Research article

Design of an electrical power supply system for 110 V equipment with photovoltaic solar energy for the Diving School of the Colombian National Navy

Diseño de un sistema de alimentación eléctrica para equipos de 110 V con energía solar fotovoltaica para la Escuela de Buceo de la Armada Nacional de Colombia

Katherine María Prada Sánchez[1,*], Fernando de Jesús Aricapa Palacio[2] and MA1 Sergio Pacheco Guzmán[1]

[1] Escuela Naval de Suboficiales "ARC Barranquilla", Barranquilla 080002, Colombia; kpradasanchezz1017@gmail.com (K.M.P.S.); sergio.pacheco@armada.mil.co (S.P.G.)
[2] Fundación Universitaria Tecnológico Comfenalco, Cartagena, Colombia; dirp.ambiental@tecnologicocomfenalco.edu.co
* Correspondence: kpradasanchezz1017@gmail.com

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Abstract: The design of a photovoltaic solar power system for the Colombian Navy's Diving School (ESBUC) aims to meet the energy demand of its 110 V equipment through a renewable, sustainable and efficient solution. This project seeks to reduce dependence on conventional energy sources and to promote energy self-sufficiency within the institution, in line with national environmental goals. The methodology was quantitative, with a descriptive and propositional design that made it possible to analyze ESBUC's current energy situation, identify its carbon footprint and evaluate viable photovoltaic options. PVsyst V7.2.4 software was used to run the simulations, model the configurations and select the most efficient alternative. Data collection included historical information and a detailed inventory of the equipment distributed across classroom and administrative areas, which served as a representative sample for estimating total energy demand. The proposed system consists of 120 photovoltaic modules of 585 Wp (70.2 kWp of installed capacity), a 337.5 kWh battery bank and a 70 kW inverter. The simulation yields an annual generation of 111,354 kWh against a projected demand of approximately 99,999 kWh/year, an average solar fraction of 93.5% and a performance ratio of 68.8%: 93,494 kWh/year are delivered to the load, 13,758 kWh/year remain unused because of battery-bank saturation, and the residual deficit (6.5%, i.e. 6,466 kWh/year) is concentrated in the months of lowest irradiation (October and November). The simulations validated the technical and operational feasibility of the system, as well as its positive impact in terms of sustainability and the reduction of greenhouse gas emissions. In conclusion, this project establishes a replicable energy transition model based on renewable sources, which covers most of ESBUC's current demand and opens the way to future expansions and improvements.

Keywords: Solar energy; Photovoltaic design; Sustainability; Energy transition.

Resumen: El diseño de un sistema eléctrico solar fotovoltaico para la Escuela de Buceo de la Armada Nacional (ESBUC) tiene como objetivo satisfacer la demanda energética de los equipos de 110 V mediante una solución renovable, sostenible y eficiente. Este proyecto busca reducir la dependencia de fuentes convencionales y promover la autosuficiencia energética de la institución, en línea con las metas ambientales nacionales. La metodología empleada fue de enfoque cuantitativo, con un diseño descriptivo y propositivo que permitió analizar la situación energética actual de la ESBUC, identificar la huella de carbono generada y evaluar opciones viables para el sistema fotovoltaico. Se utilizó el software PVsyst V7.2.4 para realizar las simulaciones, modelar las configuraciones y seleccionar la alternativa más eficiente. El levantamiento de datos incluyó información histórica y un inventario detallado de los equipos distribuidos en áreas de salón y administrativas, que sirvieron como muestra representativa para estimar la demanda energética total. El sistema propuesto está conformado por 120 módulos fotovoltaicos de 585 Wp (70.2 kWp de capacidad instalada), un banco de baterías de 337.5 kWh y un inversor de 70 kW. La simulación arroja una generación anual de 111,354 kWh frente a una demanda proyectada cercana a 99,999 kWh/año, con una fracción solar promedio del 93.5% y un Performance Ratio del 68.8%: 93,494 kWh/año se entregan a la carga, 13,758 kWh/año no se aprovechan por saturación del banco de baterías y el déficit residual (6.5%, equivalente a 6,466 kWh/año) se concentra en los meses de menor irradiación (octubre y noviembre). Las simulaciones validaron la viabilidad técnica y operativa del sistema, así como su impacto positivo en términos de sostenibilidad y de reducción de emisiones de gases de efecto invernadero. En conclusión, este proyecto establece un modelo replicable de transición energética basado en fuentes renovables, que cubre la mayor parte de la demanda actual de la ESBUC y abre la posibilidad de futuras expansiones y mejoras.

