

## Article

# Sustainability Evaluation of Rural Electrification in Cuba: From Fossil Fuels to Modular Photovoltaic Systems: Case Studies from Sancti Spiritus Province

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**Abstract:** In the last ten years, there has been a progressive improvement in rural electrification indexes in developing countries, and renewable energies are progressively being integrated into electrification programs. In Cuba, the government has set a target of 700 MW in solar photovoltaic energy by 2030, including rural electrification and off-grid systems. Within this framework, 10,000 modular systems of 300 Wp are being installed in isolated communities. Nowadays, previously diesel-electrified settlements are migrating into renewable energy technologies projects in rural Cuba. The objective of this research is to evaluate the sustainability of these changes in order to identify the implications for other developing countries, taking four different dimensions into account: environmental, technical, socioeconomic, and institutional. For this purpose, the rural communities of Yaguá (diesel-based) and Río Abajo (solar-based) in the province of Sancti Spiritus are visited and studied. Results show that the institutional dimension of sustainability is positive thanks to improvements in energy security and promotion of the Cuban national plan goals. Moreover, results confirm that the energy transition from diesel-based to solar PV is environmentally sustainable in Cuba, but improvements are still necessary in the power capacity of solar modules to strengthen the socioeconomic and technical dimensions.

**Keywords:** rural electrification; sustainability; Cuba; energy transition



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## 1. Introduction

Nowadays, 17% of the global population lacks electricity services, and most of them live in remote rural areas in developing countries [1]. However, in the last decade, people without electricity around the world has been reduced from 1.70 to 1.16 billion. Commonly, off-grid systems have been used to increase electrification indexes and reach rural communities [2,3]. Indeed, for achieving energy access for the entire world population in 2040, 60% of the additional capacity should be off-grid, through rural individual, mini, and microgrid systems. Among the off-grid technologies, diesel generators still form an important part of electrification systems. Up to 2040, diesel generators will contribute one-third of the solutions, and renewable energy technologies (RET) will contribute two-thirds of the solutions [1,4]. Initially, thanks to their low initial investment costs and easy commissioning, setup, and operation [5], diesel systems prevailed for rural electrification [6]. In this regard, the dominance of diesel projects is mainly caused by high fossil fuel subsidies, as it happens in Cuba and Venezuela [7].

Nevertheless, as diesel costs increase and renewable energy costs decrease, a progressively higher percentage of RET-based systems are enhancing the reliability of off-grid projects [8] while leveraging renewables to reduce energy dependency on pollutant and

fuels from abroad [9]. Therefore, the replacement or hybridization of the operating diesel-based distributed generators, through the use of RET-based technologies, such as photovoltaic solar modules [10], is currently in progress. This is particularly valid in countries where rural electrification indexes are still low [1]; for instance, Cuba, where the energy matrix still has a high degree of fossil fuel participation (95.7%) and only 4.3% of RET-based generation [11].

Since the beginning of the Cuban revolution, diesel-based rural electrification generation was chosen because of its lower investment cost as opposed to RET [12,13]. This situation led to high fossil fuel consumption, where 54% was imported, causing high foreign exchange expenditure, compromising energy independence, and entailing a high environmental impact [14]. The dispatch of fuel-fired power plants to cover baseload in Cuba boosted the carbon emissions of power generation, jeopardizing the compliance of the climate goals [15]. Dependence increased from 2005 with the implementation of distributed generation and off-grid electrification based on diesel generators within the framework of the “*Energy Revolution*” program [16]. The fuel for this program mostly comes from a state cooperation agreement where subsidized fuels were provided by Venezuela. However, the current crisis and oil production drop in that country [17] are negatively influencing Cuban energy security [18].

Nowadays, the Cuban energy strategy is to gradually increase RET-based electrification systems. The main technology is solar photovoltaic (PV) in places where it is difficult to extend conventional electricity and, at the same time, solar energy production is technoeconomically feasible [19], replacing the previous diesel generators [20]. In this sense, the Cuban energy policy is aimed at changing the energy matrix to raise the contribution of RET generation from 4.3% to 24% by 2030 [21]. For this purpose, the government is promoting an oil consumption reduction policy to decrease the share of fossil fuels to 76% [20]. Regarding rural electrification, the Ministry of Energy and Mines of Cuba, through the state-owned company “*Ernesto Che Guevara Electronic Components Factory*”, is producing Modular Photovoltaic Systems (MPS) of 300 Wp to be freely installed in isolated areas [22]. At present, 10,000 MPS are produced per year to be installed in poor households in the Cuban countryside [23]. However, an analysis is still needed to evaluate the sustainability of the transition from diesel-based off-grid to MPS rural electrification with these 300 Wp modules, to undertake appropriate measures for strengthening the rural electrification transformation.

The sustainability analysis of the shift from fuel to renewable technologies is complex. From a national perspective, Soomaroo et al. [24] study the decarbonization strategies of island states (Barbados, Fiji and Mauritius). Almeshqab and Ustun [25] gather lessons learned from eight developing countries that have adopted policies to achieve full rural electrification, considering technical, social, financial, and public aspects. In Latin America, Washburn and Pablo-Romero [26] review policies implemented in 18 countries to promote renewable technologies. At a regional scale, Eras-Almeida et al. [27] examine successful solar home systems experiences in Bolivia, Mexico, and Peru to identify market mechanisms that promote such technology. Tomei et al. [28] examine the impact of electrification projects in Colombia in order to propose PV-based solutions for non-electrified villages and achieve sustainable development. Bertheau [29] assess the impact of a PV-based system into the socioeconomic development of an island in the Philippines. Finally, Rosso-Cerón et al. [30] use fuzzy multicriteria tools to study the transition of a Colombian island from a diesel supply to a wind-PV supply, evaluating social, technological, economic, and environmental factors.

