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IMPACT OF PHOTOVOLTAIC SOLAR SOLUTIONS IN HIGHER EDUCATION INSTITUTIONS. CASE STUDY: UNIVERSIDAD LIBRE, BOGOTÁ, BOSQUE POPULAR CAMPUS

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ABSTRACT

Photovoltaic solar energy has become an important alternative to address problems related to climate change, reduce CO₂ emissions, and decrease dependence on fossil fuels. In Colombia, Law 1715 of 2014 and Law 2099 of 2021 have favored its implementation, extending to companies, communities, and higher education institutions. In this context, the objective of this article is to analyze the relevance of photovoltaic systems in university institutions, highlighting the experience of Universidad Libre, Bosque Popular Campus in Bogotá, and the initiatives aimed at promoting sustainability, energy efficiency, and research. In the case study, at Universidad Libre eight JAN72S30 550 W solar panels and a 4.2 kW on-grid inverter were installed, achieving an annual production of 11,944 kWh. This generated a favorable environmental impact with the reduction of 1.34 tons of CO₂ per year, and an economic impact reflected in savings of \$9,137,491 in energy consumption. The results showed impacts at different levels: in the environmental sphere, the reduction of carbon footprint; in the economic sphere, the decrease in electricity bill costs; in the social sphere, the generation of environmental awareness; and in the educational sphere, the opening of research opportunities, as well as the potential for creating specialized laboratories. Finally, by comparing this experience with that of other universities such as Universidad Popular del Cesar, Universidad Piloto, UTB, Universidad del Atlántico, and Universidad Santiago de Cali, where photovoltaic projects have also been implemented, the viability is concluded of fostering a culture of sustainability, strengthening practical learning in renewable energies, and continuing to promote training in sustainability, alignment with public policies, and growth in research at the University.

KEYWORDS: Photovoltaic Systems, Implementation in Universities, CO₂ Emissions Reductions, Energy Efficiency, Sustainable Development.

1. INTRODUCTION

Due to its inexhaustible nature and environmentally friendly character, solar energy has positioned itself as a source with great potential and applicability. Colombia has the advantage of high resource availability due to its geographic location, which has driven policies oriented not only toward the adoption of solar energies, but also other renewable sources in the electric energy matrix [1].

In November 2017, one of the most relevant solar projects in the country was inaugurated: the Yumbo Photovoltaic Farm in Valle del Cauca, developed by EPSA, a Celsia subsidiary. This installation, composed of 35,000 photovoltaic modules connected to 9 inverters that transform the energy into alternating current (AC), marked the country's energy history, serving as a precedent and benchmark for the continued growth of these projects nationwide in different regions such as the Atlantic Coast, the Santander departments, Tolima, Antioquia, and Valle del Cauca [2].

Based on this, the Legal Framework for Renewable Energies in Colombia was consolidated with the approval of Law 1715 of 2014 and its amendment by Law 2099 of 2021. These provisions regulate the integration of non-conventional renewable energies into the National Energy System, promoting actions aimed at mitigating risks derived from climate change and fostering efficient energy management systems, together with smart metering technologies [3].

According to SER Colombia, the country's wind and solar power generation potential is estimated at 30 GW and 32 GW, respectively, exceeding the current installed capacity of 18.8 GW. The La Guajira region is of particular interest, with world-class wind resources, with average wind speeds of 9.8 m/s, representing 18 GW of the country's total wind potential. However, this resource remains largely untapped: the country's installed operating capacity in solar energy in 2022 was 290 MW and in wind energy 18.4 MW, which represent 1.5% and 0.1% of electric capacity, respectively [4].

In recent years, Colombia has shown sustained growth in the adoption of photovoltaic solar systems in rural and urban areas, as well as in companies and universities, with positive results in terms of environmental and social sustainability [5]. In this context, the objective of this article is to make known the importance of the use and implementation of photovoltaic solar systems in institutions of higher education.

Photovoltaic Solar Systems

Photovoltaic solar energy is a form of renewable energy obtained by converting sunlight into

electricity through modules or photovoltaic panels composed of photovoltaic cells made from semiconductor materials. Depending on their series or parallel configuration, these systems can generate higher current or higher voltage according to the energy need. These systems have experienced significant growth in recent decades due to their capacity to produce clean and renewable energy worldwide [6].

