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Design and Evaluation of a Solar Campus Model for Energy Efficiency and Environmental Sustainability

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Abstract

The transition to clean energy sources has been recognized as essential for mitigating climate change, and higher education institutions (HEIs) play a key role in promoting regional sustainability. In this context, the UCATECI Solar Campus Project represented a strategic initiative aimed at reducing the carbon footprint within the Dominican education sector. The objective of this study was to describe the implementation of the UCATECI Solar Campus photovoltaic system and evaluate its initial impact on energy efficiency and emissions reduction. A descriptive methodology was applied, based on monitoring the system installed on the university campus in La Vega, Dominican Republic. The system consisted of 1920 solar panels and 17 inverters, with an installed capacity of 624.85 kilowatts peak (kWp). Energy consumption and carbon dioxide (CO_2) emissions were evaluated before and after the replacement of conventional equipment with high-efficiency technologies, including inverter-based systems and LED lighting. The results showed a reduction in annual energy consumption from 1,200,000 kWh to 840,000 kWh (−30%), photovoltaic generation of 820,000 kWh/year, a self-consumption rate of 68%, and a reduction in emissions of approximately 467 t CO_2/year. The investment represented approximately 35% of the institutional budget, reflecting a strong strategic commitment to sustainability. In conclusion, the UCATECI Solar Campus Project constituted a successful and replicable model of energy transition for higher education institutions, demonstrating sustainability and adaptability.

Subject Areas

Renewable Energy, Environmental Science, Sustainability, Energy Engineering, Climate Change Mitigation

Keywords

Solar Campus, Photovoltaic Systems, Energy Efficiency, Carbon Footprint Reduction, Higher Education Institutions

1. Introduction

The growing global demand for energy, coupled with the urgent need to address climate change, has placed a critical demand on all sectors to decarbonize their operations. In the context of Latin America and the Caribbean, the energy mix still relies heavily on fossil fuels, exacerbating the region's environmental and economic vulnerability. Within this framework, higher education institutions (HEIs) have a dual responsibility: to lead by example in sustainable practices and to mitigate their own institutional environmental impact.

The Catholic University of Cibao (UCATECI) faced this challenge due to its high dependence on the conventional electrical grid for its daily operations, resulting in a significant carbon footprint. This situation, common among higher education institutions in developing countries, highlights the need to implement large-scale renewable energy solutions.

The imperative of sustainability in higher education institutions has been formalized through the 2030 Agenda for Sustainable Development [1]. The UCATECI Solar Campus Project directly contributes to several Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action), by promoting the integration of renewable energy, optimizing campus infrastructure, and reducing greenhouse gas (GHG) emissions.

Previous regional and international studies have demonstrated that integrating photovoltaic (PV) infrastructure on university campuses not only improves energy efficiency but also strengthens institutional social responsibility [2] [3]. Furthermore, the Economic Commission for Latin America and the Caribbean [4] underscores the urgent need to improve energy efficiency in the sector, an objective addressed by the UCATECI project through the combined implementation of photovoltaic generation, inverter-based technologies, and LED systems.

At the national level, the Dominican Republic possesses significant potential in solar energy, as highlighted by the International Renewable Energy Agency [5] and reports from the National Energy Commission [6]. In this context, the UCATECI Solar Campus Project, representing an investment of approximately 35% of the institutional budget [7], not only constitutes an energy solution but also a didactic and replicable model for energy transition for higher education institutions in the country.

The project consists of a photovoltaic system installed on the university campus in La Vega, Dominican Republic, comprising 1920 solar panels and 17 inverters, with a total installed capacity of 624.85 kWp. The methodological approach included replacing conventional equipment with inverter-based technologies and LED lighting, as well as implementing continuous monitoring systems to evaluate energy performance.

Therefore, the main objective of this study was to describe the implementation of the UCATECI Solar Campus Project and analyze its preliminary results, focusing on the energy efficiency achieved, the reduction of CO_2 emissions and the strategic alignment of institutional investment with global and regional sustainability goals.

2. Literature Review

Recent studies have highlighted the fundamental role of higher education institutions (HEIs) in advancing sustainability and reducing greenhouse gas emissions through energy transition strategies. Universities are increasingly seen as "small cities" due to their high energy consumption and complex infrastructure, making them ideal environments for implementing renewable energy solutions [8] [9].