The above works examined from different perspectives the migration from fuel to renewable-based technologies. However, local-scale studies are needed to identify the impacts of energy transition in the beneficiaries from rural areas in developing countries. In this regard, López-González et al. [31] propose a standardized methodology to evaluate the sustainability of local-scale energy access initiatives, using a formative approach and a management perspective. Later, the authors apply the methodology to micro-hydro

projects in Venezuela [32], to enhance future electrification programs [33]. However, to the best of the author's knowledge, the sustainability of transitioning from fossil fuels to renewables has not been evaluated in rural areas of Caribbean countries such as Cuba.

In this context, the objective of this study is to develop a sustainability evaluation of the energy transition in Cuba. Thus, the contribution of this paper is twofold:

- To evaluate the sustainability of migrating from diesel generators to PV panels in rural Cuba. For this purpose, the performance of a diesel-based off-grid project in Yaguá is compared to a project using solar 300 Wp MPS (MPS-300) panels in Río Abajo; both cases are located in the province of Sancti Spiritus.
- To carry out a sustainability evaluation in the Cuban context using a multidimensional methodology. In particular, the methodology considers four dimensions (environmental, technical, socioeconomic, and institutional), assessed through eight criteria. Therefore, the assessment of the criteria is specifically designed to evaluate the energy transition problem. Moreover, information sources are defined and adapted to rural Cuba, gathering data from field visits, beneficiary surveys, interviews with local representatives, and technical reviews of equipment.

Results show the sustainability of the energy transition in Cuba regarding each dimension and criteria. Successful ones are highlighted and those with shortcomings are identified, defining the actions to be carried out to improve them. In addition, results provide useful insights for policy-makers in Caribbean countries when conceiving future energy transition initiatives.

This work is organized in five sections. Data analysis methods and description of the two case studies are explained in Section 2. Section 3 describes the methodological process for sustainability assessment. The results of the comparison of both case studies are detailed in Section 4, according to the four sustainability dimensions. Finally, the main conclusions are summarized in Section 5.

## 2. Materials and Methods

Sancti Spiritus province has a great diversity in its relief, making electrification difficult through the national grid extension in rural areas. In this province, 28% of the population lives in scattered rural settlements, with a population density of only 15 inhabitants/km<sup>2</sup>. This situation was caused by the constant migration to the main cities outside the province because of the lack of public services such as electricity. The communities of Yaguá and Río Abajo were electrified through different technologies within the rural electrification process in Cuba, and they are 14 km from each other (Figure 1).

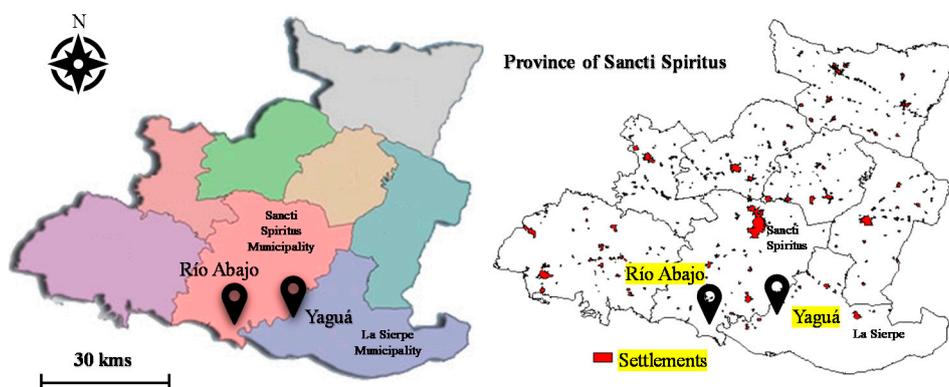


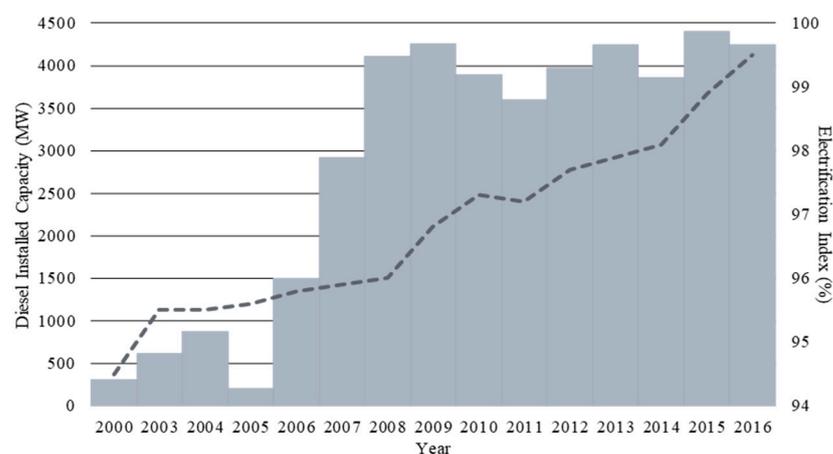
Figure 1. Map of Sancti Spiritus province and location of Yaguá and Río Abajo communities.

The analysis of the projects began with a visit to both communities to collect data in situ. On the one hand, the environmental and visual impact of the projects, concerning the possible waste from the electricity generation systems, is assessed through technical visits. In this sense, the electrified communities were visited within the case studies. On the

other hand, two structured interviews were conducted with representatives of community organizations, as well as an interview with the technician from the Cuban Electric Union (UNE) in charge of these communities. Likewise, 5 household surveys were carried out in Yaguá and 6 in Río Abajo. In each case, the surveys had an average duration of between 15 and 20 min. The number of surveys carried out is statistically representative of the entire population of the communities visited [34]. There were 5 question categories in the surveys, each one relating to (a) the environmental impact; (b) home appliances and their use; (c) the availability of public services; (d) literacy and education; and (e) the quality of the electric service. Then, the Yaguá community electrification process, using a diesel-based off-grid system, is explained (Section 2.1). Then, the case study from the Río Abajo community, using MPS assembled in Cuba, is presented (Section 2.2).