The origin of this technology dates back to the 19th century with the discovery of the photovoltaic effect, which is the ability of certain materials to generate electricity when exposed to sunlight. Nevertheless, it was in the 1950s that the first commercial crystalline silicon photovoltaic cells were developed. The discovery made by Willoughby Smith caught the attention of two British scientists, William Grylls Adams and Richard Evans Day, who created the first selenium photovoltaic cell, an achievement that marked a watershed in the history of photovoltaic energy [7]. Despite this great milestone, the amount of energy generated by the panels was still very limited and impractical; this advance, however, marked a fundamental starting point.

Over the years, photovoltaic solar energy has improved in efficiency and cost reduction, driving its adoption around the world. Countries such as China, with a photovoltaic capacity of 254 GW, the United States with 1800 MW, Germany with 53 GW, France with 12.8 GW, Spain with 26.6 GW, Italy with 21 GW, India with 57.4 GW, Japan with 2700 MW, and Australia with 15 GW [8]. These countries have invested significantly in photovoltaic solar energy, contributing in an important way to the global production of clean renewable energy.

There are several types of grid connections for photovoltaic solar systems [9].

- Grid connection without energy storage: in this type of connection, the electricity generated by the solar panels is used directly at the site where it is produced, and the excess energy is fed into the electrical grid. This allows the owners of solar systems to sell the excess electricity to the utility company and receive credits on their bill.
- Grid connection with energy storage: some photovoltaic solar systems are equipped with storage batteries that allow the excess energy to be stored for later use. This gives owners the ability to use electricity in the absence of solar radiation, such as at night or on cloudy days.
- Hybrid grid connection: this type of connection combines solar energy with other energy sources, such as wind or hydroelectric power, to provide a

more stable and reliable energy source. Hybrid systems can be an ideal option for regions where the availability of sunlight may vary significantly throughout the year.

Representation of Renewable Energies in Colombia

The development of public policies, favorable regulations, and financing programs has contributed to the development of large-scale solar projects and the promotion of energy self-sufficiency in various regions of the country. In addition, research and the development of more efficient and accessible solar energies are further driving the growth of the sector in Colombia, with the objective of diversifying the energy matrix and reducing dependence on fossil fuels. In 2022, 258 MW of photovoltaic solar capacity in operation were added, and it is expected that, in 2024, 13 photovoltaic solar energy (PV) projects will enter into operation. The solar resource in Colombia is exceptional, with sunshine (hours of sun) ranging between 4 and 12 hours per day on an annual daily average; this translates into an average daily solar radiation of 4.5 kWh/m², higher than the world average of 3.9 kWh/m². In the country, 70% of the effective capacity for solar power generation is represented with an installed capacity of 13,295 MW as of 2022; however, photovoltaic energy projects are expected to contribute to the Colombian electric system a capacity of around 1,147 MW in 2024 [9].

Participation of Academia in Renewable Energies

Academia plays a central role in the energy transition by training a new generation of experts committed to sustainability and innovation. Academic programs in renewable energies offer comprehensive training in different aspects of the field, from physics and engineering to economics and policy, preparing students to face the challenges and opportunities of the energy transition.

In the current context of growing environmental awareness and the pressing need to address the problems that exist among climate change, the use of fossil fuels, and the vulnerability of the Colombian electric energy matrix – which has aroused the interest of professionals within academia regarding the importance of renewable energy applications as a fundamental pillar in the transition toward a more sustainable and environmentally friendly energy system – the significant impact of these energies in the academic sphere is reflected in their capacity to drive the generation of knowledge that fosters interdisciplinary collaboration and promotes the training of professionals qualified in this constantly evolving field.

For this reason, the initiative arose to conduct research from the Master's in Engineering with an Emphasis on Alternative Energies at the Bosque Popular campus of Universidad Libre in Bogotá, to raise awareness among the community of the importance of implementing photovoltaic solar energy in education.

Currently, Universidad Libre of Colombia has developed different projects to implement photovoltaic solar systems at its various campuses nationwide, as have other universities in the country that have contributed to the implementation and development of this type of project, which today contribute significantly to environmental sustainability and to the efficiency of Colombia's electric capacity.

Therefore, the aim is to present the progress achieved from the implementation of photovoltaic solar solutions in institutions of higher education and, from this, to generate a positive impact in the educational sphere, where the entire community is involved and the implementation of these systems is significantly promoted, which not only represents an opportunity to reduce dependence on non-renewable sources in institutions, but also contributes to significant savings in conventional energy consumption while advancing environmental sustainability.

