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Assessing the Socioeconomic and Environmental Impact of Hybrid Renewable Energy Systems for Sustainable Power in Remote Cuba

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Abstract

This study evaluates the viability of a specific hybrid renewable energy system (HRES) installation designed for a remote community as a case study in Cuba. The system integrates solar, wind, and biomass resources to address localised challenges of energy insecurity and environmental degradation. Rather than offering a generalised evaluation of HRES technologies, this work focuses on the performance, impacts, and viability of this particular configuration within its unique geographical, social, and technical context. Using life cycle assessment (LCA) and input–output modelling, the research assesses environmental and socioeconomic impacts. The proposed HRES reduces greenhouse gas emissions by 60% (from 1.14 to 0.47 kg CO_2eq/kWh) and fossil energy consumption by 50% compared to diesel-based systems. Socioeconomic analysis reveals that the system generates 40.3 full-time equivalent (FTE) jobs, with significant employment opportunities in operation and maintenance. However, initial investments primarily benefit foreign suppliers due to Cuba's reliance on imported components. The study highlights the potential for local economic gains through workforce training and domestic manufacturing of renewable energy technologies. These findings underscore the importance of integrating multiple renewable sources to enhance energy resilience and sustainability in Cuba. Policymakers should prioritise strategies to incentivise local production and capacity building to maximise long-term benefits. Future research should explore scalability across diverse regions and investigate policy frameworks to support widespread adoption of HRES. This study provides valuable insights for advancing sustainable energy solutions in Cuba and similar contexts globally.

Keywords: hybrid renewable energy systems; sustainable energy transition; life cycle assessment (LCA); socioeconomic impact; Cuba energy security

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1. Introduction

This study aligns with Sustainable Development Goal (SDG) 7: "Affordable and Clean Energy", emphasising the need for sustainable energy sources to support human and economic development [1]. Reliable and sustainable energy is a fundamental driver of progress, influencing healthcare, education, and industry. In many remote communities, limited energy access still constrains economic growth and social well-being.

The industrial revolution reached Cuba in the mid-19th century, bringing profound socioeconomic and environmental transformations. While it improved living standards for some, it deepened social inequalities and caused large-scale environmental degradation through deforestation and greenhouse gas emissions. Today, some economic indicators show potential improvement—such as a modest projected GDP growth for 2025, increased tourism revenue, and progress in attracting foreign investment—yet, the overall conditions remain challenging [2]. Cuba's energy sustainability indicators reveal a system heavily reliant on fossil fuels, particularly oil products, with a significant portion of energy used in the manufacturing sector. Although the country is pursuing renewable energy—especially solar and biomass—and improving efficiency, it still faces obstacles in infrastructure, grid modernisation, and reducing dependence on imports [3]. The large-scale deployment of renewable energy sources (RES) presents the most significant opportunity to improve systemic performance for a long time [4].

While Cuba is transitioning to a cleaner energy mix, integrated local energy management remains underdeveloped. This gap limits efficiency gains and adoption of renewables at the community level [5].This means that while the country is making progress in shifting towards renewable sources like solar and biomass, the way energy is managed and used at the community level could be significantly improved [6]. Municipal energy management systems (MEMS) could address this, leveraging local governments' growing interest in resource management and alignment with national RES policies [7]. This approach mirrors global trends such as energy communities (ECs), which promote collaborative and inclusive renewable energy models [8]. For example, EU Member States must include renewable energy communities (RECs) in their national energy plans and offer technical and financial support [9].

The development of renewable energy sources (RES) and energy efficiency in Cuba is governed by Decree-Law No. 345 (November 2019) (GOC-2019-EX63). Its Third Section outlines prioritized RES, including sugarcane biomass, solar photovoltaic, wind energy, and other biomass applications. It also highlights distributed generation and cogeneration as key strategies to maximize RES integration into the national electric system (SEN).

Furthermore, the decree establishes that the primary economic criterion for investments will be a country-level cost-benefit analysis. Under this framework, Article 5 prioritizes investments in scientific research and technological innovation within the sector. Finally, the decree underscores the role of self-consumption and cogeneration in achieving the 24% share of RES in the energy mix by 2030 [10].

Cuba's current energy transition strategy, as outlined by [11], aims to achieve "a rapid shift toward energy sovereignty, security, and sustainability at minimal economic and environmental cost". Municipal development strategies (MDS)—mandated under Cuban law [12]—serve as key instruments for local implementation, while Decree 110/2024 institutionalizes five-year RES and efficiency programs [13]. Together, these frameworks underscore Cuba's commitment to reaching 24% RES penetration by 2030, though success hinges on decentralizing governance and empowering grassroots initiatives.

Cuba, with its dependence on imported fossil fuels, faces significant energy security issues. This dependence contributes to economic vulnerabilities and environmental degradation, highlighting the necessity for a transition toward renewable energy solutions. Hybrid renewable energy systems (HRES), which integrate multiple energy sources such as solar, wind, and biomass, offer a promising approach to address these challenges by enhancing energy reliability, reducing greenhouse gas emissions, and fostering local economic development [14]. However, the intermittency of renewables is a challenge in isolated areas, making hybrid microgrids (MHES) particularly valuable [15].

This research aims to analyse the viability of implementing HRES in Cuba, through a case study, focusing on its environmental and socioeconomic impacts, by leveraging Life Cycle Assessment (LCA) and input–output modelling. The study provides a comprehensive evaluation of both direct and indirect effects associated with these systems, offering valuable insights for policymakers and stakeholders interested in advancing sustainable energy solutions in the region. Furthermore, it contributes to the broader discussion on how local-level energy strategies can align with Cuba's national objectives for energy transition and the global agenda on sustainable development. In this context, the present study is based on the following hypothesis: integrating a hybrid renewable energy system (HRES), combining solar, wind, energy storage, and conventional backup (diesel), provides a more sustainable, reliable, and environmentally favourable energy solution for isolated Cuban communities such as Guasasa, compared to conventional diesel-only systems. This approach could reduce emissions, enhance energy security, and foster socioeconomic development in small remote communities.

2. Materials and Methods

The evaluation of environmental and socioeconomic impacts is fundamental to understanding the sustainability of HRES. In this work, the methodological approach for the sustainability assessment of the system combines two life cycle approach-based methodologies. First, environmental sustainability is assessed using the life cycle analysis method; otherwise, the socioeconomic impacts along the supply chain are calculated using an input–output methodology [16]. Both of them share the same supply chain or life cycle perspective and analyse the effects along the whole supply chain. This study employs two key methodologies: life cycle assessment (LCA) to assess the environmental impacts and the input–output model to evaluate the socioeconomic implications. These methods provide a holistic approach to analysing the feasibility and long-term benefits of the proposed system.

2.1. Life Cycle Assessment (LCA)

A life cycle assessment (LCA) was conducted to evaluate the environmental impacts associated with the hybrid renewable energy system, encompassing all phases from raw material extraction to end-of-life disposal. This methodology enables the quantification of greenhouse gas emissions, energy consumption, and resource depletion, thereby facilitating a comprehensive comparison between the existing fossil fuel-based energy system and the proposed hybrid configuration.

Life cycle inventory (LCI) data were sourced primarily from the Ecoinvent database (https://ecoinvent.org/, accessed on 19 May 2025) [17] and Social Hotspot Data Base (http://www.socialhotspot.org/, accessed on 19 May 2025) [18]. The assessment was performed using SimaPro software (SimaPro Analyst 9.6), a widely recognized LCA tool employed by researchers and practitioners for evaluating the environmental performance of technologies and products. In this study, SimaPro was instrumental in modelling the hybrid system and calculating the associated environmental impacts based on standardized midpoint and endpoint indicators (https://simapro.com/, accessed on 19 May 2025) for impact calculations; this tool is widely used by researchers, designers, environmental departments, and innovation teams to assess the sustainability of systems and products, and in this case, has been crucial for assembling the hybrid plant and obtaining the environmental impacts associated with it. The LCA framework ensures that environmental considerations, such as the carbon footprint and resource efficiency, are factored into decision-making processes.

The key steps in this work are structured around the four main phases of life cycle assessment (LCA): goal and scope definition, inventory analysis, impact assessment, and interpretation. The sequence of steps followed in this study is illustrated in Figure 1.

Figure 1. Overview of the methodological steps in the LCA process.