### 2.1. Diesel-Based Rural Electrification and the Community of Yaguá

In 2005, there was a low rural electrification rate in Cuba and seven large and inefficient oil-fed power plants, with an average lifetime of 25 years, began to suffer frequent interruptions. These failures appeared during peak demand, due to lack of maintenance and poor fuel quality, causing corrosion and failure of the pieces. Therefore, in 2006, the Cuban authorities stated a national power grid and generation matrix transformation called “*Energy Revolution*” that included the acquisition of new gas-fired power plants and more efficient turbines and diesel generators [35]. Distributed Generation (DG) was widely spread with small and medium-sized diesel power plants, which would substitute the big old power plants. Currently, there are 6000 small diesel generators (1320 MW) and 416 fuel generators (904 MW), in addition to 893 high-efficiency diesel generators (1219.8 MW) for rural electrification in distribution grids [16]. This diesel-based DG program was only possible thanks to economic agreements between Cuba and Venezuela. In 2012, 47% of the total imports of goods and services in Cuba corresponded to Venezuelan fuel, with a total annual value of 6.4 billion dollars [21]. The installed capacity increased 10-fold between 2005 and 2008, and the electrification rate in Cuba overcame the previous stagnation, around 95%, to reach 99.6% in 2016 (Figure 2), which was the last year of reliable data found [21]. Contrary to what may be thought, in most developing countries, the rate of rural electrification and installed capacity are not indices whose growth is uniform and constant. In the case of electrification indices, the variations are due to changes in technology that occur at a slower speed than that necessary to achieve an immediate transition from one electrification system to the other. In addition, specific shortages in the supply of fuel for systems based on generator sets have an influence, which is something that is very important in Cuba. Regarding installed capacity, in Cuba, the migration process from old to new thermoelectric technologies was not immediate. In this sense, some generation systems went out of service before replacement, and this causes fluctuations in installed capacity.



**Figure 2.** Growth in installed capacity of generator sets and electrification rate in Cuba.

Distributed Generation has a power capacity from 1 MW up to 50 MW; it is installed as off-grid or at extreme points of the distribution network to supply an electrical load close to the generation placement [36]. The most important advantages of centralized, compared with the individual, fossil fuel generators are better performance in the use of fuel, the reduction of emissions intensity, and the extension of the energy access threshold thanks to greater generation capacity. In the case of Yaguá, a centralized off-grid diesel generator is used to provide electricity to a group of households that previously could only be fed by low-capacity domestic gasoline or diesel power generators. Currently, Yaguá is a community of 12 houses with a 20 kVA (16 kW) generator, which was originally installed in 2010 to supply 30 houses (Figure 3). About 30 people live permanently in the community, and up to 70 live intermittently. The young population travels during the week to study in the nearest cities, while elders stay to perform agricultural and livestock work.



**Figure 3.** Generator set of 20 kVA (16 kW) and fuel storage tank in Yaguá.

The closest access to the grid is more than 16 km away from the community, via a dirt road. The state-owned Cuban electricity company is responsible for the diesel generator's operation and maintenance. The fuel for the generator is supplied by the Cuban state oil company (CUPET) and stored locally in a 1500-l capacity tank. Considering that the operating regime is 10 h/day (8:00–13:00/17:30–22:30), the average fuel consumption is 3.2 l/h, which implies about 960 l of diesel per month. However, the performance of the generator varies, ranging between a thermal efficiency of 12% and 38% due to variations in the electric load of the community, depending on the time slot examined.

From the surveys carried out, the average consumption per house was estimated at 3.42 kWh/day. The appliances used include fridge, electric stove, TV, radio, and lightbulbs. In general terms, 86.3% of energy consumption is destined for refrigeration in fridges and cooking food in electric stoves. This situation evidences a significant opportunity for savings, for example, in the case of changing these devices for others that use natural gas as the primary source of energy. As for lighting, this is responsible for only 6.1% of the energy consumed inside the houses due to the use of high-efficiency LED lightbulbs and generator operating hours restricted until 10:30 p.m. Later, night lighting is provided through employing conventional kerosene lamps, which leads to a respiratory health impact, particularly on women and children.

The area covered by the electricity low-voltage (LV) distribution lines (Figure 4) is about 450 ha (4.5 km<sup>2</sup>), and there are distribution lines that reach up to 1.4 km in length. This situation causes voltage drops of up to 45% in the hours of highest electricity demand, which implies significant energy losses and excessive fuel consumption. Half of the houses (6) are more than 1 km away from the generator location, 33% (4) are between 200 and

1000 m away, and only 17% (2) are within the 200 m range, with voltage drops being lower than an estimated 5%. Globally, this topology implies that 34.6% of the energy generated and, therefore, the fuel consumed, is lost in the community electric distribution system (Table 1). The values in Table 1 represent the average for the households located at each distance stretch, and they are estimated according to the load and assuming a 10 AWG section of the electrical cables. These circumstances show the significant limitations of using a diesel microgrid instead of a set of individual isolated systems. It is evident that at the time of developing this project, there was no financial availability to consider other alternatives, and therefore, significant energy losses are assumed which, in the medium and long term, translate into significant economic losses.



Figure 4. Electricity low-voltage distribution network in Yaguá.

Table 1. Households' relative location and voltage drop.

