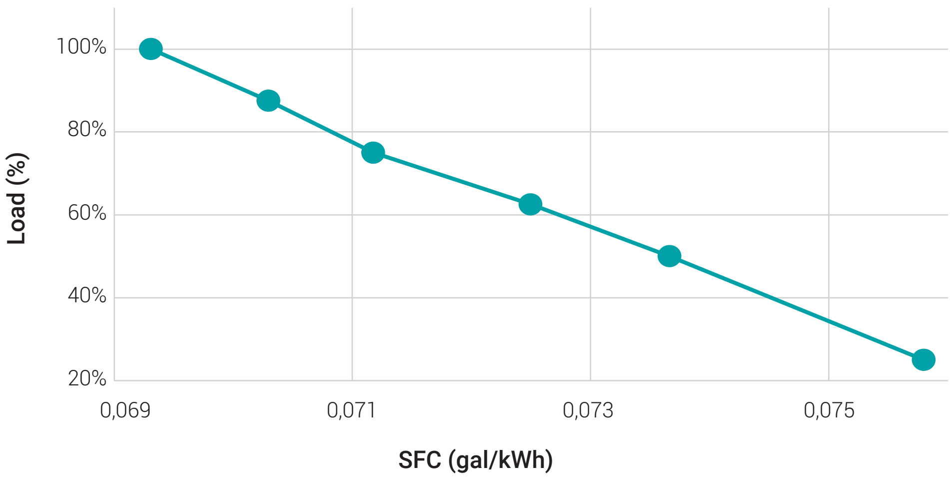

Figure 7. Fuel efficiency diesel generator set 80 kW.
Source: Own work .

Table 10. Specific consumption as a function of load for Chorro Bocón

Rated Power (*kW)*	Load (%)	Output power (*kW*)	SFC (*gal/kWh*)
144	100	144	0.0697
	88	126	0.0702
	75	108	0.0706
	63	90	0.0716
	50	72	0.0724
	25	36	0.0736

Source: Own work using [60]

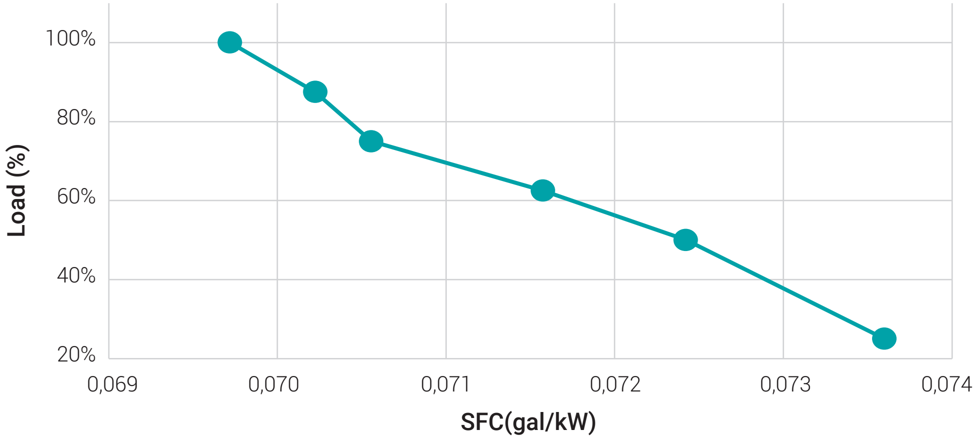

Figure 8. Fuel efficiency Generator set diesel 144 kW.
Source: Own work

Table 11. Specific consumption as a function of load for Pueblo Nuevo and Laguna Colorada

Rated Power (*kW*)	Load (%)	Output power (*KW*)	SFC (*gal/kWh*)
275,2	100	275,2	0.0691
	88	240,8	0.0762
	75	206,4	0.0832
	63	172	0.0902
	50	137,6	0.0973

Source: Own work using [61]