1. Data collection: environmental, technical, and social data were gathered from a variety of sources such as Ecoinvent [17] and SHDB [18], as well as national statistics and technical reports.
2. Inventory assembly: the detailed data on the equipment involved in the hybrid system were incorporated into the inventory [19].
3. Impact calculation: using SimaPro, the environmental, social, and economic impacts of the system were quantified for each life cycle phase [20].
4. Impact interpretation: the calculated impacts (e.g., carbon footprint, resource use, social effects) were used to inform decisions regarding the design, operation, and potential improvement of the hybrid plant [21].
5. Social impacts: the potential social consequences of sourcing materials, labour conditions, and community effects were considered [22].

2.1.1. Assumptions and Limitations of the Analysis

These assumptions and limitations aim to ensure the transparency and reproducibility of the present analysis. Although they are consistent with established modelling practices for hybrid energy systems in remote regions, the results should be interpreted within the scope of these constraints. Future research should incorporate sensitivity analyses to enhance the robustness of system optimization under a range of environmental, economic, and technological scenarios.

Assumptions

The analysis of the hybrid renewable energy system (HRES) proposed for Guasasa, Cuba, is based on the following technical, operational, and contextual assumptions:

- Local Climatic Conditions

The local climatic conditions of Guasasa, located in the southern coastal region of Matanzas Province, Cuba, present favourable characteristics for hybrid renewable energy deployment. Based on long-term datasets, the average wind speed at 10 m height is estimated at 5.0 m/s, according to the Global Wind Atlas and NASA meteorological datasets (https://globalwindatlas.info/en/, accessed on 17 August 2025). While this wind speed is moderate, it allows for the integration of small-scale wind turbines as part of the hybrid configuration, particularly when considered alongside other dispatchable sources such as biomass [23]. The average daily solar irradiance in the region is approximately 5.4 kWh/m^2/day. This high solar potential supports the effective operation of photovoltaic

(PV) systems throughout most of the year, aligning with findings from previous studies on solar energy resource availability in the Caribbean region [14,24]. Additionally, biomass availability in the Guasasa area has been assessed as sufficient to support continuous operation of a 10 kW gasifier for 8 h per day. This conclusion is based on the sustainable harvesting potential of local biomass species such as *yarúa*, *soplillo*, and *ocuje*, as well as previous field studies and laboratory analyses of biomass feedstock availability and energy content [14]. These species exhibit favourable combustion and gasification characteristics, supporting their use in small-scale community-level energy systems.

- Load Profile and Demand

The projected daily electricity demand for the Guasasa community is estimated at 437 kWh/day. This figure was derived by extrapolating from existing consumption data under a 12 h electricity supply regime, combined with assumptions regarding increased usage associated with the planned transition to a 24 h continuous supply. This method is consistent with approaches used in energy planning for remote or underserved communities undergoing electrification expansion [15]. Peak demand is estimated at 35 kW, aligning with observed demand curves [25].

- System Configuration and Operation

The diesel generator operates at a fixed output of 80 kW, continuously supplying part of the demand and stabilizing the system.

The photovoltaic (PV) plant of 40 kWp is split equally between direct AC supply and battery charging.

The 3 kW wind turbine assumed to operate at nominal capacity under average wind conditions.

The 160 kWh lithium-ion storage is sized for the short-term storage of excess PV output, and the depth of discharge is assumed to be 80%.

The biomass gasifier operates on a fixed daily schedule (10 kW for 8 h).

All renewable systems are integrated via Victron Energy inverters and monitoring equipment [26].

- Economic Parameters

The discount rate is 9%, reflecting typical rates for energy infrastructure in developing contexts.

The component costs are aligned with current international market prices; Cuba's import dependency is assumed to continue.

The labor costs within Cuba are low; local employment primarily affects the O&M phase.

- Environmental Analysis

The life cycle assessment (LCA) data were sourced from Ecoinvent v3 and the Social Hotspot Database (SHDB), modelled using SimaPro software.

The emission baseline of 1.14 $kgCO_2eq/kWh$ for diesel generation aligns with emission factors reported for medium-sized Tier III generators in the Ecoinvent v3 database under similar operational profiles [17]

The cumulative energy demand (CED) is calculated over full life cycle phases.

- Research period for the statistical data used

For demographic and energy consumption data related to the Guasasa community, we clarify that data were obtained from municipal reports and national statistical yearbooks covering the years 2020–2023.

For renewable resource availability (solar, wind, biomass), we specify the reference period of 2015–2023, based on the publicly available datasets and meteorological records.

For economic and environmental data used in the LCA, we indicate that the input–output tables and emission factors correspond to the most recent datasets available for Cuba, primarily from 2022 to 2023, unless explicitly stated otherwise.

Limitations

The study acknowledges the following methodological and contextual limitations, which may affect the generalizability or precision of the results:

- Load Data Uncertainty

The 24 h demand profile is extrapolated from limited measurements under current 12 h supply conditions; behavioural changes due to expanded access are estimated but not measured.

- Simplified Diesel Operation

We assume a constant 80 kW diesel output does not reflect a practical load-following generator operation, potentially overestimating the fuel consumption and emissions.

- Renewable Resource Variability

Solar and wind resources are based on long-term average datasets; site-specific anomalies, seasonal effects, and extreme weather events were not explicitly modelled.

- Battery Storage Constraints

The existing battery capacity (160 kWh) does not ensure full autonomy during extended periods without renewables. True 24 h autonomy for the current loads would require approximately 500 kWh usable capacity.

Battery degradation (capacity fade) and replacement cycles are not dynamically simulated.

- Economic Dependencies and External Factors

Heavy reliance on imported technology makes the system vulnerable to supply chain, policy, and currency risks.

The analysis excludes potential future changes in Cuba's energy policy or grid development.

- Excluded Technologies and Scenarios

Grid interconnection scenarios, which might affect the technical sizing, were not considered.

2.1.2. System Description

The hybrid renewable energy system (HRES) analysed in this study is designed as a hypothetical but realistic proposal tailored specifically to the energy needs and local conditions of Guasasa, Cuba, a small and remote community currently supplied with electricity for only 12 h per day via a diesel generator. Although the system has not been physically implemented, its configuration is grounded in actual resource availability, demand profiles, and logistical constraints characteristic of the area.

The proposed system integrates solar photovoltaic (PV), wind energy, and biomass-based generation, combined with a diesel backup generator. The division of renewable generation resources is supported by a detailed assessment of site-specific factors:

- Solar and wind capacities were dimensioned based on reliable resource datasets (SolarGIS v2, Meteonorm v7, NASA), recognizing the intermittent nature of these energy sources and the need to avoid oversizing in light of seasonal variations.

- Biomass potential was evaluated with consideration of locally available feedstocks (e.g., yarúa, soplillo, ocuje) and the logistical feasibility of sustainable collection and supply. The biomass unit complements the variable contributions of solar and wind by offering dispatchable renewable generation.
- The backup diesel generator was intentionally sized to cover the peak energy demand independently during adverse conditions when renewable resources may be insufficient (e.g., low solar irradiance, poor wind conditions, temporary biomass shortages). This reflects a conservative design approach typical for isolated microgrids where energy security is paramount, especially for critical services such as healthcare and water supply.

While this design may make the diesel generator appear disproportionate relative to the installed renewable capacity, this sizing strategy ensures system reliability under worst-case scenarios. In isolated communities like Guasasa, the lack of grid interconnection or rapid supply chains justifies this redundancy.

In the context of the life cycle assessment (LCA), this conservative sizing allows for a more realistic and comprehensive evaluation of environmental impacts [27]. It captures not only the potential environmental benefits of renewables but also the necessary reliance on fossil fuels under specific operating conditions, which is critical for assessing the true sustainability performance of the proposed system.

Data for the LCA were sourced from the Ecoinvent database and the Social Hotspot Database (SHDB), while socioeconomic analysis relied on Cuban economic data and input–output modelling.

The portion of an LCA study that is specific to the product the system being modelled is often called the foreground of the model, while the parts that reflect the industrial economy as a whole and are drawn from reference databases are the background [17]. The various factors influencing the system's operation are outlined below and further detailed in the following items. These include site characteristics (such as loads, topography, and available resources like biomass, solar, and wind); system components (including the biomass gasifier, generator set, photovoltaic generator, wind turbine, batteries, and electronic converter); and relevant economic parameters.

System Boundaries and Functional Unit

The system boundaries for this study follow a cradle-to-grave approach, encompassing all stages in the life cycle of the hybrid renewable energy system (HRES). This includes raw material extraction, manufacturing of components, transportation, construction and installation, operational use, maintenance, and end-of-life treatment (including decommissioning, recycling, and disposal). Both foreground processes (specific to the hybrid microgrid) and background processes (sourced from standard databases such as Ecoinvent and SHDB) are included within these boundaries to ensure consistency and completeness in the assessment.