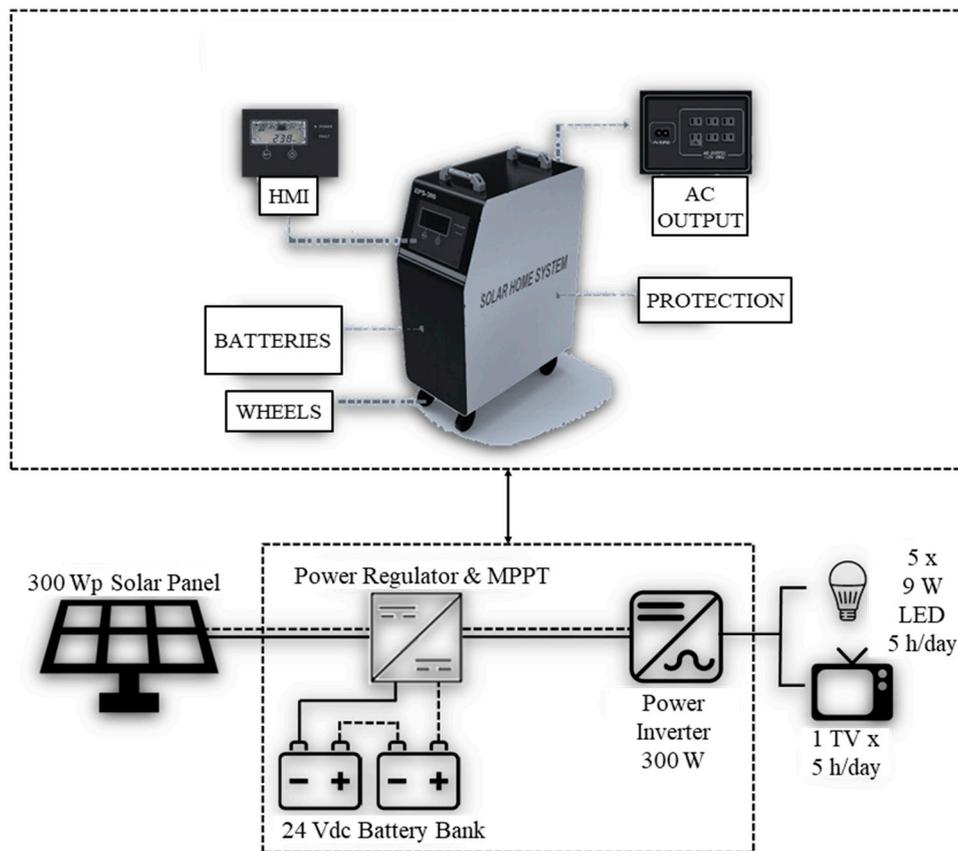
Households	Distance from Load Center [m]	Voltage Drop [%]	Energy Losses [kWh/month]	Monthly Consumption [kWh/month]
2	$x < 200$ m	$x < 5$	11	216
4	$200 < x < 1000$	$5 < x < 45$	137	548
6	$1000 < x$	$45 < x$	504	1121
<b>Total [kWh/month]</b>			<b>652</b>	<b>1885</b>

## 2.2. Solar PV Systems for Rural Electrification and the Community of Río Abajo

In recent years, the Cuban government has started to change its rural electrification policy to gradually increase the use of RET-based systems, such as wind turbines and solar photovoltaic modules, in places where it is difficult to extend conventional electricity [20]. In this sense, nowadays, Cuba plans to install 700 MW of solar PV panels. The production of these panels will be carried out by a state-owned company located in the province of Pinar del Río. The current annual production capacity, 15 MW, is currently expanding up to 60 MW to be able to execute a national program in which electricity generation through renewable sources includes solar PV for grid-connected and off-grid systems in rural Cuba [37].

The Río Abajo community was electrified through this PV-based program, installing an MPS-300 system at each household. The MPS-300 was specially designed for the electrification of rural houses with 5 outputs at 110 V for domestic appliances (alternating current) and allows a daily electricity consumption ranging between 1.2 and 1.5 kWh/day. The MPS-300 is composed of 1 PV module of 300 Wp capacity with a support control box including 1 Tracer 1210 charge regulator with maximum power point tracking technology; 2 batteries of 12 V and 100 Ah; 1 pure sine wave inverter type STI300 of 300 W, 24 V (direct current) to 110 V (alternating current) at 60 Hz. Additionally, a cable with polarized connectors for the connection of the PV module to the control box is included. There is

another cable connector and switch, with different lengths for the connection of each LED lightbulb to the control box. The program also includes 5 LED lamps of 9 W for each benefited house. Figure 5 shows the electrical scheme of an MPS-300 modular PV system installed in Río Abajo.



**Figure 5.** Electrical scheme of a modular solar system installed in Río Abajo.

Currently, Río Abajo is a community of 50 houses. The young inhabitants travel during the week to study in the nearest cities, while the elders stay within the community working in agriculture and livestock. The most widespread products are onions and bananas, which are gathered in the community center and then sold to the most important cities and population centers in the province of Sancti Spiritus. The MPS is totally portable, so there is no need for excessive wiring in the houses, and the panels are installed on the roof (Figure 6). The visual impact of the panels is very limited, since they can be installed on the roof of the houses without needing additional buildings or infrastructure. In addition, note that although the roof structure might seem weak to support the panels' weight, no issues in this regard were reported during the field visits. The operation and maintenance are carried out by the state-owned Cuban electricity company. The houses are scattered over an area of 180 ha (1.8 km<sup>2</sup>). The area has a length of 2.5 km and a maximum width of 900 m and extends alongside a small river that leads to a reservoir used for irrigation. Therefore, a low-voltage diesel or RET-based microgrid would have voltage regulation problems due to the long distances between houses, so only domestic electrification is possible.



**Figure 6.** Portable solar system installed in Río Abajo, inside (A) and outside (B) the household.

According to the power demand, electricity from solar panels is used to charge batteries and/or supply domestic appliances, usually a TV and five LED lightbulbs. From the surveys carried out, the average consumption per house was estimated at 496 Wh/day (including TV, radio and lightbulb). In general terms, it was determined that 55% of energy consumption is used for watching TV and the other 45% is used for lighting, avoiding, for example, kerosene lamps as the primary source for the light at night. Low energy consumption inside the houses is due to the use of LED lightbulbs, which are permanently provided by the Cuban government. The quantity and type of household appliances per household, as well as the typical daily hours of use thereof, were determined from the corresponding section within the carried out surveys. It must be noted that the system was designed for 500 Wh but users manage energy according to their own particular needs; for instance, not turning on all the lamps to extend power availability at night.