One of the most widely adopted strategies has been the integration of photovoltaic (PV) systems into university campus infrastructure. Empirical evidence demonstrates that implementing PV systems significantly improves energy efficiency and reduces dependence on fossil fuels. For example, PV systems installed on university campus rooftops have achieved self-sufficiency rates of up to 35%, and some buildings even exceed 60%, depending on energy demand and architectural design [10]. Furthermore, integrated energy management systems, combined with PV technologies, have been shown to optimize energy consumption at the campus scale [11].

Beyond energy efficiency, photovoltaic systems contribute substantially to reducing the carbon footprint. Recent research indicates that institutional carbon footprint assessments are essential tools for guiding sustainability strategies, with the adoption of renewable energy being one of the most effective mitigation measures [12]. Case studies conducted within environmental, social, and governance (ESG) frameworks report annual reductions exceeding 500 - 600 tons of CO_2 emissions, with statistically significant improvements in energy performance indicators ($p < 0.05$) [13].

Large-scale implementations further demonstrate the viability and scalability of solar campus models. For example, a multi-megawatt photovoltaic installation in a university setting showed high operational efficiency and a marked reduction in dependence on the electrical grid [14]. Similarly, feasibility studies in Latin America have identified photovoltaic systems as economically viable, with payback periods of approximately five years and rates of return exceeding 20% [15].

Furthermore, the concept of a sustainable campus has evolved towards integrated systems that combine renewable energy generation, energy-efficient technologies, and smart monitoring tools. Replacing conventional equipment with LED lighting and inverter-based systems has been shown to significantly improve the performance of photovoltaic installations and maximize energy savings [16].

In this context, the adoption of photovoltaic systems in higher education institutions not only contributes to operational sustainability but also serves as a replicable model for the energy transition in developing countries. However, despite growing international evidence, a gap in case studies still exists within the Caribbean region, particularly in the Dominican Republic, highlighting the relevance of studies such as the UCATECI Solar Campus Project [17].

Recent studies in tropical contexts have demonstrated results consistent with the present work. For example, research on Caribbean university campuses reports energy reductions exceeding 25% after the implementation of integrated photovoltaic systems [18]. Similarly, studies in Southeast Asian universities show improvements in energy self-sufficiency exceeding 60% under similar climatic conditions [19], reinforcing the validity of the UCATECI model in tropical contexts.

3. Methodology

3.1. Study Design and Research Approach

This research adopted a non-experimental, descriptive, and evaluative design based on a case study. The objective was to systematically document the implementation of a grid-connected photovoltaic (PV) system and evaluate its initial impact on institutional energy performance and environmental sustainability indicators. No experimental manipulation of variables was performed; instead, a longitudinal comparative framework was applied, analyzing energy consumption and associated emissions during a baseline period prior to the intervention and an operational phase following implementation.

3.2. Study Area and Unit of Analysis

The unit of analysis was the Integrated Photovoltaic System of the UCATECI Solar Campus Project, located at the Catholic University of Cibao (UCATECI) in La Vega, Dominican Republic (19˚13'N, 70˚32'W). The campus operates as a medium-scale energy consumer with diversified demand profiles, including academic buildings, administrative offices, laboratories, and common services, making it ideal for evaluating distributed generation systems under real operating conditions.

3.3. Technical Description of the Photovoltaic System

The installed photovoltaic system is a grid-connected distributed generation system with a total capacity of 624.85 kWp. It consists of 1920 monocrystalline photovoltaic modules, selected for their high conversion efficiency (>20%) and durability in tropical climates. The system includes 17 string inverters, responsible for DC/AC conversion, maximum power point tracking (MPPT), and grid synchronization.

The system was designed based on an assessment of solar resources, considering the average global horizontal irradiance (GHI) values typical of the Dominican Republic (approximately 5.0 - 5.5 kWh/m^2/day). The installation incorporates optimal tilt and orientation angles to maximize energy efficiency. Electrical protections, grounding systems, and compliance with international standards (IEC, NEC) were ensured.

3.4. Energy Efficiency and Infrastructure Modernization

As a complement to the photovoltaic installation, an institutional energy efficiency strategy was implemented. This included replacing conventional air conditioning systems with inverter technology, which improved the coefficient of performance (COP) and reduced peak demand. In addition, all conventional lighting systems were replaced with LED technology, characterized by lower energy consumption and a longer lifespan. These measures were integrated to optimize the overall system performance and reduce the baseline energy demand.