Palabras clave: Energía solar; Diseño fotovoltaico; Sostenibilidad; Transición energética

1. Introduction

The Diving School of the Colombian National Navy (ESBUC) faces a growing energy demand that implies relevant operating costs and a structural dependence on conventional sources, with environmental impacts associated with the generation of greenhouse gases. Faced with this problem, the implementation of a photovoltaic solar system is proposed as a comprehensive solution, since solar energy allows a significant reduction in the carbon footprint, strengthens energy self-sufficiency and ensures a stable and reliable supply. Likewise, the modular and scalable nature of this technology facilitates its adaptation to future institutional expansions, optimizing investment in the medium and long term and reducing vulnerability to external supply failures. From an environmental perspective, the adoption of renewable energies contributes to mitigating impacts on ecosystems and natural resources, while, in strategic and educational terms, it positions ESBUC as a benchmark in the incorporation of clean technologies within the public and military sector. Consequently, this study acquires relevance not only for its technical contribution, but also for its demonstrative and replicable value, by showing how institutions can lead energy transition processes aligned with the environmental, economic and social challenges of the twenty-first century.

The remainder of this article is organized as follows. Section 2 presents the main contributions of the research, emphasizing the technical and environmental assessment of the proposed photovoltaic system, its sizing and validation, its potential contribution to reducing dependence on conventional electricity sources, and its replicability in other naval or public facilities. Section 3 reviews the theoretical and technical background related to photovoltaic solar energy, energy efficiency in military institutions, and the main components required for the operation of photovoltaic systems. Section 4 describes the materials and methods used in the study, including the quantitative and propositional research approach, the characterization of the energy demand, the design of the photovoltaic system, and the simulation and validation procedure. Section 5 presents the main results, including the estimated energy demand of the ESBUC facilities, the sizing of the photovoltaic modules, battery bank, inverter and distribution system, as well as the results obtained from the simulations performed in PVsyst V7.2.4. Section 6 discusses the technical performance of the proposed system, its energy efficiency, the identified limitations, and the opportunities for optimization, particularly regarding energy storage and surplus management. Finally, Section 7 summarizes the main conclusions of the study and highlights the technical, environmental, and operational implications of implementing photovoltaic solar energy at the National Navy Diving School, as well as possible directions for future research.

2. Contributions

This research presents the following contributions:

i. A contextualized technical and environmental assessment of a photovoltaic solar energy system for the National Navy Diving School (ESBUC) is developed, considering the institution's projected energy demand, solar resource availability, and operational requirements.

ii. The study proposes and sizes a photovoltaic system composed of 120 solar modules of 585 Wp, with a total installed capacity of 70.2 kWp, a 337.5 kWh battery bank, and a 70 kW inverter, providing a technically feasible configuration for supplying the institution's 110 V equipment.

iii. The photovoltaic system is validated through simulations performed in PVsyst V7.2.4, allowing the evaluation of annual energy generation, system losses, Performance Ratio, solar fraction, unused energy, and periods of energy deficit under the climatic conditions of Cartagena.

iv. The proposed system demonstrates the potential to reduce dependence on conventional electricity sources and decrease greenhouse gas emissions, thereby supporting the sustainability objectives and energy transition strategy of the Colombian National Navy.

v. The research identifies opportunities for improving the use of surplus photovoltaic energy, particularly through optimization of the battery storage system and possible future integration with the electricity grid.

vi. Finally, the proposed methodology and system configuration provide a scalable and replicable model that may serve as a reference for the implementation of photovoltaic solutions in other naval facilities and public institutions with similar energy requirements.