### 3. Evaluation Methodology

This paper aims to assess the transition from fuel-based to PV-based technologies for rural electrification in Cuba. For this purpose, the sustainability of these two strategies is analyzed through two real projects in Cuban communities, each one using a different technology. The evaluation of sustainability is complex, and several criteria have been proposed in the framework of the Sustainable Development Goals [38]. In this research, a standardized methodology recently developed for the assessment of rural electrification projects is used [31]. The methodology considers four dimensions (environmental, technical, socioeconomic, and institutional) to properly evaluate from all the perspectives. In turn, each dimension is assessed by means of several qualitative and quantitative criteria (Figure 7), which are flexible enough to be easily replicated into different regions and countries [39]. For instance, the methodology was previously used in Venezuela, obtaining useful results from real projects to assist decision makers in defining future rural electrification policies [7,32]. Based on reference [31], Table 2 summarizes the evaluation criteria for each sustainability dimension. The assessment of the criteria is specifically designed to evaluate the energy transition problem. Moreover, the information sources (last column of

Table 2) are defined adapted to rural Cuba, gathering data from field visits, beneficiary surveys, interviews with local representatives, and technical reviews of equipment. Therefore, the results in next section are linked to these real sources of information.

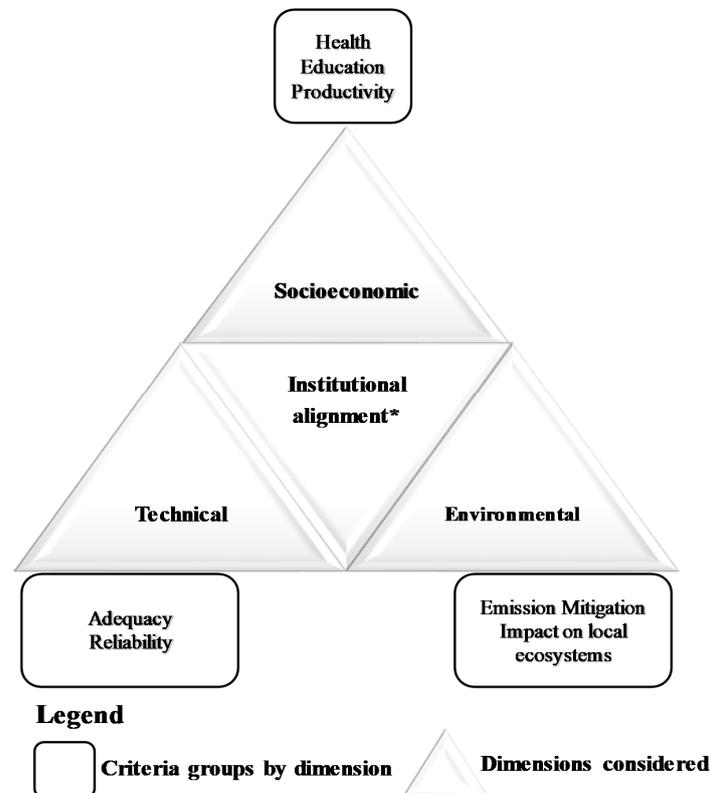


Figure 7. Sustainability assessment dimensions and criteria [31]. (\*) The institutional dimension is shown through the unique criterion considered in this regard.

Table 2. Sustainability dimensions and criteria of the evaluation methodology.

Dimension	Criteria	Definition	Information Source
Environmental	Emission mitigation	- Greenhouse gases (CO <sub>2</sub> equivalent) avoided when replacing conventional by renewable sources - Comparison with communities without electricity	- Estimated from users consumption (gathered through surveys)
	Impact on ecosystems	- Deterioration of the environment due to toxic waste - Impact on the landscape due to infrastructures	- Qualitatively evaluated in community visits
Technical	Adequacy	- System capacity to meet users' electricity needs - Comparison with minimum thresholds [40,41]	- HOMER simulations [42], from production and consumption reported by operators
	Reliability	- System capacity to supply electricity with minimum techno-economic interventions [43]	- HOMER simulations [42], considering non-powered loads [44]
Socioeconomic	Education	- Impact on access to education [45] - Impact in youth persistence for studies	- Surveys
	Health	- Impact on food preservation and water purification - Impact on access to health care	- Surveys, considering electrical appliances and drinkable water supply
	Productivity	- Impact on productive incomes [46] - Development of new activities using electricity [47]	- Surveys
Institutional	Institutional alignment	- Interaction between institutions to promote the development of communities thanks to electricity [48,49]	- Interviews with community representatives and technicians from UNE (Cuba)

## 4. Results and Discussion

The following section details the results regarding the sustainability assessment in the four dimensions considered. Results are examined through a management perspective, assuming that projects are framed within a broad national program aiming to migrate from diesel electrification to solar energy systems. Moreover, a formative purpose is sought, analyzing the elements to be improved to achieve sustainability in the four dimensions. In addition, the energy policy implications within Cuba are discussed.