The functional unit for this assessment is defined as 1 kWh of electricity delivered to the end-user. All environmental and socioeconomic impacts are calculated relative to this unit. This choice of functional unit provides a consistent basis for comparing the HRES with conventional energy supply systems and ensures that the results are meaningful and actionable from both technical and policy perspectives.

By establishing these system boundaries and the functional unit, this study ensures a robust and comprehensive evaluation of the environmental and socioeconomic impacts associated with the HRES throughout its full life cycle. This approach aligns with international standards and best practices in life cycle assessment and sustainability evaluation.

Site Characteristics

Site characteristics play a crucial role in determining the suitability and effectiveness of a hybrid energy system. Key factors include renewable energy potential in terms of the site's exposure to solar radiation, wind speed and direction, and available water resources for hydropower for maximising the use of renewable sources. Factors like terrain, soil type, and potential for grid connectivity influence the feasibility and cost of implementing these systems. An in-depth study was carried out by Geographic Information Systems (GIS) [24]. The study addressed all relevant aspects of the Guasasa community. This coastal community is located in the south of the country, in the municipality of Cienaga de Zapata in the province of Matanzas.

The placement and capacity of distributed energy units play a critical role in enhancing the overall efficiency of microgrids (MGs) [28]. In this study, site characteristics are defined as the comprehensive set of physical, social, technical, and resource-related factors that influence the design, operation, and performance of a hybrid energy microgrid. These factors are categorized as follows:

1. General Site Conditions
    - Geographic location: including GPS coordinates, accessibility, topography, and land conditions.
    - Existing infrastructure: assessment of current power systems and available buildings suitable for equipment installation.
    - Legal and environmental constraints: consideration of protected areas, aviation regulations, and potential environmental impacts (e.g., effects on local wildlife).
2. Socioeconomic Analysis
    - Demographics: population size, household distribution, and age/gender composition.
    - Economic activities: primary sources of income, such as fishing, forestry, and community services.
    - Community organization: the role of local institutions and stakeholders in project development.
    - Needs and motivations: specific demands, such as the transition from the current 12 h electricity supply to a continuous 24 h service.
3. Energy Consumption Analysis
    - Building typology: Type and number of residential and service buildings.
    - Energy usage patterns: Electrical appliances, typical loads, hours of operation.
    - Growth projections: Expected increase in energy demand over time.
4. Available Renewable Resources
    - Solar: potential assessed through databases such as Meteonorm and SolarGIS.
    - Wind: resources evaluated using datasets from NASA and the Global Wind Atlas.
    - Biomass: assessment of biomass availability, including carbon content, calorific value, considerations for collection and supply.
5. Technical and Installation Conditions
    - Land evaluation: suitability of the terrain for equipment installation and accessibility for transportation.
    - Grid integration options: feasibility of cable routing (overhead or underground) and identification of optimal connection points.
6. Load Characterization

The population of Guasasa comprises 214 residents distributed across 85 dwellings, in addition to essential community facilities such as a healthcare centre, pharmacy, school, and other collective-use buildings. Within this context, the project aims to extend the electricity supply from the current 12 h regime to a full 24 h daily supply. Although measurement campaigns were conducted to characterize the existing 12 h genset-based supply, the projected 24 h load profile for the microgrid was estimated to support the system design, as illustrated in Figure 2.

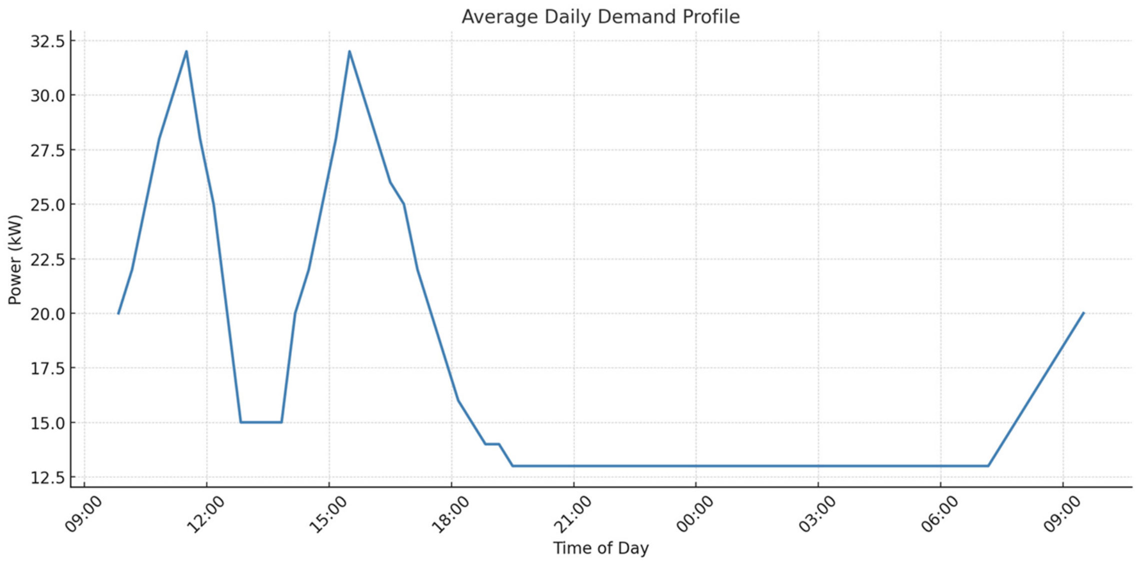

Figure 2. Estimated daily demand behaviour graph.

Characterization of Renewable Resources

The renewable resources considered in this study include solar, wind, and biomass. Their characterization is detailed below:

1. Solar Resource

   The assessment of solar potential was conducted using several well-established databases, including Meteonorm, NASA's Surface Meteorology and Solar Energy database, and the Global Solar Atlas powered by SolarGIS. These sources provide reliable data on solar irradiance and other relevant parameters for the selected location. This location receives about 1800–1970 kWh/m^2/year, according to global satellite data [29].

2. Wind Resource

   Two main data sources were used for wind characterization: NASA's meteorological database and the Global Wind Atlas. The Global Wind Atlas offers a variety of data, including wind roses, average wind speeds, and energy density at altitudes of 50, 100, and 200 m, along with GIS layers compatible with ArcGIS 10.8. However, since hourly average values are not provided, NASA's database was used for time-resolved wind data.

3. Biomass Resource

   The biomass resource assessment is based on several key parameters:

   Available biomass (tons/day): Biomass is assumed to be used as feedstock for a gasifier to generate syngas, which is then converted into electricity by generators. In Guasasa, the primary biomass sources include *yarúa*, *soplillo*, and *ocuje*. The available biomass is considered to exceed the plant's needs by a significant margin. The required biomass to meet the estimated electricity demand is calculated using the following formula:

$$\text{Biomass (kg/h)} = \text{Gas Consumption (kg/h)}/\text{Gasification Ratio (kg/kg)}.$$

The gas consumption is determined based on the generator's power output and fuel consumption curve. A gasification ratio of 1.89 kg/kg is used, as detailed in subsequent sections.

Average price: estimated at 120 CUP/ton, equivalent to 5 USD/ton (using an exchange rate of 1 USD = 24 CUP).

Carbon content (%): based on laboratory analyses, the average carbon content of the biomass is estimated at 48%, and this value is used consistently across calculations.

System Components

As noted above, in this work, the system is composed of a 40 kWp solar PV generator, 20 kWp of which are connected to the AC bus through two solar inverters, and the other 20 kWp are connected to the DC bus through the respective two charge regulators; there is one 3 kW wind turbine, a 10 kW gasifier, 50 kWh Li-Ion battery (the evolution of this technology through these years has made it possible to enter in the final configuration); there are three bidirectional converters 10 kW each, one for the gasifier and two for the microgrid; the role of the genset is performed by the grid, which is a particular bi-phase one; and includes also all the necessary equipment for the implementation of the microgrid. In Figure 3, a single line diagram for the layout of the final microgrid is shown.