3. Related Works

Solar energy is the most abundant and autonomous source of energy, i.e. capable of unlimited renewal. It can be harnessed in two main ways: solar thermal energy, which involves capturing heat from the sun to heat water or air, and solar photovoltaic energy, which involves the direct conversion of sunlight into electricity through the use of photovoltaic cells. This source is valued for being clean and sustainable, with a low environmental impact compared to fossil fuels. Its use allows reducing greenhouse gas emissions and contributing to the diversification of the energy matrix. In addition, it is a technology that is constantly evolving, with continuous advances in efficiency and cost reduction.

Military institutions are strategic actors in the management of energy resources, not only because of the magnitude of their demand, but also because of the operational, economic and environmental implications of their consumption. These organizations rely heavily on energy sources to keep their facilities operational, ensure the operation of technological equipment, and deploy forces in various scenarios. According to Carrasco et al. [2], the transition to sustainable energy models is not only a response to global environmental demands, but also an operational necessity that ensures greater efficiency and resilience in the face of strategic challenges.

Dependence on fossil fuels, such as diesel and gasoline, remains prevalent in military operations, leading not only to high operating costs, but also to vulnerabilities to fluctuations in the prices of these resources. In addition, this type of dependence contributes significantly to the generation of greenhouse gas emissions [2]. The implementation of renewable technologies and energy efficiency strategies makes it possible to mitigate these impacts, promoting a more balanced model between environmental sustainability and operational capacity.

On the other hand, the Strategic Energy Transition Plan [1] stresses that energy sustainability not only benefits the environment, but also strengthens the energy autonomy of military institutions. This approach reduces vulnerability to power outages and strengthens operational security, especially in critical missions where access to external power sources may be compromised. In addition, investment in renewable energies, such as solar and wind, allows for a long-term economic return by reducing costs associated with fossil fuel consumption and maintaining outdated infrastructure.

The development of energy efficiency strategies is not limited to land-based installations. In the naval field, Carrasco et al. [2] highlight that warships have a high potential for optimising energy consumption. By incorporating real-time monitoring systems, more efficient propulsion technologies, and optimized operating practices, it is possible to significantly reduce energy consumption without compromising operational performance. These experiences can be extrapolated to other areas, such as military bases and training centers, to maximize energy efficiency at all levels.

The logistical and economic challenges associated with the energy transition in military institutions should not be underestimated. While the initial investment in renewable technologies and efficient systems can be significant, the long-term benefits justify this effort. The Strategic Energy Transition Plan [1] points out that these investments not only promote environmental sustainability, but also reinforce institutional commitment to the Sustainable Development Goals (SDGs). In addition, developing internal capabilities to manage and maintain these technologies strengthens the operational autonomy of the armed forces, reducing dependence on external suppliers.

Solar panels, also known as photovoltaic modules, are devices designed to transform the sun's energy into electricity. This is achieved by a process known as the photovoltaic effect, identified by Edmond Becquerel more than a century ago. This phenomenon allows photovoltaic cells, composed of semiconductor materials such as silicon, to capture the energy of photons coming from sunlight, thus generating electric current. These cells are structured in layers, one of them combined with phosphorus to obtain a negative charge and the other with boron to create a positive charge, which produces an electric field capable of mobilizing electrons when receiving solar radiation [8]. The set of these cells generates a direct current that, thanks to an inverter, is converted into alternating current for use in various domestic and industrial applications.

Solar panels are widely used not only in homes, but also in specialized systems such as solar irrigation, due to their ability to produce clean and renewable energy. These panels are in turn connected to a battery that stores the electricity generated and it is this load that is used. These panels are made up of photovoltaic (PV) cells, which convert sunlight into direct current (DC) electricity during the day. Solar energy can be used in two main ways: through active systems, such as photovoltaic and thermal energy, and through passive systems.