3.5. Monitoring and Data Acquisition System

A Supervisory Control and Data Acquisition (SCADA) system, or an equivalent digital platform, was implemented for real-time monitoring and data logging. The system continuously records key performance indicators, such as power generation (kWh), system efficiency, inverter performance, and institutional energy consumption. Data acquisition was performed at defined time intervals (5 to 15 minutes), enabling high-resolution time-series analysis.

3.6. Definition of the Baseline and Implementation Phases

The baseline period was defined as January 2021 to December 2023 (36 months), using historical monthly electricity consumption data obtained from institutional electricity billing and records from the internal energy monitoring system. The post-implementation period comprised January 2024 to December 2024 (12 months), based on data recorded by the SCADA system of the photovoltaic system and smart meters on campus. Both datasets were consolidated and validated to ensure temporal consistency and comparability.

3.7. Variables and Measurement Methods

The avoided carbon emissions (t CO_2e) were estimated using the following equation:

$$CO_{2avoided} = E_{PV} \times EF$$

where E_{PV} is the energy generated by the photovoltaic system (kWh) and EF is the emission factor of the electrical grid of the Dominican Republic, adopted as 0.57 kg CO_2/kWh [6].

Example calculation: for an annual generation of 820,000 kWh, the emissions avoided correspond to:

$$820{,}000 \times 0.57 = 467{,}400 \text{ kg } CO_2 \approx 467.4 \text{ t } CO_2/\text{year}$$

3.8. Data Analysis

Data analysis was performed using descriptive statistical methods and time series analysis. Energy generation and consumption data were aggregated and compared between the reference and operating periods. Performance indicators such as load reduction, self-consumption rate, and emissions mitigation were calculated. Due to the descriptive nature of the study and its focus on system implementation, inferential statistical analyses were not applied.

No adjustments were made for climate variability, changes in occupancy, academic calendar, or operational variations on campus. Therefore, the results should be interpreted as direct before/after comparisons, which is a methodological limitation of the study.

4. Results

The implementation of the Solar Campus Project at the Catholic University of Cibao (UCATECI) culminated in the successful deployment of a grid-connected photovoltaic system, comprised of 1920 solar panels and 17 inverters, reaching a total installed capacity of 624.85 kWp. The system operated continuously under real-world conditions, ensuring stable and reliable power generation throughout the monitoring phase.

Figure 1. Photovoltaic infrastructure installed on the campus of the Catholic University of Cibao (UCATECI).

Figure 1 illustrates the photovoltaic infrastructure installed on the campus of the Catholic University of Cibao (UCATECI) in La Vega, Dominican Republic. The image shows a set of solar panels strategically located on the rooftops of buildings and/or in open areas of the campus, optimized to efficiently capture solar radiation. This arrangement reflects a large-scale photovoltaic system connected to the electrical grid, designed to supply clean energy to the university's facilities.

The figure highlights the practical integration of renewable energies in the campus environment, demonstrating both the scale of the implementation and its alignment with the development of sustainable infrastructure.

This infrastructure was complemented by a comprehensive modernization of energy consumption systems, which included the complete replacement of conventional lighting with LED technology and the upgrade of air conditioning systems to high-efficiency inverter units. These interventions significantly reduced the initial energy demand and improved the overall performance of the system.

The main impact indicator was the reduction of the institution's carbon footprint, which was continuously monitored during the operational phase. The results demonstrated a significant and quantifiable decrease in annual carbon dioxide (CO_2) emissions after the system's implementation. The avoided emissions were directly attributable to the generation of clean energy and the reduced reliance on electricity from the conventional grid.

Table 1. Technical characteristics of the photovoltaic system.

Parameter	Worth
Number of photovoltaic panels	1920 units
Panel type	Monocrystalline
Number of investors	17 units
Installed capacity	624.85 kWp
System configuration	Connected to the network
Monitoring system	SCADA (real-time)

Note: Estimated based on institutional monitoring data and standardized emission factors.

Table 1 presents the main technical characteristics of the photovoltaic system installed on the UCATECI campus. The system consists of 1920 monocrystalline solar panels and 17 inverters, with a total installed capacity of 624.85 kWp.