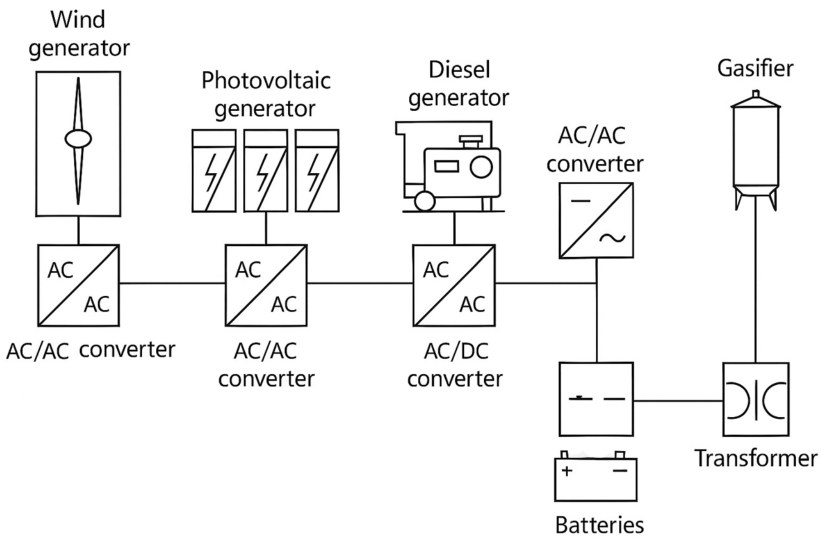

Figure 3. Single-line diagram optimised case.

1. Current Diesel Generator: The diesel generator will maintain the current generation level, providing a fixed amount of power (80 kW).
   For this analysis, we assumed it operates at a constant output.
2. Photovoltaic (PV) Plant
   - Capacity: 40 kW
   - Power distribution:
     - o 50% directly to the microgrid: 40 kW × 50% = 20 kW delivered to the grid.
     - o 50% to storage: 40 kW × 50% = 20 kW directed to storage for later use.
   - Storage: The storage system needs to be sized to accommodate this 20 kW input, depending on the expected charging time and the capacity required to meet demand during times of low solar generation (nighttime or cloudy weather). For example, if you need 8 h of storage, the required storage capacity would be 20 kW × 8 h = 160 kWh.
3. Biomass Gasification Plant
   - Capacity: 10 kW

- Operating time: 8 h a day (since it is a demonstration plant).
- Daily generation: 10 kW × 8 h = 80 kWh/day.
- The biomass plant will contribute 10 kW for the 8 h it is in operation. If the system requires continuous power, the biomass plant will provide a portion of that during its operational hours, and the other power needs will need to be fulfilled by other generation sources like the diesel generator, PV, or storage.

4. Wind Turbine
    - Capacity: 3 kW
    - Voltage output: 220 V AC, three-phase alternator with permanent neodymium magnets.
    - This turbine will generate 3 kW of power when operating at peak conditions. However, it is important to account for variable wind conditions; so, the actual output could be lower. In areas with intermittent wind, the turbine might not produce its full rated power all the time.

      The system supplies 545 kWh/day, exceeding the estimated demand (437 kWh/day) by 25% [24].
5. Sizing Considerations:
    - Total generation capacity:
        - o Diesel generator: unspecified but assumed to be part of the system's base load.
        - o Photovoltaic plant: 20 kW to the grid.
        - o Biomass gasification plant: 10 kW for 8 h.
        - o Wind turbine: 3 kW when operating.

    Total available generation (Peak): Diesel + 40 kW (PV) + 10 kW (biomass) + 3 kW (wind). Depending on the diesel generator's capacity, this could range from a minimum of 33 kW (if the diesel generator is not contributing additional power) to a larger total if the diesel is more powerful.

    - Energy storage requirements: As previously discussed, storing the output of the photovoltaic (PV) system requires careful sizing of the storage component. For instance, to store an output of 20 kW from the PV array over a duration of 8 h, a minimum storage capacity of 160 kWh is necessary, assuming ideal conditions and no system losses. In addition, the contribution of the wind turbine to the overall energy supply must be considered in the design of the storage system. Given the intermittent nature of wind energy, incorporating its variability into the storage model is essential to ensure system reliability and energy availability during low-generation periods.
    - Distribution and load management: The storage will likely need to be managed to balance the load during times when generation exceeds demand or when demand exceeds generation. A combination of energy management systems (EMS) and possibly power converters (like inverters for DC to AC) will be required to integrate the diverse generation sources and storage into the microgrid effectively.

Storage system:

At least 160 kWh to store the 50% output of the PV system (20 kW) for 8 h, ensuring energy is available when solar generation is low or demand exceeds production.

Load balancing:

Balancing the generation and storage system will ensure the microgrid can meet both peak and off-peak loads, especially considering intermittent wind and solar power. This configuration is intended to ensure a reliable power supply to the microgrid by combining renewable energy sources with conventional backup generation (diesel), while the inclusion of energy storage facilitates the management of fluctuations between energy supply and demand. In this sense, the different sources (diesel, solar, biomass, and wind) and storage are required to ensure a continuous power supply.

2.1.3. Inventory Analysis

The inventory analysis phase was conducted to compile and structure all necessary data required for evaluating both the environmental and social impacts of the hybrid plant under study. This inventory serves as the foundation for the subsequent impact assessment phases and was developed through a combination of primary data collection and secondary data sources, as outlined below.

Environmental data:

Collected from Ecoinvent, a global database containing comprehensive and consistent life cycle data for various processes, materials, and technologies.

Social data:

Gathered from the Social Hotspot Database (SHDB), which provides social impact data (e.g., working conditions, human rights) related to industries and materials used in the project.

National statistics and technical reports:

Data from these sources were used to monitor the project's evolution and to fill in any gaps in the environmental and social impact data.

Inventory Considerations

The inventory for this study includes a detailed catalogue and analysis of the specific equipment proposed for the hybrid energy system. To clarify the scope and assumptions, a structured comparison is provided between the existing energy system in Guasasa and the modelled future hybrid system. This comparison highlights differences in demand, generation capacities, and the roles of each subsystem in the energy balance. Table 1 summarizes the main components and operational assumptions for the photovoltaic (PV) subsystem and related infrastructure. It distinguishes between the actual situation (existing system) and the modelled scenario for future design under a 24 h energy supply target.

Table 1. Summary of components and operational assumptions for the system.

Aspect	Actual (Existing System)	Modelled (For Future Design)
Demand	~300 kWh/day (12 h)	437 kWh/day (24 h, projected)
Generation	Diesel-dominant	Diesel fixed + renewables modelled explicitly
Diesel Role	Full supply during 12 h	Constant 80 kW assumed (oversupply modelled)
Renewable Role	Small % of daily energy	Modelled to offset diesel where possible
Battery Role	Minimal influence	Short-term smoothing only, no autonomy modelled

In the existing system, diesel generation fully covers the energy needs during the 12 h supply window, with only minor contributions from renewables. In contrast, the modelled future scenario assumes a diversified generation mix where renewables are prioritized to reduce diesel reliance. The diesel generator remains intentionally oversized (80 kW) to ensure system robustness during periods of low renewable output, reflecting a conservative design choice appropriate for isolated rural microgrids. The battery system in the model is designed solely for short-term fluctuations and smoothing of the renewable output rather than providing long-term autonomy.

In addition to the functional assumptions presented in Table 1, the specific equipment inventory proposed for the hybrid energy system in Guasasa is detailed below. This inventory includes all primary components necessary for the installation of the photovoltaic

(PV), wind, and battery subsystems, as well as auxiliary systems required for monitoring, control, and energy management. The selection of components reflects realistic and commercially available technologies suited to the scale and technical requirements of the project. Table 2 provides a comprehensive list of the main components, including their type, model, and quantity.

Table 2. Detailed equipment inventory for the proposed hybrid energy system. Source: Equipment manufactured and distributed by Bornay Aerogeneradores SLU, Castalla (Spain).

Item	Description	Count
1	FV Sunrise SR-M660L—320 W Mono PERC Module	70
2	1-family floor-standing structure, 60 cell modules, Aluminium, Sunfer Energy Structures, SS915-5P	14
3	Junction kit	13
4	SmartSolar MPPT 450/100 controller	2
5	SMA Sunny Boy SB5.0 PV Inverter	2
6	Transformer	1
7	Wind Turbine Bornay Wind 25.3+	1
8	MPPT regulator Wind 25.3+	1
9	Four-legged self-supporting tower	1
10	Battery Pylontech US3000C 48V 3500 Ah	14
11	Rack 19′—7 elements	1
12	Quattro 48 V/10,000 W/100–120 V 60 Hz	3
13	Cerbo GX	1
14	GX Touch 50 display	1
15	Current sensor/intensity monitoring Gasifier/Wind turbine	4
16	Weather station (2 radiation, 2 temperature, 1 anemometer, 1 direction)	1
17	RJ 45 cable—5 mts.	10
18	Cable type VE. Can Type A Pylontech/Cerbo 5 mts.	1

This equipment inventory constitutes the foundational input for the modelling of the system's environmental and operational performance within the frameworks of life cycle assessment (LCA) and socioeconomic analysis. The selection of components was guided by the criteria of technical compatibility, durability, and appropriateness for off-grid and remote applications, thereby ensuring the credibility and realism of the proposed scenario.