The implementation of renewable energies in institutions of higher education can serve as an example of leadership and commitment, inspiring other entities in the country by demonstrating that it is possible to adopt sustainable practices that respect the environment without compromising quality of life or economic development. Likewise, it provides students with the opportunity to participate in research and development projects in this field.

Some institutions of higher education have opted to implement photovoltaic solar energy systems on their campuses with the purpose of reducing their environmental impact and fostering sustainability. Among them is Universidad Libre, Bosque Popular campus in Bogotá, which has developed photovoltaic solar energy projects at its facilities, complemented by the academic training offered by the Master's in Engineering with an Emphasis on Alternative Energies, which includes a photovoltaic solar energy laboratory and a curricular plan oriented toward training professionals qualified in the calculation, design, and assessment of renewable energy installations. In addition, it promotes the conceptualization, design, and efficient operation of systems for harnessing renewable sources and energy infrastructure, as well as the evaluation of the

energy potential of various sources, through multidisciplinary work and within a framework of ecological, ethical, and social responsibility.

Other universities in the country have implemented projects with photovoltaic systems, for example:

At Universidad Popular del Cesar, the region's first photovoltaic solar laboratory was inaugurated, consisting of 90 solar panels, inverters, and micro-inverters that will enable progress at the training level in research and social outreach processes with the aim of improving the environment. In the future, the project seeks to energize the administrative area of the Valledupar Mayor's Office and the Educational Institution of the municipality of La Paz.

In 2017, Universidad Piloto de Colombia developed a research project that supplied 7.31% of its energy demand, generating 11.84 kWh from the installation of solar panels, serving as an example of commitment to the sustainability of clean energies and demonstrating leadership in the promotion of responsible environmental practices [10].

Universidad Tecnológica de Bolívar inaugurated the UTB Solar Park, considered the largest university photovoltaic solar farm in Colombia, with the capacity to generate renewable energy and replace approximately 50% of the energy consumed by the university, thus contributing to the reduction of greenhouse gas emissions [11].

For its part, Universidad del Atlántico is advancing in the construction of a photovoltaic solar generation system on its rooftops, with the purpose of contributing to sustainable development, promoting the use of renewable energies, and achieving a 30% savings in the cost of the public electric service. The institution announced that it is working on the construction of a photovoltaic solar

generation system on the rooftops of the buildings, contributing to sustainable development through the use of renewable and non-polluting energies. As an academic institution at the forefront and understanding the importance and necessity of the energy transition, Universidad del Atlántico is advancing the construction of a system with an average of 990 kWh of photovoltaic solar energy generation [12].

Finally, Universidad Santiago de Cali implemented a photovoltaic system installed on the roof of the corridor that connects the Boulevard with Block 5. The project includes 156 photovoltaic panels with a generation capacity of 52 kWp that supply the electrical system of Block 6. This initiative was executed under the instructions issued by the Faculty of Engineering and was based on multiple practical research works developed within the Electronic Engineering program [13].

2. Case Study: Universidad Libre

Within Universidad Libre, Bosque Popular campus in Bogotá, there is an on-grid interconnected photovoltaic solar system, composed of the following equipment:

- 8 photovoltaic panels, model JAN72S30, 550 W.
- 1 on-grid inverter, model MIN 300TL-X, 4.2 kW.

To determine the available solar resource, the European Commission's PVGIS Platform was used, entering the geographic coordinates where the university is located, which are: (4.668408, -74.103096). Based on the information provided by the software, the standard sun hours (HSS) for the case study were calculated, obtaining an average of 3.3 kWh/m². Figure 1 presents the standard sun hours corresponding to the area where the campus under study is located.



Figure 1: Solar irradiation (HSS) Universidad Libre of Colombia.

Likewise, in Table 1, the technical parameters obtained from the panel's datasheet are shown,

which are those used for the sizing of the system.

Table 1: Parameters of the Solar Panel used in the project.