The essential difference between these two methods lies in how energy is handled. Active systems convert solar energy into electricity, transforming the direct current generated by solar panels into alternating current for use in household electrical devices. On the other hand, passive solar energy directly harnesses sunlight without requiring additional conversion, as it is efficiently integrated into the building's design. Active solar energy, by requiring technological devices such as solar panels, inverters and, in some cases, batteries, allows a direct conversion of solar radiation into usable electricity. According to Perpiñán [6], this technology is best suited to contexts where a continuous and manageable power source is needed, making it suitable for homes, industries, and applications in isolated areas. However, this advantage also entails higher upfront costs due to equipment installation and maintenance. On the other hand, passive solar energy, by being directly integrated into the design of buildings, efficiently takes advantage of orientation, construction materials, and the arrangement of windows and walls to maximize the capture of solar light and heat [10]. This approach not only reduces energy costs, but also minimizes the need for auxiliary heating and cooling systems. However, its implementation requires careful planning in the architectural design phase, which limits its applicability in existing buildings.

The components of the photovoltaic solar electricity system constitute the set of technical elements that allow the capture, transformation, regulation, storage and supply of energy from solar radiation. Likewise, these components operate in an integrated manner to guarantee the efficiency, security and continuity of the electricity supply. According to Gutiérrez [4], the performance of the system depends directly on the correct selection and configuration of each element. Consequently, their proper articulation is essential to ensure reliable operation in domestic, industrial or isolated applications.

Photovoltaic modules are the main element of the system, responsible for converting solar radiation into electricity through the photovoltaic effect. They are composed of solar cells made mainly of semiconductor materials such as silicon, which generate electricity when exposed to sunlight. Monocrystalline modules are one of the available photovoltaic technologies [7]. These modules are designed to operate under standard conditions and are evaluated in terms of peak power (Wp), an indicator of their performance under optimal radiation conditions. In addition, the modules are encapsulated in rugged structures that protect them from environmental factors such as water, dust, and ultraviolet radiation. Its arrangement in series or parallel allows the voltage and current to be adjusted to meet the specific requirements of the system [4].

On the other hand, the charge controller is an important component for battery systems, it manages the flow of energy between PV modules and batteries. Its main function is to protect batteries from overcharging and deep discharge, which can reduce their lifespan. It also allows electrical loads to be disconnected when energy levels in the batteries reach critical levels, ensuring stable and prolonged operation. Modern regulators incorporate additional functions, such as maximum power point tracking (MPPT), to optimize the energy performance of the system [4].

Batteries are also essential in autonomous solar systems, as they store the energy generated during the day for use at night or in periods of low solar radiation. Generally, lead-acid or lithium batteries are used, designed to withstand continuous charge and discharge cycles. The storage capacity of the batteries is a determining factor in the autonomy of the system, allowing it to operate for extended periods without solar generation. In addition, its design must be safe and efficient to minimize risks and maximize its useful life [4].

The Auxiliary Power System is defined as a set of devices whose main function is to provide the necessary energy for the start and proper operation of the electrical accessories associated with the main system. This system plays a crucial role in ensuring the operability and efficiency of electrical equipment, especially in situations where the primary power supply is not sufficient or requires additional support [5].

The inverter is an electronic device whose main function is to transform direct current (DC) generated by photovoltaic solar panels or stored in batteries into alternating current (AC), which is the form of electricity used in most electrical devices and power distribution systems [3]. This equipment is essential in photovoltaic systems, as it allows the energy captured from the sun to be converted into a form that can be used for household appliances and other applications.