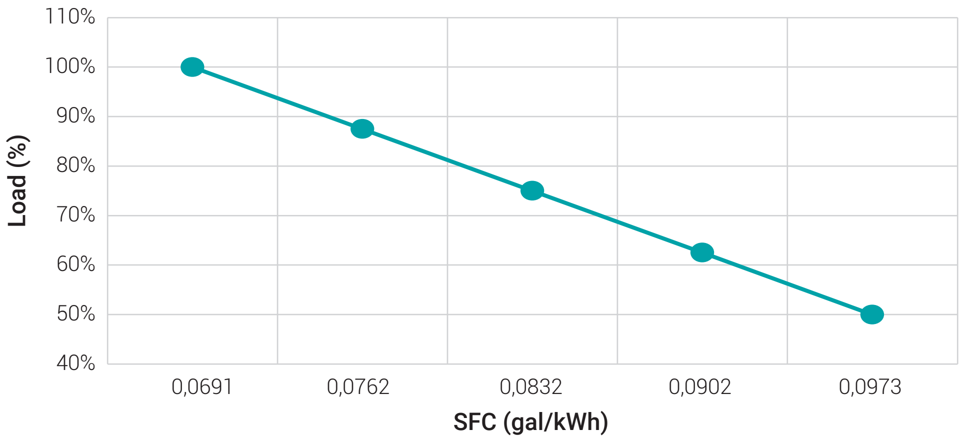

Figure 9. Fuel Efficiency Diesel Generator Set 275.2 kW.
Source: Own work

4.6. Carbon footprint calculation

Therefore, Table 12 shows the calculation of the carbon footprint for each of the locations.

Table 12. Calculation of emissions (kg_{eq} CO_2/h) by locations

	Remanso		**Chorro Bocón**		**Pueblo nuevo y Laguna colorada**		**Caranacoa**	
Source	**[55]**		**[56]**		**[57]**		**[58]**	
	Stand by	**Prime**	**Stand by**	**Prime**	**Stand by**	**Prime**	**Stand by**	**Prime**
Diesel Consumption (L/h)	20	16	45	38	80	72	27	24
Air consumption (kg/h)	591.675	591.68	650.25	549.18	952	856.8	378.675	427.68
Stoichiometric amount of air (kg/h)	246.50	197.20	554.625	468.35	986	887.4	332.78	295.80
% Total air	240.03	300.04	117,24	117.24	96.553	96.551	113.79	144.58
% Excess air	140.03	200.04	17.24	17.24	3.448	-3.448	13.79	44.58
Emissions (kg_{eq} CO_2/h)	51.61	41.29	116.12	98	212.46	192.45	69.67	61.93

Source: Own work

5. Analysis Of Results

The efficiency results obtained for each complement of the Hybrid Photovoltaic Solar Systems implemented have indicated the following:

Under the energy conversion method, for polycrystalline solar panels of 270 Wp, a theoretical efficiency of 16.5% was obtained under standard conditions corresponding to a real efficiency of 16.49% when taking into account the radiation in situ; both results being similar compared to the study by Laseinde O et al [62] where they determined an efficiency of 16.56% under ideal conditions. With the form factor method, a theoretical efficiency of 100% and a real efficiency of 78. 39% were obtained; the difference of 21.6% under this method is due to the fact that for the real case, the average solar radiation of the area was taken into account.

The grid-linked inverter showed a maximum efficiency of 98.2% for a power of 10kW and a voltage level of 440 VDC, while the bidirectional inverter showed an efficiency between 92% and 96%, compared with the efficiency ranges cited in the literature between 96% and 98% [63], [64], which has allowed to infer that the devices respond efficiently to important variables in their usability.

As for the performance of the battery with a capacity of 1200 Ah, the DoD is inversely proportional to the useful life; that is to say, that for a DoD of 50%, the battery has 1,800 to 3,500 life cycles. When compared to the literature, it is evident that for this type of battery with the same DoD, its useful life is around 3,500 cycles and up to 5,000 at a DoD of 45% [30].

Finally, the diesel generator sets have shown a theoretical conversion efficiency of 80% in all the ZNI mentioned locations. When analyzing the results of Tables 6, 7, 8 and 9, it has been graphically observed that the generator sets are more efficient in their fuel consumption at powers closer to the nominal one, that is, more than 70% of their capacities.

In addition, to analyze the efficiency by means of the load according to the specific consumptions for the localities, it could be inferred that when comparing with Resolution 091 of 2007 [65], the fuel consumption in these units, for a load of 100%, were lower than those established by the aforementioned standard, as can be identified in Table 13.