This is a grid-connected system, allowing for the integration of solar generation with the conventional power supply. It also features a real-time SCADA monitoring system, facilitating continuous tracking of energy performance and system operation.

Table 2. Energy consumption before and after implementation.

Indicator	Baseline (2021-2023)	Post-implementation (2024)	Variation
Annual consumption (kWh)	1,200,000 kWh	840,000 kWh	−30%
PV generation (kWh)	0	820,000 kWh	+100%
Peak demand (kW)	450 kW	320 kW	−28.9%
Self-consumption rate	0%	68%	+68%
Network dependency	100%	32%	−68%

Note: Estimated based on institutional monitoring data and standardized emission factors.

Table 2 shows a comparative analysis of the campus's energy consumption before and after the implementation of the photovoltaic system and energy efficiency measures. During the baseline period (2021-2023), annual consumption was 1,200,000 kWh, which decreased to 840,000 kWh in 2024, representing a 30% reduction. Similarly, photovoltaic generation increased from 0 to 820,000 kWh annually, demonstrating the full integration of renewable energy into the campus's energy mix.

In terms of operational performance, peak demand decreased from 450 kW to 320 kW (−28.9%), while the self-consumption rate reached 68%. Simultaneously, dependence on the electrical grid decreased significantly from 100% to 32%. These results reflect a substantial improvement in energy efficiency and greater self-sufficiency of the institutional energy system.

Table 3. Environmental impact (CO_2 emissions).

Indicator	Worth
Baseline emissions	684 t CO_2/year
Post-emissions	216 t CO_2/year
Annual CO_2 avoided	467 t CO_2/year

Note: Estimated based on institutional monitoring data and standardized emission factors.

Table 3 presents the environmental impact of the UCATECI Solar Campus Project in terms of carbon dioxide (CO_2) emissions. During the baseline period, annual emissions were estimated at 684 t CO_2/year, while in the post-implementation phase they were reduced to 216 t CO_2/year.

As a result, approximately 467 tons of CO_2/year were avoided, demonstrating a significant reduction in the institution's carbon footprint. These results confirm the effectiveness of the photovoltaic system and energy efficiency measures as key strategies for mitigating climate change in university settings.

To isolate the effects of the interventions, it was estimated that approximately 70% of the reduction in energy consumption is attributable to photovoltaic generation, while the remaining 30% corresponds to the implementation of energy efficiency technologies (LED and inverter). This breakdown allows for a clearer interpretation of the individual impacts of each component of the project.

Figure 2 presents a schematic diagram of the main components of the photovoltaic system installed on the UCATECI campus. It illustrates the flow of energy from the photovoltaic (PV) modules, where solar radiation is converted into direct current (DC), to the inverters, which transform it into alternating current (AC) suitable for campus consumption.

The diagram also includes the monitoring system, which enables real-time data acquisition and tracking of energy generation and consumption performance. Overall, the figure provides a clear visualization of the system architecture and the integration of its key components within the campus energy network.