To achieve efficient conversion, the inverter uses techniques such as pulse-width modulation (PWM), which regulates frequency and voltage to generate a stable sine wave of 50 or 60 Hz. In addition, modern inverters often include a maximum power point tracker (MPPT), which optimizes solar energy harvesting by continuously adjusting the operation to the optimal level of the PV panels. This not only maximizes the efficiency of the system, but also ensures stable operation under different solar radiation conditions [3].

4. Materials and Methods

The focus of this research is quantitative, since measurable data were collected to quantify various aspects, such as the calculation of equipment consumption and the determination of energy demand. The type of research is propositional, since it provides ideas for the solution of a specific problem: the dependence of the National Navy's Diving School on a single source of energy. The research is also cross-sectional. To explain how the results are obtained, three phases are defined, established according to the objectives set, in which the tools and techniques used for their development are indicated.

- In phase 1, the analysis and evaluation of energy demand was carried out. The activities carried out were the inventory of the equipment that will be powered by the photovoltaic solar energy system, the calculation of the approximate energy demand of each equipment and, finally, the identification of the solar energy potential in the facilities of the National Navy Diving School.
- In phase 2, the photovoltaic solar electric system was designed. This phase includes the design of an electrical system that must contain solar panels, inverters, batteries and other components of a

photovoltaic solar system, adjusted to the energy demand of the 110 V equipment of the National Navy Diving School.

- In phase 3, simulation and validation of the system, simulations were carried out using specialized PVsyst software to evaluate the performance of the system designed under different scenarios; Subsequently, the results of these simulations were analyzed and the necessary adjustments were made.

5. Results

5.1. Analysis of the approximate energy demand of the equipment projected to be used in the new ESBUC facilities and determine the energy potential

The analysis of the energy demand of the facilities of the National Navy Diving School (ESBUC) was a fundamental pillar for the design of an efficient photovoltaic solar energy system adapted to the specific needs of the institution. This analysis not only identified the approximate energy consumption of the equipment to be used, but also determined the technical basis to ensure the sustainability of the proposed system and its ability to meet the daily energy needs of the school.

The collection of information began with the construction of a representative sample of the electrical equipment that will operate in the new facilities. These equipment were cataloged based on their technical and functional characteristics, taking into account aspects such as nominal power, the number of devices, the daily hours of use, and the projected daily, monthly and annual consumption.

The approximate energy consumption of the projected equipment was calculated using the basic electricity consumption formula: multiplying the nominal power of each equipment (in watts) by the number of hours of daily use and adjusting these values according to the number of devices. This method made it possible to consolidate the total energy demand in terms of kilowatt hours (kWh), which made it easier to interpret the results for the system design. Among the most significant equipment in terms of energy consumption are sound systems, televisions, computers, fans and LED lighting systems as detailed in Table 1.

Table 1. Energy supply of ESBUC equipment.
Source: The authors.

Team	Quantity	Power (W)	Hours of daily use (h/day)	Daily consumption (kWh/day)	Monthly consumption (kWh/month)	Annual consumption (kWh/year)	Category
Desktop Computer	20	400	8	64.00	1,920.00	23,360.00	1. Office and Computing
HP Laptop	10	240	6	14.40	432.00	5,256.00	
Computer	1	240	8	1.92	57.60	700.80	
Photocopier	2	120	8	1.92	57.60	700.80	
Video beam	5	220	6	6.60	198.00	2,409.00	
Dynamic display	4	190	8	6.08	182.40	2,219.20	
Marine VHS Radio	1	500	24	12.00	360.00	4,380.00	
Coffee maker	2	195	8	3.12	93.60	1,138.80	2. Kitchen and appliances
Kettle	2	1200	2	4.80	144.00	1,752.00	
Sandwich maker	1	1200	2	2.40	72.00	876.00	
Microwave oven	2	1000	3	6.00	180.00	2,190.00	
Office fridge	2	250	24	12.00	360.00	4,380.00	
Fridge 379L	2	480	24	23.04	691.20	8,409.60	
Refrigerator 192L	1	336	24	8.06	241.92	2,943.36	
Water Dispenser	3	110	24	7.92	237.60	2,890.80	
Empanadas warming display case	1	1200	2	2.40	72.00	876.00	
Televisor Samsung 65”	10	190	6	11.40	342.00	4,161.00	3. Lighting
LED reflector	11	190	12	25.08	752.40	9,154.20	
LED Turtle	5	21	12	1.26	37.80	459.90	
LED indirecta	22	12	12	3.17	95.04	1,156.32	
Square LED	107	10	12	12.84	385.20	4,686.60	
A-Series Emergency LED	1	43.2	5	0.22	6.48	78.84	
Ceiling fan	2	900	8	14.40	432.00	5,256.00	4. Air conditioning and ventilation
Fan	2	120	8	1.92	57.60	700.80	
Extractor	7	200	8	11.20	336.00	4,088.00	