Table 13. Comparison of consumptions obtained vs those given by the standard

Locality	Fuel consumption according to resolution (*gal/h*)	Fuel consumption for implemented plants (*gal/h*)
Remanso	5.844	4.23
Caranacoa	7.792	5.544
Chorro Bocón	12.672	10.037
Pueblo Nuevo y Laguna Colorada	22,704	19,016

Source: Own work

As for the environmental factor, this was measured by the carbon footprint, and the emissions generated for each of the localities were considered according to Figure 10, where the emissions in standby load are higher compared to the prime load. Therefore, it was inferred that the localities of Laguna Colorada and Chorro Bocón have more significant emissions than the other localities, since they have a greater power, fuel consumption, and additionally, an excess of insignificant air. For the towns of Remanso and Caranacoa, the opposite is true, due to lower power capacities, affecting lower fuel consumption, and significantly greater excess air in combustion. Additionally, according to X. Qi et al [17], hybrid generation systems such as those studied, compared to power generation with only diesel generators, reduce CO_2 emissions by 235945 kg/year, that is, 26.9 kg/h, guaranteeing a more sustainable supply.

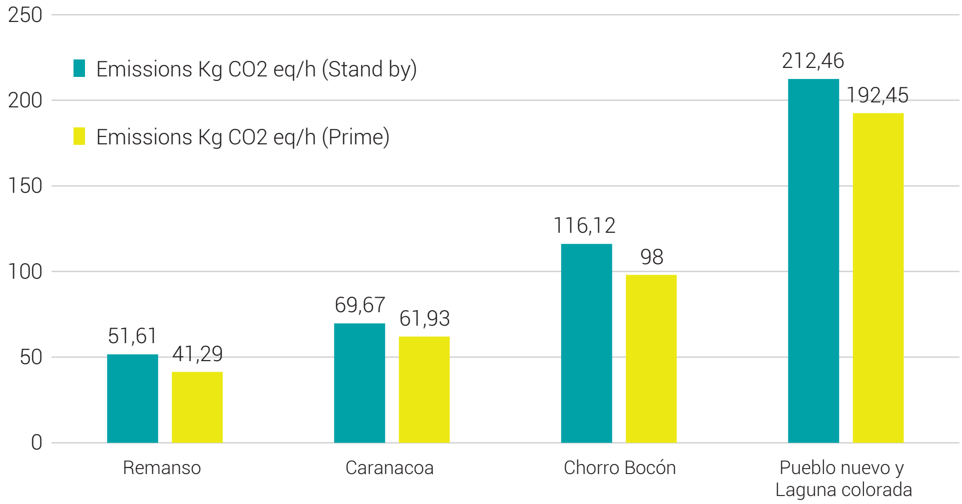

Figure 10. Emissions according to the load for each locality of $kg_{eq}\ CO_2/h$.
Source: Own work

6. Conclusions

Considering the literature review associated with the preparation of this article, it was evident that energy efficiency is a crucial factor for the good performance of energy systems. Additionally, although hybrid energy systems represent the functional integrality of an energy system with several sources, it is important to do the efficiency analysis for each of their components, which leads us to understand the complementarity of each one.

The evaluation of the efficiency of the HPSS installed in the localities and the obtention of results were achieved with the adaptation of technical sheets and theoretical information, through which, it was possible to identify that there is some margin of error for them; this is directly related to the absence of data taken or supplied directly at the sites. Additionally, panels, batteries and inverters for each of the localities, generally retain the same characteristics, while the diesel generator sets have different capacities in each project.

In line with the above, it is inferred that, with respect to the evaluation of efficiency for photovoltaic solar panels using the energy conversion method, the results obtained were not very favorable; while the form factor method under standard conditions and those calculated in situ gave satisfactory results.

The results obtained for inverters linked to the grid and bidirectional inverters have presented significant efficiencies in a wide operating margin, so it is assumed that this equipment is efficient in the hybridization of energy systems.

As for the useful life of batteries, it was evidenced that this depends to a large extent on the DoD, thus, it was deduced that if the DoD is greater, the energy conversion efficiency may be affected due to the proportional decrease in their useful life.

The final evaluation has concluded that the efficiency of the generator sets is directly related to SFC and GHG emissions. The localities recorded an SFC on average 2.5 gal/h lower than indicated by the standard, suggesting a good conversion of energy in the generator sets implemented. It was demonstrated that the emissions for the localities of Laguna Colorada and Chorro Bocón are higher as a result of higher fuel consumption and less excess air in combustion. In the case of the localities of Remanso and Caranacoa, fewer emissions are generated in proportion to their fuel consumption and greater air consumption.

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