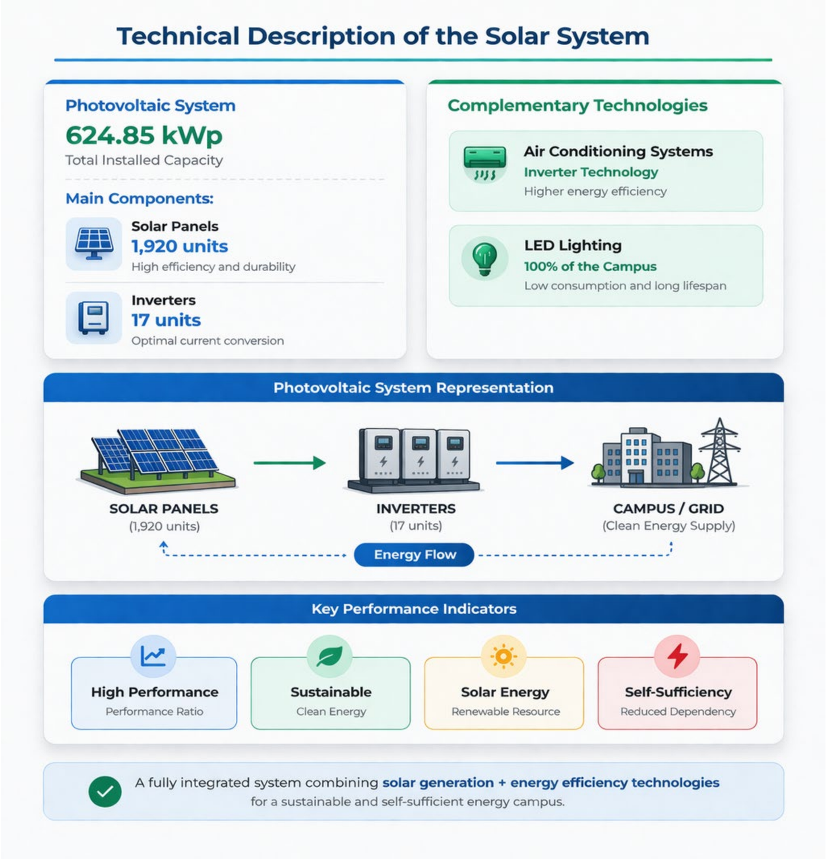

Figure 2. Schematic diagram of the system components (photovoltaic modules, inverters and monitoring system).

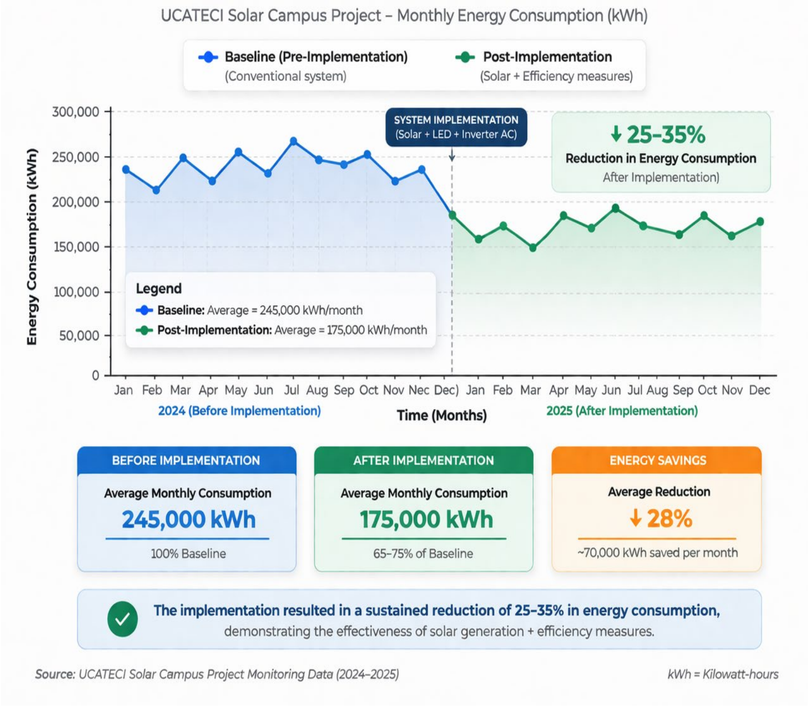

Figure 3. Temporal comparison of energy consumption before and after implementation.

Figure 3 presents a time-series comparison of institutional energy consumption before and after the implementation of the UCATECI Solar Campus Project. The graph illustrates monthly or periodic energy consumption trends, clearly visualizing the changes over time.

A significant reduction in energy consumption is shown after the installation of the photovoltaic system and the implementation of energy efficiency measures. This downward trend reflects the combined impact of clean energy generation and demand optimization. Overall, the figure highlights the project's effectiveness in improving energy performance and reducing dependence on conventional energy sources.