2.1.4. Environmental Impact Assessment

Once the inventory of the hybrid plant system was compiled and quantified, the next step involved evaluating the most significant environmental impacts associated with the system. This process focused on assessing impact categories that are most relevant to the system and that could be characterised based on the available data. For this analysis, the environmental impacts were assessed using the following key indicators:

- Environmental footprint

The environmental footprint quantifies the potential impacts that a specific activity, system, or organization exerts on the environment, with particular attention to key environmental pressures [30]. In this study, the analysis focuses on the following impact categories: ozone depletion, acidification, eutrophication, water scarcity, and climate change. These categories capture critical environmental burdens related to emissions and resource consumption throughout the life cycle of the hybrid energy system. The assessment aims to provide a comprehensive understanding of how the system contributes to or mitigates these environmental issues, thereby informing strategies for reducing its overall environmental impact.

- Climate change (global warming potential, GWP):

This indicator focuses on the greenhouse gas emissions produced throughout the life cycle of the system [31]. It quantifies the contribution of the hybrid plant to global warming by evaluating the emissions of carbon dioxide (CO_2), methane (CH4), nitrous oxide (N_2O), and other greenhouse gases.

- Cumulative energy demand (CED)

This indicator measures the total energy consumption over the life cycle of the system, taking into account both the direct and indirect energy inputs required for the production, operation, and disposal of the equipment used in the system [32]. CED includes energy from all sources (renewable and non-renewable) and helps to evaluate the overall energy intensity of the hybrid system.

2.2. Socioeconomic Analysis

The socioeconomic analysis was carried out using the EORA Multi-Regional Input–Output (MRIO) database to assess the economic and employment impacts associated with the deployment of the proposed hybrid renewable energy system. This approach enables the estimation of direct, indirect, and induced effects in terms of job creation, value-added, and domestic economic linkages. A multiregional input–output method (MRIO) was employed to assess the economic impacts, estimating employment generation and production multipliers based on Cuban economic data. The input–output methodology, originally developed by Wassily Leontief, analyses interdependencies between economic sectors, providing insights into how investments in renewable energy systems influence job creation, value-added production, and economic stimulation [33].

By integrating cost specific data into a multi-country perspective, this study estimates both direct and indirect economic effects, both inside Cuba and abroad, considering how renewable energy investments contribute to broader economic activity. MRIO tables usually cover developed countries due to data unavailability. Cuba is not represented in almost any publicly available MRIO table. Hence, the EORA database has been used as the source of the MRIO [34]. This is a balanced global MRIO dataset, which includes 26-sector harmonized classification for each country covered, for a complete timeseries for 1990–2022 in its latest edition. The year 2016 was selected as the baseline for this analysis due to its alignment with multiple components of the broader HIBRI2 project framework. Specifically, the technical and economic parameters of the hybrid system (e.g., component costs, fuel prices, system sizing) were developed using 2016 as the reference year within HIBRI2, ensuring internal consistency across datasets. The EORA MRIO database, used for socioeconomic modelling, provides complete and harmonized data for Cuba up to 2016. It is the most recent year for which reliable disaggregated economic data are available in this format. Climatic and geospatial datasets used in related modules of the project (e.g., solar and wind resource mapping, infrastructure analysis) were also benchmarked to this period.

This dual-method approach (LCA and MRIO) ensures a comprehensive assessment of both environmental sustainability and socioeconomic viability, providing a solid foundation for policy recommendations and future energy planning in Cuba.

3. Results

The proposed hybrid system reduces greenhouse gas emissions by 60%, from 1.14 to 0.47 kg CO_2eq/kWh, aligning with Cuba's commitments under the Paris Agreement. Additionally, the system reduces fossil energy consumption by 50%, demonstrating its potential to enhance energy security and sustainability. The socioeconomic analysis reveals that the system generates 40.3 jobs, with the majority of initial investment benefits accruing to foreign suppliers. However, the operation and maintenance phases offer significant opportunities for local employment, highlighting the need for workforce training and capacity-building. The results of the different components of the study are described in detail below.

3.1. Environmental Impact Assessment

The environmental performance of the hybrid energy system was assessed across key impact categories, namely ozone depletion, acidification, eutrophication, water scarcity, and climate change.

3.1.1. Environmental Footprint

This indicator measures the impact an individual, organisation, or activity has on the environment, specifically how many natural resources they consume and how much waste they produce. The distribution obtained by components is shown in Figure 4.

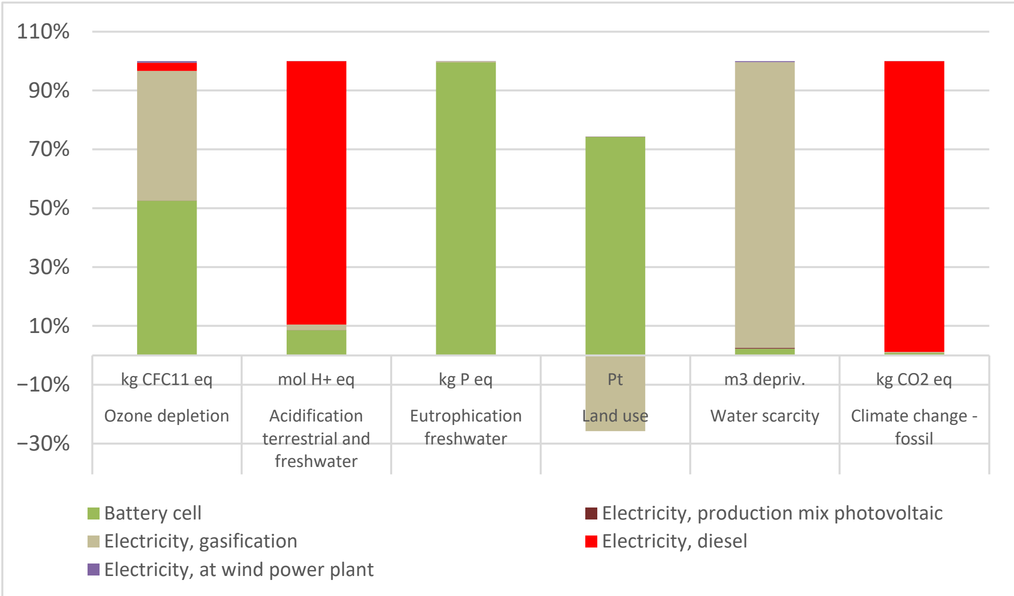

Figure 4. Environmental footprint of the system. Distribution by component.

The analysis reveals that diesel-based electricity generation is the predominant contributor to acidification and climate change impacts, accounting for over 90% of the burden in both categories. This outcome is consistent with the well-documented emissions profile of diesel combustion, which includes high levels of sulphur and nitrogen oxides as well as significant greenhouse gas emissions. Battery systems represent the primary source of impacts in ozone depletion and freshwater eutrophication categories, largely due to upstream processes associated with raw material extraction and manufacturing. In particular, the battery contribution to ozone depletion reaches approximately 50%, while its contribution to eutrophication exceeds 90%. Gasification, although intended as a renewable energy source, emerges as the main contributor to water scarcity impacts, reflecting the water-intensive nature of biomass processing technologies, particularly for cooling and gas cleaning. In contrast, photovoltaic and wind energy technologies exhibit negligible contributions across all categories assessed, reaffirming their relatively low environmental burdens during operation. These findings highlight that, while the hybrid renewable energy system significantly reduces greenhouse gas emissions compared to diesel-only scenarios, the integration of storage and biomass components introduces specific environmental trade-offs. Careful consideration of these trade-offs is essential to optimize the system's overall environmental performance, particularly in relation to battery production and water use for gasification.

3.1.2. Climate Change (Global Warming Potential, GWP)

The goal was to assess how the system's generation sources (e.g., diesel, PV, biomass, wind) contribute to climate change. Figure 5 shows the climate change impact of the system in gCO_2eq/kWh.