### 4.1. Environmental Dimension Results

First, the evaluation of the emission mitigation criterion is considered. Different emission factors are considered according to the comparison made against individual domestic generation systems or community generation systems. In the first case, the emission factor considered is 1.293 kg CO<sub>2</sub>/kWh, while, in the second case, for community diesel generators, the emission factor is 0.607 kg CO<sub>2</sub>/kWh [7]. In this particular case, the mitigation of emissions in Yaguá is 53.6% per year. This reduction in emission intensity means a decrease of 10.4 tCO<sub>2</sub> per year thanks to the installation of a central generator. In Río Abajo, 100% of emissions were avoided. Considering an annual consumption for each house of 181 kWh/year and 50 electrified houses (9.05 MWh/year), 11.7 tCO<sub>2</sub> are avoided. Therefore, regarding this criterion, diesel-based centralized generation implies a significant improvement concerning the previous individual generation. At present, Cuba can install MPS systems to completely mitigate emissions [50]. Therefore, the assessment regarding emission mitigation implies a need for migration from diesel-based to RET-based electrification in Yaguá and an expansion of the MPS program studied in Río Abajo.

Regarding the impact on local ecosystems, the noise caused by the combustion engine coupled to the electricity generator causes a negative impact on the two houses located less than 200 m from the generation center in Yaguá. There is a very negative and unavoidable visual impact as well. Unlike solar technologies, which can be camouflaged on house roofs, the presence of a 20-kVA generator is not environmentally friendly. Although the maintenance and cleaning of the area where the generator is installed are impeccable, the impact on the local ecosystem cannot be assessed in any other way but negatively. On the other hand, in Río Abajo, there is no impact. Therefore, the transition to MPS systems means effective mitigation of the impact on the local ecosystems.

Considering all these aspects related to the environmental dimension of sustainability, the impact of the transition from centralized diesel systems to MPS would be positive.

### 4.2. Technical Dimension Results

With regard to the adequacy, the average consumption of 3.42 kWh/day per house is estimated from household appliances, the number of usage hours in Yaguá, and the load surveys carried out. These results show a consumption that is 45% lower than the average consumption of rural homes in Cuba [51]. On the other hand, if it is compared with the minimum adequacy threshold, it turns out that the estimated value of 1248 kWh/year is five times higher than that value proposed by the IEA. In this sense, the generator of the Yaguá community has been sufficient to cover basic demand in terms of electricity supply. However, it is still insufficient to satisfy the minimum demand necessary for sustainable development, as calculated by the Cuban government, in rural households. Therefore, the performance of the Yaguá generator in terms of electricity supply has been enough to cover basic demand, but it is not enough to cover the amount calculated by the Cuban government as necessary for a comfortable life in rural households. In Río Abajo, the daily average energy demand is estimated at 496 Wh/day, including an average power demand of 20.7 W and a peak power demand of 136 W. This is not even 10% of the minimum requirements for rural electrification in Cuba. Additionally, the load factor is 0.152 due to the partially discretized values of the demand because of the low number of house appliances. MPS-300 produces 491 kWh/year, which is high enough to supply the 181 kWh/year of electrical consumption. However, considering the average solar radiation

of 5.52 kWh/m<sup>2</sup>/day, the PV module is working at a capacity factor of 19.4%, and the average daily generation is 1.34 kWh/day. Therefore, there is an excess of generated energy not being used for household needs. Figure 8 shows the average daily production and consumption in Río Abajo. The former is significantly higher than the latter over the entire year. As a result of Cuba's location, only small production variations are observed, while consumption remains constant and mainly destined to illumination and communication purposes.

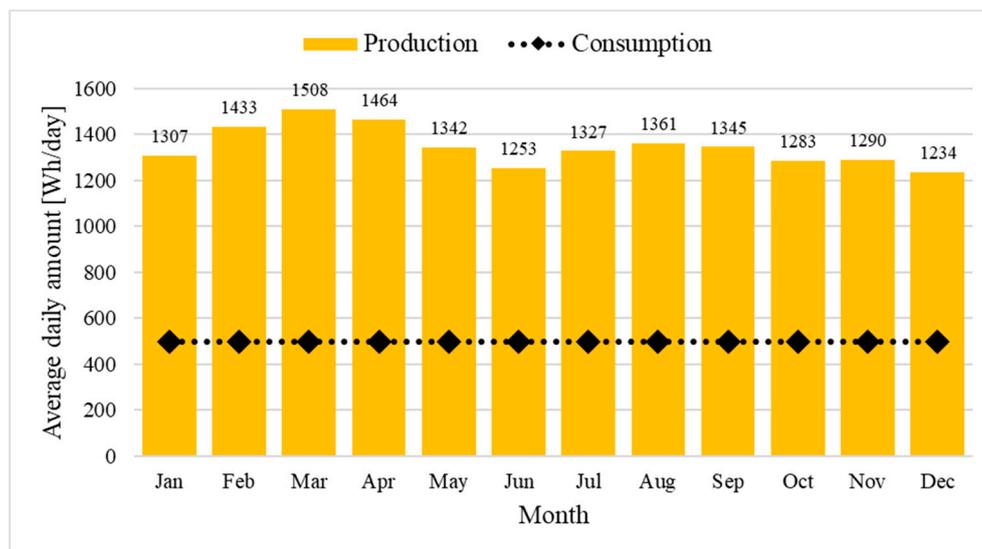


Figure 8. Typical daily performance of a PV-based system installed in Río Abajo (kWh/day).

Regarding reliability, the Yaguá generator has been operating continuously 10 h a day for the last 8 years. Few problems with diesel supply have been found, as the monthly consumption is lower than the diesel tank capacity, and providers are easily able to supply the fuel once a month. According to the interviews, failures are infrequent and are mostly due to the distribution network, which is an inefficient wooden structure. When the distribution grid is not working, it usually takes more than 1 day to be restored. Low voltage in southern households is due to the long distances, which are also the most reported cause of power failure in these houses. On the other hand, the MPS-300 in Río Abajo has been operating continuously for 1 year, with no problems at all. According to the interviews and surveys, failures have never occurred in any of the MPS-300 installed. The calculations show that there is no unmet electricity load throughout the year and there is also an excess of electricity generated. In Figure 8, the typical monthly day is shown and simulated. At every hour of each day, the load is met. On the other hand, the state of charge never falls below 92%.