Selected panel	JAN72S30 550W
Power per unit (Wp)	550
Total number of panels	8
Generated power (Wp)	4400
Voc	49,9
Vmp	41,96
Isc	14
Imp	13,11
Efficiency	21,3
NOCT (°C)	45
δ - Maximum power temperature coefficient (%/°C)	-0.35
Open-circuit temperature coefficient (%/°C)	-0.275
Short-circuit current temperature coefficient (%/°C)	0.045

Taking into account that this is a real and not an ideal system, the losses that occur due to the effect of temperature on the panel's voltage parameters must be analyzed. These parameters are obtained in Table 1, taken from the panel's datasheet. In equation (1), the temperature at which the cell will be at the ambient temperature of the location is indicated, based on the Nominal Operating Cell Temperature – NOCT in its English acronym:

$$T_c = T_a + \left(\frac{NOCT - 20}{800} \right) * I \quad (1)$$

Equation (2) makes it possible to determine the actual power generated by the panel considering the effect of temperature. In this expression, δ corresponds to the temperature coefficient of maximum power, a value that is specified in the photovoltaic panel's technical datasheet.

$$P_T = P * \left(1 + \frac{\delta}{100} * (T_c - 25^\circ C) \right) \quad (2)$$

Equations (3), (4), and (5) make it possible to obtain the actual operating values of open-circuit voltage, short-circuit current, and maximum power voltage.

$$VOC(46,25) = VOC + (\Delta T * \beta) \quad (3)$$

$$ISC(46,25) = ISC * \left(1 + \frac{\alpha}{100} * (\Delta T) \right) \quad (4)$$

$$\Delta V_{mpp}(46,25) = 0,76 * \gamma \quad (5)$$

By applying all the equations, the actual values of the panel parameters are obtained, since these are directly affected either by solar irradiation or by temperature effects. The higher the temperature present at the site, the more the voltage values will be modified, and solar irradiance affects the current values:

Table 2: Parameters of the real solar panel.

Parameters	Value
PT (Wp)	509,09
Generated power (Wp)	4072,72
Voc (V)	44,05
Vmp (V)	37,52
Isc (A)	14,13

The energy injected into the grid based on the actual power generated by the panel is given by equation (6):

$$Energy = \frac{\sum_{i=1}^n (P_{AC} * n)}{\eta_{inversor}} \quad (6)$$

$$= \frac{4,072W * 8}{0,982}$$

$$Energy_{AC} = 33178,98 Wh$$

$$Energy_{AC} = 33,17898 kWh$$

Now then, it is essential to establish the configuration of the panels, which depends on the electrical parameters of the solar inverter, presented in Table 3 and provided by the manufacturer. In equations (7) and (8), the maximum quantities with which the photovoltaic panel array can be arranged can be obtained.

$$N_{serie\ max} = \frac{V_{inv\ max}}{VOC} \quad (7)$$

$$N_{parallel} = \frac{I_{inv\ max}}{Isc} \quad (8)$$

Table 3: Electrical Parameters of the On-Grid Inverter.

Selected inverter	MIN 300TL-X
Power (W)	4200
Max DC voltage	500V
Min DC voltage	100V
Max DC current	12,5A
Efficiency	98,20%

$$N_{series\ max} = \frac{500V}{49,9V}$$

$$N_{series\ max} = 10$$

$$N_{parallel} = \frac{14}{14}$$

$$N_{parallel} = 1$$

In accordance with the above information, a series arrangement will be used with the eight photovoltaic

panels. In Figure 2, the arrangement of the panels installed on the roof of the university's laboratory is presented.



Figure 2: Arrangement of Photovoltaic Panels Located at the Universidad Libre - Bogotá Campus.

Once the entire process has been carried out, it is possible to make an estimate and analysis of the impacts that the implementation of photovoltaic systems can generate in the educational community of institutions of higher education. These impacts are reflected mainly in the environmental and economic spheres.

Environmental and Economic Impact

To estimate the environmental impact associated with the implementation of photovoltaic systems, the savings in carbon footprint were calculated.

According to data obtained by FECOC – Total CO₂ Emissions of UPME [14], the emission factor for conventional electricity is 0,126 Kg CO₂/kWh, while for photovoltaic systems it is 0,112 ton CO₂/MWh.

With the photovoltaic solar system, there is an annual production of 11.944 kWh/year, so the equivalent tons of CO₂ correspond to 1,3378 ton CO₂/year.

As for the economic impact, considering the aforementioned data on energy consumption, the annual energy production generated by the photovoltaic system, and taking as a reference an electricity tariff of 765 \$/kWh, the annual savings can be calculated as indicated by equation 9:

$$\begin{aligned} \text{Annual savings} &= \frac{\text{Energy}_{AC} * \# \text{ hours} * \# \text{ days}}{\text{kWh}} \quad (9) \\ \text{Annual savings} &= \frac{33,17898 \text{ kWh} * 12 \text{ h} * 30 \text{ days}}{765 \text{ \$/kWh}} \\ \text{Annual savings} &= \$9.137.491 \end{aligned}$$

This savings value can increase insofar as the system is expanded or other photovoltaic systems are installed, which would help reduce consumption from the conventional electric grid.