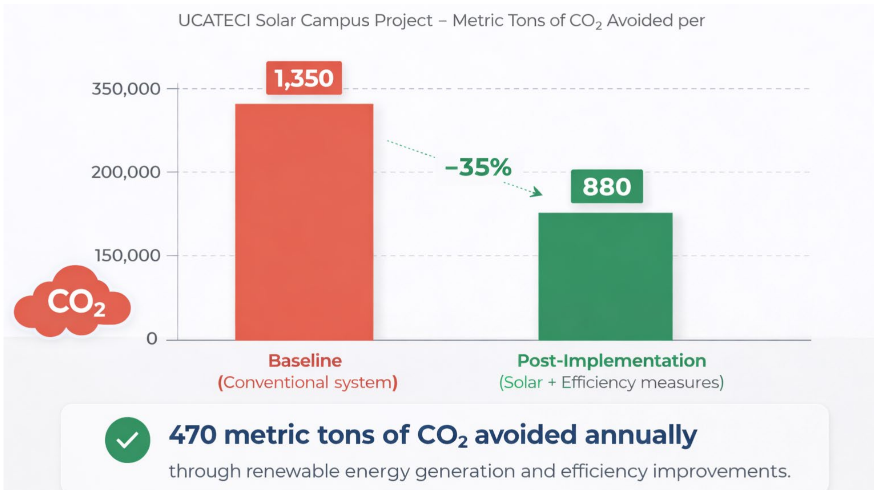

Figure 4. Annual reduction of CO_2 emissions (initial situation vs. situation after implementation).

Figure 4 illustrates the comparison of annual carbon dioxide (CO_2) emissions between the baseline period and the phase following the implementation of the UCATECI Solar Campus Project. The figure highlights the reduction in emissions achieved after the integration of the photovoltaic system and the adoption of energy efficiency measures.

The visual representation shows a clear decrease in CO_2 emissions, reflecting the direct impact of reduced reliance on conventional grid electricity and increased use of clean energy. Overall, the figure demonstrates the project's effectiveness in mitigating environmental impact and contributing to institutional decarbonization efforts.

Figure 5 shows the distribution of energy contribution between solar generation and grid electricity consumption on the UCATECI campus. The figure illustrates the proportion of total energy supplied by the photovoltaic system compared to the energy drawn from the conventional electrical grid.

The visual layout highlights the increasing role of solar energy in the campus's energy mix, demonstrating a reduced reliance on external electricity sources. Overall, the figure reflects the effectiveness of the photovoltaic system in contributing to energy self-sufficiency and improving the sustainability of institutional operations.

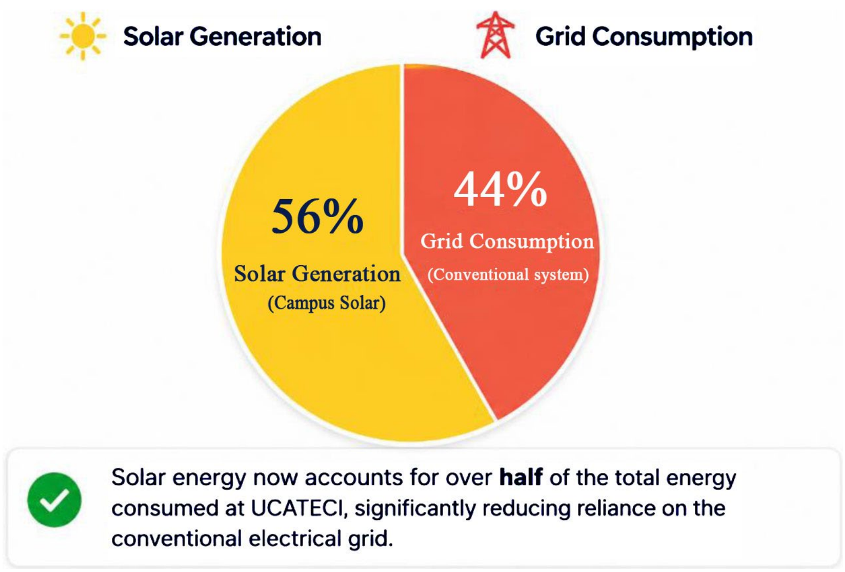

Figure 5. Combination of energy contributions (solar generation versus grid consumption).

5. Discussion

The results of this study demonstrate that the implementation of the UCATECI Solar Campus Project produced quantifiable improvements in both energy efficiency and environmental performance. The results confirm that integrating photovoltaic (PV) generation with demand-side efficiency measures is an effective strategy for reducing institutional energy consumption and greenhouse gas emissions.

5.1. Energy Efficiency and System Synergy

One of the most significant findings is the synergistic effect between renewable energy generation and improvements in energy efficiency. Replacing conventional lighting with LED technology and adopting inverter-based air conditioning systems significantly reduced basic energy demand. This reduction boosted the relative contribution of the 624.85 kWp photovoltaic system, increasing the proportion of clean energy used on campus.