Regarding the technical dimension of sustainability, the migration from a centralized diesel system as in Yaguá to MPS-300 is not completely sustainable, due to a significant lack in adequacy regarding the Cuban standards for proper energy access. In short, improvements must be made to take advantage of the solar energy generation to enhance this dimension.

#### 4.3. Socioeconomic Dimension Results

Regarding the impact on health, due to electrification, houses in Yaguá have refrigerators or freezers that allow the preservation of meat, which is the main ingredient in the daily diet of people in this community. In this sense, the decomposition of this food is avoided, which would occur when it is subjected to high levels of humidity and temperatures, which is typical of the location [21]. In this way, infant mortality and diseases derived from bacterial contamination are reduced [52]. In contrast, in Río Abajo, refrigerators and

freezers cannot be installed with an MPS-300 system. Therefore, there is no improvement in food preservation. Regarding cooking, although in Yaguá inhabitants have electric burners, there is usually not enough power for the total replacement of coal and firewood. Moreover, both in Yaguá and Río Abajo, electric lighting reduces the risk of tuberculosis and cancer due to reduced emissions of gases and particles that can cause asthma and infectious diseases from burning kerosene lamps and other conventional sources of lighting in rural settings such as wood, oil, etc. [53]. Therefore, a general improvement in the sanitary conditions of the Yaguá community is achieved, but it is not equally accomplished in Río Abajo.

In terms of education, in Yaguá and Río Abajo, electricity has provided access to information and news due to TV and radio. In this community, there is no school, as there are not enough children in the village to justify such a service. However, the inhabitants consider that electricity enables additional night hours for study and, consequently, improves the children's school performance. Both communities have 100% literacy rates and have attended school, regardless of age. This situation existed before electrification. Therefore, the impact on education is only linked to more study hours at night.

As for productivity, the relation is indirect. In this sense, the migration from the countryside to the city has been restrained thanks to the improvements in living conditions that electrification has brought to both communities. From the surveys, electricity has no direct impact on the productivity levels, as no energy usages in this regard are observed. Nevertheless, the role of electricity in stopping migration and preventing the total depopulation of the villages must be viewed positively.

Summarizing, the differences between the diesel and solar modules are not particularly relevant in the socioeconomic dimension of sustainability. There are no significant improvements in the socioeconomic conditions of inhabitants related to the migration from diesel to solar systems, and even in health, the conditions can be worse. Therefore, a change in the technologies from current diesel to MPS-300 is not sustainable in the socioeconomic dimension.

#### 4.4. Institutional Dimension Results

Community organization in Yaguá and Río Abajo is similar to other countries with comparable socio-political regimes, such as Venezuela [54]. In Cuba, the institutional alignment between the organized community and the electricity company UNE is harmonious, and the periodic supply of fuel in Yaguá, combined with timely executions of scheduled maintenance in both communities, accounts for this situation. The management model is based on previous training for the community operator in Yaguá and MPS-300 users in Río Abajo. Simultaneously, communities have direct and continuous communication with the operators and technicians of the electricity company, who are also responsible for the supply of fuel to the community of Yaguá and the operation and maintenance in both communities. Health, productive conditions, and education have improved due to the alignment of the electrification program with other public programs to strengthen them through the use of electrical facilities. This way, electrification is indirectly improving the socioeconomic dimension of sustainability, although not particularly due to clean technologies. However, the dependence of the "Energy Revolution" program on oil and refined products from Venezuela could have an impact on the reliability of the oil supply and, therefore, the capacity for diesel supply to the Cuban market. Consequently, the internally appropriate institutional alignment (an organized community with electricity company) can be damaged by a failure at the international level (Cuba and Venezuela cooperation). In this sense, the implementation of such an important national electrification program, which depends on external oil, is the determining factor in reaching a negative assessment of the institutional dimension for the diesel-based projects, such as in Yaguá. Therefore, there is a need to migrate from these diesel technologies to solar PV to improve national energy security and the institutional accomplishment of the 2030 Agenda in Cuba.

Summarizing, in the institutional dimension of sustainability, the migration from diesel to solar PV technologies for rural electrification in Cuba is sustainable thanks to the improvements in energy security and institutional goals included in the Cuban national development plan and international commitments.

#### 4.5. Global Discussion

In order to sum up the comparison of the electrification projects of Yaguá and Río Abajo, Table 3 shows all the indicators considered for the evaluation criteria of the sustainability dimensions. In addition, Figure 9 illustrates the sustainability of the migration from diesel to PV systems on a triple-scale (green: sustainable; red: not sustainable; yellow: to be improved). Although the sustainability is not guaranteed regarding the technical dimensions and no clear advantages are identified in the socioeconomic dimension, results show the sustainability of the migration from diesel to PV-based technologies in terms of the environmental and institutional dimensions. Thus, the recommendations detailed in the previous subsections to strengthen the technical and socioeconomic dimensions would allow the complete achievement of sustainability in the energy transition.