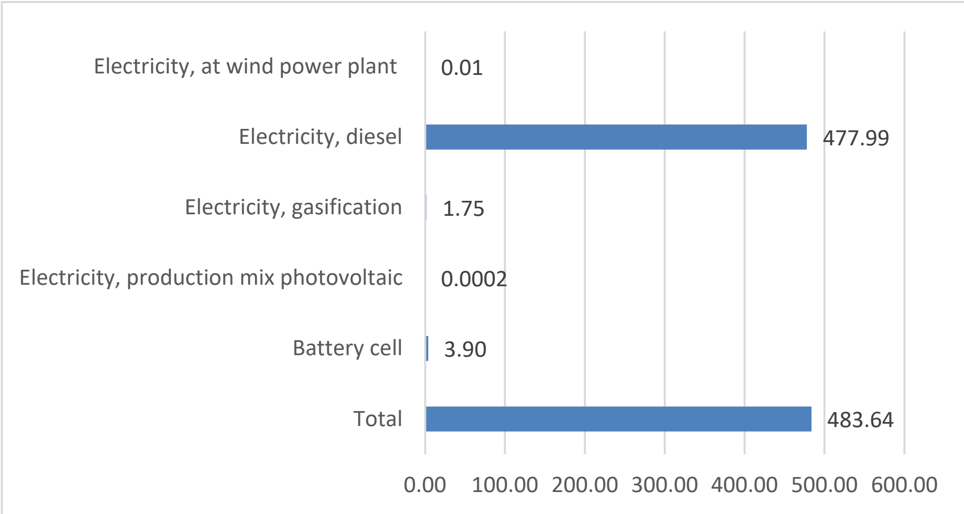

Figure 5. The climate change impact of the system by component.

Figure 5 illustrates the contribution of each subsystem within the hybrid renewable energy system (HRES) to the overall climate change impact, expressed in grams of CO_2-equivalent per kilowatt-hour (gCO_2eq/kWh). The results clearly indicate that diesel-based electricity generation is the primary contributor to greenhouse gas emissions, accounting for 477.99 gCO_2eq/kWh, which represents approximately 99% of the total climate impact (483.64 gCO_2eq/kWh). This finding highlights the substantial environmental burden associated with the continued reliance on diesel as a backup energy source, despite the integration of renewable energy technologies within the system. In contrast, the contributions from renewable components are negligible, with photovoltaic and wind systems contributing only 0.0002 and 0.01 gCO_2eq/kWh, respectively, underscoring their minimal impact on climate change relative to fossil-fuel-based generation. The gasification subsystem accounts for 1.75 gCO_2eq/kWh, reflecting the emissions linked to the energy and resource inputs required for biomass conversion. Similarly, the battery storage system contributes 3.90 gCO_2eq/kWh, largely due to upstream processes such as material extraction and manufacturing rather than operational emissions. These results emphasize that, although the integration of renewable technologies reduces the dependency on fossil fuels, the current system configuration remains heavily reliant on diesel generation, thereby limiting the potential for meaningful reductions in greenhouse gas emissions. Future system designs should prioritize further reductions in diesel use through increased renewable energy penetration, enhanced storage capacity, and improved energy management strategies to achieve more significant climate benefits.

The analysis confirms that the proposed system significantly reduces greenhouse gas emissions by close to 60% lowering emissions from 1.140 to 0.484 g CO_2eq/kWh. This improvement requires a deep understanding of the emission sources for further improvements. (See Figure 6).

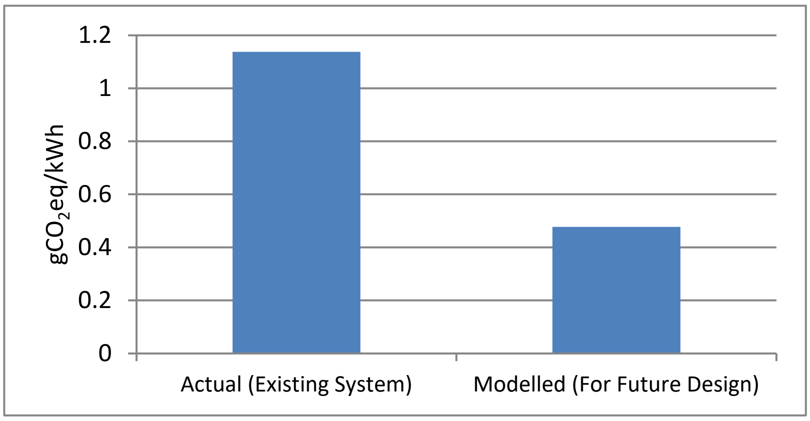

Figure 6. Comparative analysis of the systems under study.

The results presented in Figure 6 demonstrate a substantial reduction in greenhouse gas emissions achieved through the implementation of the proposed hybrid renewable energy system. Specifically, the emissions decrease from 1.140 gCO_2eq/kWh in the current system to 0.484 gCO_2eq/kWh in the proposed configuration, representing an approximate reduction of 60%. This significant improvement highlights the potential of integrating renewable energy sources and optimized system design to mitigate climate change impacts in isolated communities. However, achieving further reductions will require a detailed understanding of the specific sources of emissions within the system, particularly those related to the backup diesel generator and battery storage life cycle impacts. These insights are essential to guide future developments toward even more sustainable and resilient energy solutions.

In this sense, potential optimisations can be identified, such as

- Increasing the share of renewable energy.
- Improving the system efficiency.
- Reducing indirect emissions from energy storage or backup sources.

3.1.3. Cumulative Energy Demand (CED)

The CED analysis was conducted by evaluating the specific energy requirements associated with the operation of each individual component within the hybrid energy system. These components include the diesel generator, photovoltaic (PV) system, biomass gasification unit, wind turbine, and battery storage. As illustrated in Figure 7, the results reflect the distinct contribution of each technology to the overall energy demand, highlighting the influence of both renewable and non-renewable sources within the system's life cycle. This breakdown enables a more precise understanding of which components are the most energy-intensive and where potential improvements could further enhance the system's energy efficiency and sustainability performance.

For this indicator, the results indicate that the proposed system reduces fossil energy consumption by approximately 50% compared to the current diesel-based system, as can be seen in Figure 8.

The results suggest that the proposed hybrid renewable energy system achieves a reduction of approximately 50% in fossil energy consumption when compared to the current diesel-based system. This significant decrease is attributed to the integration of renewable energy technologies, which substantially lessen the reliance on fossil fuels. As illustrated in Figure 8, this improvement underscores the potential of hybrid systems to enhance energy sustainability, particularly in remote communities where traditional energy solutions are heavily dependent on diesel generation. Finally, there is the potential for further optimisation, considering that some fossil energy is still being used (e.g., backup generators, grid electricity), where further reductions could be explored through increased renewable integration, energy storage solutions, or demand-side management.

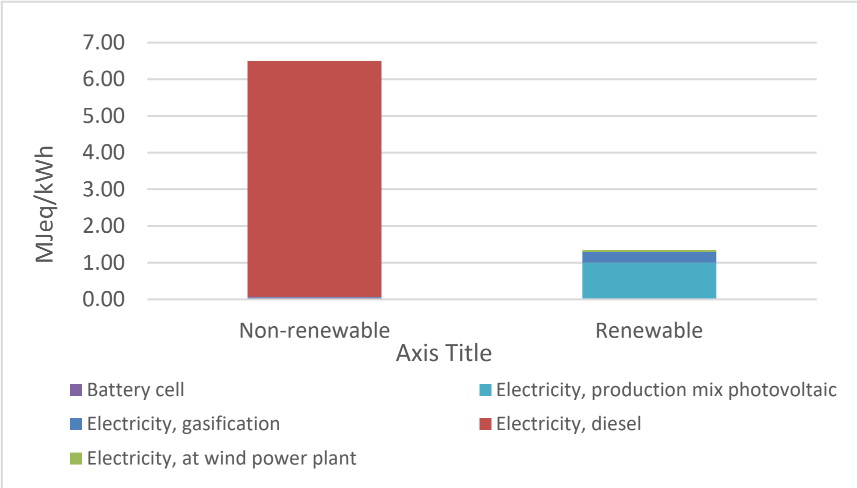

Figure 7. CED. Renewable and non-renewable contribution by source. Current system.