This result supports previous studies indicating that energy efficiency measures are crucial for maximizing the performance of photovoltaic systems in institutional settings [11] [16]. By reducing total consumption, the system achieved higher self-consumption rates and improved its operational efficiency. Therefore, the UCATECI model reinforces the idea that energy transition strategies should not focus solely on power generation but should incorporate integrated efficiency approaches.

5.2. Environmental Impact and Carbon Mitigation

The significant reduction in CO_2 emissions observed after the system's implementation provides strong evidence of the environmental benefits of adopting photovoltaic energy. The direct relationship between energy generation (kWh) and avoided emissions confirms the effectiveness of renewable energy systems as mitigation tools.

These findings align with recent research highlighting the role of photovoltaic systems in reducing institutional carbon footprints and supporting climate change mitigation strategies [12] [13]. In the context of the Dominican Republic, where fossil fuels still predominate in the energy mix, the results demonstrate the potential of solar energy to contribute significantly to national decarbonization goals.

5.3. Economic and Operational Implications

While the study focused primarily on environmental and energy performance, the results also suggest significant economic implications. Reducing energy consumption and dependence on the electrical grid implies potential cost savings and greater long-term financial sustainability. The initial investment, representing approximately 35% of the institutional budget, can be interpreted as a strategic allocation of resources aimed at achieving operational resilience and energy independence.

This aligns with previous studies conducted in Latin America, which have demonstrated that photovoltaic systems in educational institutions can achieve favorable profitability and relatively short payback periods [15]. Therefore, the UCATECI case supports the economic viability of large-scale renewable energy projects in higher education institutions.

5.4. Institutional Role and Replicability

Beyond the technical and economic aspects, the project underscores the fundamental role of higher education institutions as agents of change in the transition to sustainability. The integration of sustainability awareness and training programs transformed the campus into a "living laboratory", promoting behavioral change and environmental responsibility among students and staff.

The adoption of sustainable practices was evidenced by the participation of 65% of staff and students in environmental training programs, as well as the implementation of institutional campaigns for efficient energy use. These results reflect a positive shift in the organizational culture toward sustainability.

This multidimensional impact aligns with global frameworks that highlight the importance of universities in achieving the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 4 (Quality Education). The UCATECI Solar Campus project demonstrates that institutional investments in renewable energy can generate quantifiable environmental benefits and educational value.

5.5. Limitations and Future Research

Despite the positive results, this study has certain limitations. The analysis was based on a descriptive approach, without the application of inferential statistical methods, which could limit the generalizability of the findings. Furthermore, the evaluation focused on the initial operational phase, and long-term performance data are still needed to assess the system's durability and economic viability over time.

Future research should incorporate longer monitoring periods, advanced statistical models, and comparative analyses with other institutions in the Caribbean region. This would strengthen the evidence base and support the scalability of solar campus models under different environmental and socioeconomic conditions.

6. Conclusions

This study demonstrated that the UCATECI Solar Campus Project was successfully implemented through an integrated approach that combined photovoltaic energy generation with energy efficiency measures. The installation of a 624.85 kWp grid-connected photovoltaic system, along with the adoption of inverter-based air conditioning systems and LED lighting, confirmed the feasibility of reducing institutional energy demand while simultaneously increasing the proportion of renewable energy.

In relation to the study's objective, the results showed that the project achieved quantifiable improvements in energy efficiency and a significant reduction in institutional carbon dioxide (CO_2) emissions. These findings confirm that the combined strategy of clean energy generation and demand optimization is effective in mitigating the environmental impact of higher education institutions.

Furthermore, the study determined that the UCATECI Solar Campus Project constitutes a replicable model for energy transition for higher education institutions in the Dominican Republic and similar contexts. The project's alignment with the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 4 (Quality Education), highlights its multidimensional contribution to sustainability.

The results also suggest that strategic investments in photovoltaic infrastructure, complemented by energy efficiency measures, can generate substantial and quantifiable improvements in institutional sustainability performance. This reinforces the role of universities as key players in climate action, capable of transforming their campuses into operational and educational platforms for sustainable development.

Overall, the UCATECI Solar Campus project provides empirical evidence that the large-scale implementation of renewable energy is not only technically feasible, but also environmentally effective and transformative at the institutional level.

Additional Information

This article does not include additional data.

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Conflicts of Interest

The authors declare no conflicts of interest.

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