**Table 3.** Comparison between the electrification projects in Yaguá and Río Abajo.

Dimension	Criteria	Indicator	Yaguá (Diesel-Based)	Río Abajo (PV-Based)
Environmental	Emission mitigation	Relative reduction	53.6%	100%
		Total reduction	10.4 tCO <sub>2</sub>	11.7 tCO <sub>2</sub>
	Impact on ecosystems	Noise impact	Close households	None
		Visual impact	Significant	Limited
		<b>Conclusion</b>	<b>Migration from diesel to PV sustainable</b>	
Technical	Adequacy	Consumption	3420 Wh/day	496 Wh/day
		Coverage of basic needs	Sufficient	Insufficient
		Comparison to national average	45% lower	90% lower
	Reliability	Operation	Continuously 10 h/day, 8 years	Continuously, 1 year
Technical failures		Infrequent and in the network	Not reported	
Source supply		Few reported	Not reported	
	Unmet demand	None (excess generation)	None (excess generation)	
		<b>Conclusion</b>	<b>Migration from diesel to PV not sustainable</b>	
Socioeconomic	Education	Access to TV and radio	Yes	Yes
		Children study at night	Yes	Yes
		Literacy	100% prior to electrification	100% prior to electrification
	Health	Food preservation	Yes, thanks to refrigerators	No improvements
		Cooking with traditional sources	Partial reduction	No improvements
	Illumination with traditional sources	Partial reduction	Total reduction	
Productivity	Production increases	Not observed	Not observed	
	Migration to cities	Limited thanks to electricity	Limited	
		<b>Conclusion</b>	<b>No relevant differences between technologies</b>	
Institutional	Institutional alignment	Administrative support	Timely and effective	Timely and effective
		Maintenance training	Community operator	End-users
		Parallel development programs	Strengthened by electricity	Strengthened by electricity
	Dependence on importations	Yes	Limited	
		<b>Conclusion</b>	<b>Migration from diesel to PV sustainable</b>	

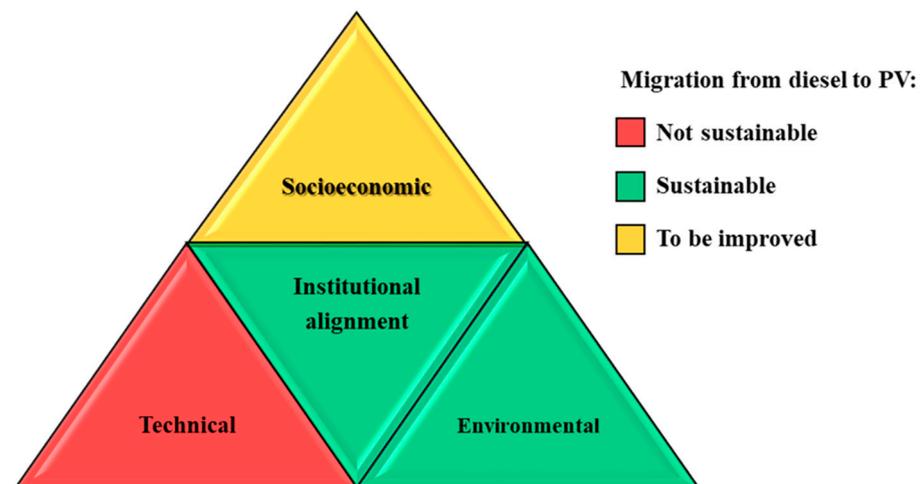


Figure 9. Sustainability of the migration from diesel to PV-based technologies.

## 5. Conclusions

Although diesel generators are the most used technology for rural electrification in remote communities of developing countries, other empirical sustainability assessments are required to the long-term performance assessment of renewable energy technologies based projects. In this investigation, the sustainability of a diesel-based project in the community of Yaguá is evaluated after 8 years of continuous operation, and its performance is compared to modular PV systems for domestic applications in the rural community of Río Abajo. Four dimensions of sustainability are considered for the comparative evaluation, and corresponding criteria are defined to evaluate different impacts within each dimension. Databases and historical records are useful to know more regarding the technical and environmental dimensions. On the other hand, regarding the institutional dimension, the technical visits and structured interviews evidence the alignment between different programs.

The results show the strengths and weaknesses of each strategy. Regarding the environmental dimension, the transition to MPS projects leads to effective emissions mitigation, which is higher than replacing domestic diesel by centralized generators. For their part, improvements in the socioeconomic and technical dimensions of sustainability must be achieved to make the technology migration from diesel to RET-based rural electrification completely sustainable. The application of parallel programs in education, health, and the improvement of the productive conditions of the population, aligned with the use of electrification, has been an important factor in supporting the socioeconomic dimension of the sustainability of the projects. Finally, the national institutional alignment is solid and well structured, but there are deficiencies at international levels that negatively affect the diesel supply. It is worth mentioning that collaboration between local, national, and international institutions has led to significant improvements in the electricity service and coverage in Cuba. Despite this, successive changes in the international institutional alignment show the importance of this dimension regarding long-term completely sustainable rural electrification and the migration from diesel to RET-based rural electrification.

In short, the general recommendation from this paper is that the institutional dimension of sustainability is positive thanks to the improvements made in terms of energy security and the promotion of the Cuban national plan goals. Moreover, results confirm that the energy transition from diesel-based to solar PV is environmentally sustainable in Cuba, but improvements are still necessary in the power capacity of solar modules to strengthen the socioeconomic and technical dimensions. In this regard, technical viability could be achieved through a hybridization process in which individual modules of solar energy are considered for the furthest from the load center houses of the communities and centralized grids in hybrid systems or solar systems with battery backup for the central nucleus of the rural villages. It is also possible to consider a second-level hybridization in

which there are houses with individual solar modules but also with interconnection to the isolated rural grid for emergency and backup cases (reducing the house load and distribution losses). In any case, the continuity of the use of rural electrification with generators is not viable, and the solution of individual domestic solar modules is insufficient in the current scheme. Only projects with hybrid generation systems could support the universal rural electrification process in the Republic of Cuba.

The sustainability assessment methodology allows the identification of sustainability dimensions to strengthen programs from a management perspective, both at the design and implementation phases. Therefore, this research identifies key problems that stakeholders in Cuba and developing countries must consider in rural electrification projects based on diesel generators, to migrate to RET-based electrification when dependence on foreign fuel is an issue. This is particularly relevant in small island states of the Caribbean. The Cuban experience provides elements for the promotion and development of better programs, considering hybridization or complete replacement. A transition is necessary from many diesel projects to RET, considering the experience acquired and the lessons learned from ex-post evaluated projects. The lessons learned and conclusions regarding project management are useful in similar settings in developing countries in Latin America, sub-Saharan Africa, and Southeast Asia.

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