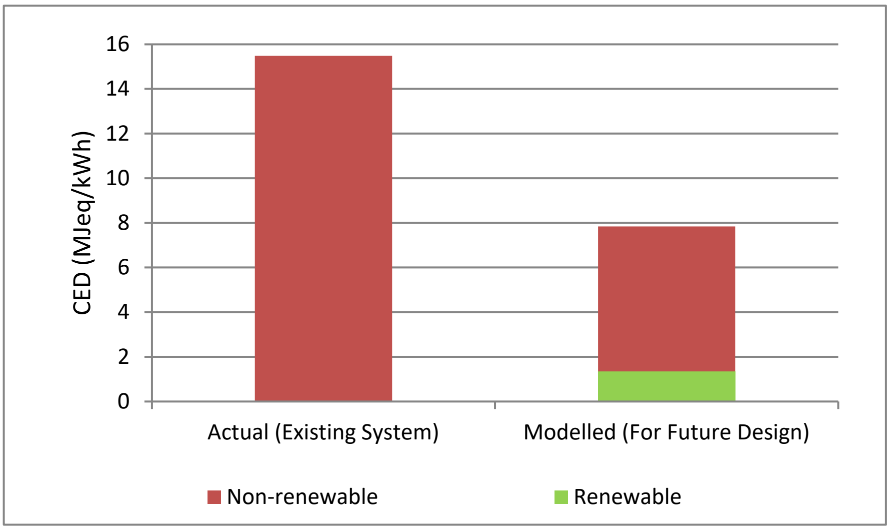

Figure 8. CED comparative for the systems under study.

3.2. Socioeconomic Impact

In the case of the HIBRI2 project (https://hibri2.portales.ciemat.es/, accessed on 20 May 2025), the initial investment (the investment costs, including the diesel generator already installed, and an estimate of the operating and maintenance cost streams, duly discounted to present values) amounts to USD 336,264. Cuba imports almost all of the necessary components and spends a miniscule amount on transporting the biomass. In this sense, the countries that benefit most are Venezuela (we assume that the diesel comes from that country), followed by China (generator, batteries and transformers), India (biogas gasifier), Germany (photovoltaic generator), and Spain (wind turbine) (see Figure 9, first bar). We bring the investment to the net present value (at a discount rate of 9%) to assess the socioeconomic impacts.

The initial investment entails the purchase of components produced through complex manufacturing processes. The concept of value added helps redistribute this investment by tracing the origin of labour and capital compensation associated with each good or service involved. In this context, the value added reflects the contribution of global value chains and highlights the significance of international trade in intermediate goods from the rest of the world for the production of final goods and services (see Figure 9, second bar).

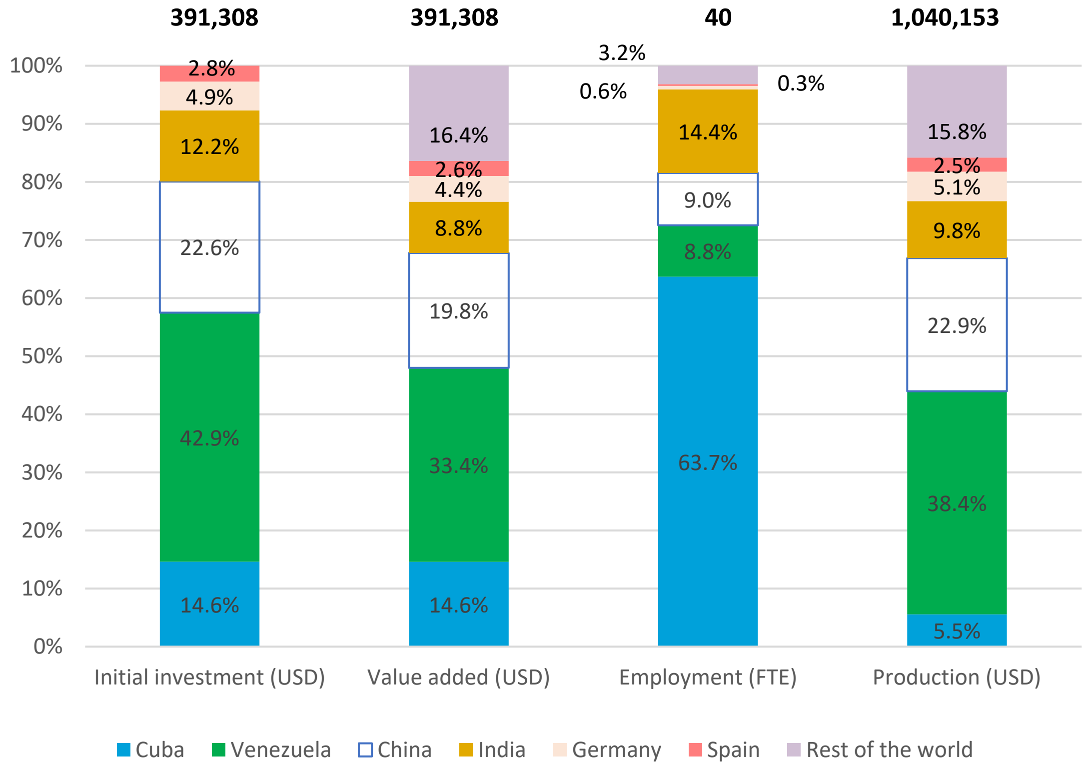

Figure 9. Socioeconomic impacts from HIBRI2 deployment.

In terms of employment, and excluding jobs within the plant itself, nearly 15 full-time equivalent (FTE) jobs would be generated directly and indirectly throughout the process and the life cycle of the hybrid plant. Although these figures are estimates and subject to the limitations of the input–output methodology, they provide a useful indication of the potential employment impacts. India appears to be one of the biggest beneficiaries, due to its employment-intensive production structure. The rest of the world also generates 1.3 jobs despite not having directly stimulated final demand in this region. Overall, almost all employment is generated outside Cuba. Employment indicators such as jobs/million USD or jobs/MW installed are within the range offered by other similar studies in the literature [35]. Specifically, almost 44 jobs/million USD and 102 jobs/MW. Recall that these data include indirect jobs.

Estimating in-plant employment for the operation and maintenance phase, there is a very sharp increase in job creation in Cuba (see Figure 9 third column). However, this should not be interpreted solely as a signal of improved economic opportunity, since it is partly driven by the country's low labour costs and high labour intensity. Assuming labour costs of around 55,000 USD as well as an annual salary per worker of 2152 USD over the 20-year life of the hybrid plant, 63.7% of the employment generated would be in Cuba. This increases the two indicators previously mentioned considerably: 103 jobs/million USD, and more than 280 jobs/MW. These values are consistent with, or above, international benchmarks for solar PV, biomass, and hybrid systems in labour-intensive economies. These figures are subject to uncertainty, due to data limitations concerning Cuban compensation of employees. However, the key message remains the same: employment generation in Cuba comes hand in hand with plant employment.

Although it cannot be derived from our results, recent evidence suggests that hybrid renewable energy systems (HRES), which combine technologies like solar, wind, and biomass, tend to generate more and more diverse employment than single-technology systems. Their complexity supports sustained local jobs in areas such as operations, fuel supply, and grid management. Evidence from rural regions in Asia, Africa, and Latin America [36] shows that HRES can create 30–90 direct local jobs per project, while fostering community participation and skills training, which translates into jobs per installed MW ranging from 180 to 4800. Unlike centralized systems that depend on imports and external contractors, HRES often promote local sourcing and ownership, making them especially valuable for rural development and inclusive energy transitions—even in contexts with high import dependency, as seen in Cuba [37,38]. The Cuban case analysed in this paper confirms that even in a highly import-dependent context, hybrid systems can deliver strong socioeconomic returns through employment and local economic activity, particularly during the operational phase.

From the obtained results, we see that the impacts on production are remarkable: this investment exerts a multiplier effect of 2.66 on production, which means that one monetary unit invested in the project triggers 2.66 times the effects on production (including indirect linkages).

The benefits in terms of value-added retention and job creation would be much greater if Cuba could develop a domestic industry in renewable energy manufacturing. Currently, dependence on foreign components negatively influences their participation in creating growth and employment, as well as the very sustainability of the facilities. However, in terms of energy security and achieving goals towards energy decarbonisation, this is a positive example for the country.

Table 3 summarises in full the results obtained, highlighting the top contributors to value-added creation, jobs, and the increase in production. Jobs in Cuba (approximately 26 employees) are likely to be located locally or regionally, since practically all employment creation is subject to in-plant tasks.

Table 3. Socioeconomic impacts of HIBRI2 deployment.

	Region	Initial Investment (USD)	Value Added (USD)	Jobs (FTE)	Production (USD)
In the value chain	Cuba	2132.5	2048.8	0.1	2564.3
	Venezuela	167,789.1	130,700.5	3.6	399,638.4
	China	88,373.2	77,334.8	3.6	238,257.5
	India	47,892.4	34,476.4	5.8	102,039.8
	Germany	19,336.7	17,360.1	0.2	52,880.2
	Spain	10,740.9	10,119.8	0.1	25,156.0
	Rest of the world	0.0	64,224.3	1.3	164,573.8
In plant	Cuba	55,043.4	55,043.4	25.6	55,043.4
TOTAL		391,308.1		40.3	1,040,153.3

Although the initial investment is made in the aforementioned countries (Venezuela, India, Germany, and Spain), due to the fragmentation of value chains, the value added to satisfy the initial investment is created in these countries as well as abroad. For example, although the PV generator may be produced in Germany, the intermediate inputs and jobs required to produce the generator come from both German and foreign producers. Thus, the value added is created partially in Germany and partially abroad.