Nevertheless, it is important to highlight that the components of photovoltaic solar systems can also

generate negative impacts on the environment, such as the pollution of water sources and soil, as well as impacts on biodiversity [15].

At the end of their life cycle, photovoltaic panels become waste electrical and electronic equipment (WEEE), which must be treated, separated, recycled, and transformed. Most of their components can be recovered, but it is essential to establish proper management mechanisms to protect the environment. Elements such as cadmium, lead, silver, and silicon can be harmful to both ecosystems and human health, which is why it is indispensable to ensure correct handling and disposal [16].

Among the methods used for the recovery and recycling of materials, manual, magnetic, and mechanical separation stand out, as well as incineration and shredding processes. In the case of hazardous components, techniques such as leaching and electrolysis can be applied [17].

In this regard, it is essential that academia promote research and development opportunities that make it possible to complement and improve current technologies, fostering the responsible use of renewable sources and comprehensively assessing their impacts on the environment.

3. SOCIAL IMPACT

Research and advances regarding the social impacts of photovoltaic systems have not been extensively studied, therefore it remains a broad subject yet to be explored. Currently, the literature indicates some impacts that can also be related to economic effects. Some of the impacts can be classified into land use and landscape, infrastructure, political, energy market, industry, and education, among others [18].

Within the aforementioned classifications, there are impacts on the reduction of land use compared to how conventional resources do, the use of little-explored sites such as deserts, the reduction of grids or transmission lines – thus decreasing the impact on rights-of-way – job creation, a higher level of development and education, among others [19].

At the level of electric power generation, photovoltaic systems have impacts in those areas where conventional electric grids cannot reach, whether due to high installation costs or access difficulties, as occurs in Non-Interconnected Zones (ZNI), which, together with coordination with other generation methods such as diesel plants, have functioned as hybrid and backup solutions, extending the periods of provision of electric service for those communities and populations that are affected [20].

Among the positive impacts identified, the improvement in the community's quality of life stands out, by having more time with lighting during the night, allowing the development of coexistence among people and the carrying out of other activities that drive economic development. In the educational sphere, an increase has been observed in the quality of nutrition and the health of students in rural schools, thanks to the conservation and preservation of food through the use of sustainable energy systems [21].

Academia must develop constructive thinking aimed at identifying and addressing social needs by implementing renewable technologies, thereby contributing to the sustainable development of communities.

4. CONCLUSIONS

The implementation of photovoltaic systems in institutions of higher education offers the academic community a practical and direct approach to renewable energies, particularly solar energy. This fosters active learning, raises awareness among students and teachers about the importance of alternative energy sources in mitigating climate change, and promotes a culture of sustainability in the educational sphere.

This project, developed in an educational environment, fosters a space for research and technological development in the field of alternative energies. In addition to motivating the academic community to delve deeper into study and innovation, it contributes to scientific and technological progress in a strategic area for a sustainable future, with universities being key actors in the energy transition, contributing through applied research to the search for replicable solutions by means of scientific and technological advances.

This type of project not only motivates students to

deepen their research on its advantages and possible optimizations, but also contributes to environmental care by reducing the carbon footprint generated associated with energy consumption.

Although the photovoltaic system implemented at Universidad Libre, Bogotá campus has a lower installed capacity compared to the systems of other universities, its impact remains significant in several areas: social, economic, and environmental. These projects benefit both educational institutions—by promoting sustainable practices and generating energy savings—and the environment, by reducing the carbon footprint. Furthermore, it provides a replicable model that can positively influence the community and others.

This project paves the way for the reduction of the carbon footprint, but also represents a considerable economic saving. As a result, institutions' interest in implementing this type of alternative generation system increases, contributing both to environmental sustainability and to economic efficiency.

In this sense, it is recommended that the Universities carry out strategic plans that allow:

- Maximize environmental impact through the scaling of photovoltaic projects.
- Involve different programs from an interdisciplinary approach in order to generate comprehensive solutions.
- Articulate with national public policies that promote the integration of renewable energies into the country's energy system.
- Manage equipment at the end of its life cycle, including recycling plans and final disposal of these elements.

Finally, the progressive reduction in dependence on conventional electric energy, along with the potential growth of the system or the implementation of new solar projects at the institution, will generate a considerable economic impact on energy consumption.

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