4. Discussion and Conclusions

The findings of this study align with previous research on hybrid renewable energy systems, which have demonstrated significant environmental and economic benefits in other regions [34]. However, the unique socioeconomic context of Cuba presents both challenges and opportunities. While the majority of initial investment benefits accrue to foreign suppliers, the long-term economic benefits of local job creation and energy security are substantial. Policymakers should consider strategies to incentivize local manufacturing of renewable energy components, such as tax breaks or subsidies for domestic producers. Additionally, workforce training programs could enhance the local capacity for system operation and maintenance, further maximizing the socioeconomic benefits of renewable energy investments.

Comparisons with the existing literature confirm the emission reduction potential of hybrid energy systems [39]. Previous studies highlight that the integration of renewable energy sources in microgrids can significantly decrease the reliance on fossil fuels, leading to lower emissions and increased energy resilience. The findings of this study align with these conclusions, demonstrating that hybrid systems can achieve substantial environmental benefits in the Cuban context.

In addition to environmental advantages, the economic impacts of the proposed system reveal critical insights. While the majority of the initial investment benefits foreign suppliers due to Cuba's reliance on imported components, the long-term benefits in job creation within the country are noteworthy. The operation and maintenance phase of the system provides the most significant employment opportunities, emphasizing the need for local workforce training and capacity-building to maximize the socioeconomic benefits of renewable energy investments.

The socioeconomic assessment highlights the fragmented nature of value creation associated with the hybrid renewable energy system (HRES) deployed in Cuba. Although the initial investment of USD 336,264 mainly benefits foreign suppliers (from countries such as Venezuela, China, India, Germany, and Spain), the distribution of the value added across global supply chains underscores the importance of international trade in intermediate goods. Even regions not directly involved in the final purchase capture value, revealing the complexity of global value chains. These findings stress the importance of considering embodied value chains in renewable energy investments, particularly in small economies like Cuba's that are heavily dependent on imports.

Despite the low local content during the investment phase, the long-term local socioeconomic benefits are significant. Over the 20-year operational period, around 26 full-time equivalent (FTE) jobs are created in Cuba—63.7% of total employment—mainly in operation and maintenance, which are essential for system reliability.

From a macroeconomic perspective, the investment yields an employment multiplier of over 100 jobs per million USD invested when in-plant jobs are included, which aligns with comparable international benchmarks. Moreover, the production multiplier of 2.66 indicates a strong ripple effect across the economy, further validating the investment's contribution to economic activity.

Despite the promising socioeconomic and environmental benefits associated with hybrid renewable energy systems, several barriers and risks may hinder their large-scale deployment in Cuba. Institutional capacity limitations, such as limited technical expertise, slow administrative procedures, and fragmentation across regulatory bodies, can delay implementation and maintenance. Political and economic constraints, including limited access to international financing, trade restrictions, and currency instability, also affect procurement and long-term sustainability.

A major limitation is Cuba's continued dependence on foreign technologies, as evidenced by the high share of imported components in the investment phase. This reliance undermines energy sovereignty and exposes the system to supply chain disruptions and price volatility. Overcoming this will require strategic investment in local manufacturing, technology transfer, and vocational training to gradually build domestic capabilities.

In addition, HRES in island or coastal regions like Guasasa are particularly vulnerable to natural disasters, such as hurricanes and floods, which can damage infrastructure and disrupt supply, as well as technical challenges due to their complexity, such as component failures or limited spare parts. To ensure reliable operation and successful scale-up, it is essential to complement financial and technological support with strong local maintenance capacity, resilient institutions, and robust supply chains. Acknowledging these risks is key to designing effective policies, as the success of HRES depends on systemic readiness across governance, workforce, logistics, and regional resilience.

The findings of this study can be contextualized by examining similar experiences in other Latin American and island-based developing countries, where hybrid renewable energy systems have been deployed under comparable socioeconomic and geographic conditions. In particular, Pacific Island states have developed hybrid mini-grid systems that combine solar, diesel, hydro, and storage to reduce reliance on fuel imports and improve energy reliability in isolated coastal communities These systems are operated with strong community participation and have contributed to job creation, capacity-building, and energy independence [40–42].

These international cases echo the key conclusions drawn from the Cuban case examined in this paper: namely, that hybrid systems offer significant socioeconomic benefits, particularly in remote and underserved areas, but their success depends on institutional support, community involvement, and long-term planning to overcome structural constraints. As such, the Cuban experience contributes to a growing body of evidence demonstrating that hybrid renewable energy systems are a viable and scalable solution for energy access and sustainable development in isolated and vulnerable territories.

Future research should explore the scalability of HRES across different regions of Cuba, considering variations in resource availability and economic conditions. Additionally, further investigation into policy frameworks and financial mechanisms could facilitate the large-scale adoption of renewable energy technologies in the country.

Beyond the quantitative results, future research should incorporate qualitative indicators and mixed methods approaches to better capture the broader socioeconomic impacts of hybrid renewable energy systems. While input–output models and employment multipliers reveal economic trends, they overlook aspects like well-being, energy affordability, and community empowerment. Including indicators such as income changes, user satisfaction, and life satisfaction—alongside surveys and participatory methods—would provide a more comprehensive understanding of how these systems influence social resilience, equity, and local development.

In conclusion, this case study demonstrates the potential of hybrid renewable energy systems (HRES) not only to reduce environmental impacts but also to generate significant socioeconomic benefits in Cuba. The integration of multiple renewable energy sources enables more reliable and resilient electricity supply, especially in remote and underserved areas. The findings confirm that HRES can create sustained local employment and increase the value added through diverse supply chains. Comparisons with similar contexts in Latin America and island nations—such as Haiti, Fiji, and Vanuatu—suggest that these benefits are generalizable across other developing and insular regions.

However, scaling up HRES in Cuba faces important barriers, including dependence on imported technologies, vulnerability to natural disasters, limited institutional capacity, and access to financing. Addressing these challenges requires coordinated policy interventions to support local manufacturing, workforce training, and resilient infrastructure development. Additionally, future research should adopt mixed method approaches to capture broader impacts, including qualitative dimensions such as household income, perceived quality of life, and energy affordability. By combining environmental gains with inclusive development, HRES represent a viable pathway toward a just and sustainable energy transition in Cuba and similar settings.

Finally, this study does not aim to provide a macro-level analysis representative of Cuba as a whole. Instead, it focuses on the specific case of the small and remote community of Guasasa to assess the environmental and socioeconomic impacts of a localized hybrid renewable energy system (HRES) installation. Guasasa serves as a case study, highlighting the unique challenges and opportunities associated with deploying decentralized renewable energy solutions in isolated rural contexts. The results emphasize that site-specific factors—such as social organization, patterns of energy demand, available natural resources, and existing infrastructure—play a decisive role in determining the viability and performance of such systems. While the insights gained from this research may inform similar projects in other Cuban communities with comparable conditions, generalizing these findings to the national scale is not appropriate without further studies that reflect the country's broader regional diversity in social, economic, geographic, and technical aspects.

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Abbreviations

The following abbreviations are used in this manuscript:

CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Spain)
HRES	Hybrid Renewable Energy Systems
LCA	Life Cycle Assessment
SDG	Sustainable Development Goal
RES	Renewable Energy Sources
MEMS	Municipal Energy Management System
SEN	Electrical National System (Cuba)
MDS	Municipal Development Strategies
MG	MicroGrids

MHES	Hybrid Microgrids
SHDB	Social Hotspot Data Base
GPS	Global Position System
NASA	National Aeronautics and Space Administration (USA)
GIS	Geographic Information System
CUP	Cuban Peso
PV	Photovoltaic
EMS	Energy Management System
AC-DC	Alternating Current/Direct Current
PERC	Passivated Emitter and Rear Contact Solar Technology
GWP	Global Warming Potential
CED	Cumulative Energy Demand
MRIO	Multiregional Input–Output Method
HIBRI2	Integrated Control System for Energy Supply Through Hybrid Systems in Isolated Communities in Cuba. Phase II
FTE	Full Time Equivalent (Jobs)
CUBAENERGIA	Cuban Center for Information Management and Energy Development
CUBASOLAR	Cuban Society for the Promotion of Renewable Energy Sources and Respect for the Environment

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