Continued on the next page

Table 1. Continued.

Team	Quantity	Power (W)	Hours of daily use (h/day)	Daily consumption (kWh/day)	Monthly consumption (kWh/month)	Annual consumption (kWh/year)	Category
Sound System	2	600	24	28.80	864.00	10,512.00	5. Audio and communication
Speaker system	1	250	6	1.50	45.00	547.50	
Plates	2	500	4	4.00	120.00	1,460.00	6. Personal Care & Cleaning
Hair dryers	1	1200	1	1.20	36.00	438.00	
Paper Shredder	3	580	2	3.48	104.40	1,270.20	
Dual GFCI 15A socket	6	180	2	2.16	64.80	788.40	7. Electrical outlets and connections
Dual socket available	16	150	8	19.20	576.00	7,008.00	

From the sample data, a daily energy consumption of 273.97 kWh/day was determined, which is equivalent to approximately 8,334.17 kWh/month if an average month of 30.42 days is considered. When projecting these values to a full year, an estimated annual consumption of 99,999.05 kWh/year is obtained. These results make it possible to identify usage patterns and prioritize critical loads, i.e., those pieces of equipment whose continuous operation is essential for school operations.

5.2. Design of the photovoltaic solar electricity system for the ESBUC facilities

The design includes the integration of photovoltaic modules, battery storage and an efficient energy distribution and conversion system, adapted to the particular characteristics of the entity. The first step in its development was to assess the energy needs of the equipment present in the facilities. Detailed information on the number, type and technical characteristics of the equipment was collected. The calculations showed a total consumption of 273.97 kWh/day, which is equivalent to an approximate monthly consumption of 8,334.17 kWh and an estimated annual consumption of 99,999.05 kWh.

The analysis of the available solar resource was carried out from the geographical location of the ESBUC (Cartagena), with coordinates of 10.42° N and -75.55° W and an altitude of 9 meters above sea level. The region has an average annual solar resource of 5.5 kWh/m²/day.

1. The optimal configurations were defined to maximize solar radiation capture:
2. Inclination of the modules: 10°, adapted to the latitude of the region.
3. Orientation: Towards the south, with an azimuth of 0°.
4. Shading conditions: An installation area free of obstructions and with an arrangement of modules that avoids mutual shading was assumed.

These configurations ensure that the modules operate at high efficiency throughout the year, even in the months of lower radiation.

5.2.1. PV System Sizing

The photovoltaic system sizing was carried out based on the estimated energy demand, the available solar resource, and the selected technical characteristics of the PV modules and storage system. The main sizing parameters are described below.

1. Total installed capacity: According to the preliminary sizing results, 120 photovoltaic modules rated at 585 Wp each were selected. The modules are arranged in 15 strings of 8 modules connected in series (see Table 2).
   The total installed photovoltaic capacity is calculated as:

$$P_{\mathrm{PV}} = N_{\mathrm{modules}} \times P_{\mathrm{module}} \tag{1}$$

   where:

   - $N_{\mathrm{modules}} = 120$ is the total number of photovoltaic modules.
   - $P_{\mathrm{module}} = 585$ Wp is the rated power of each module.

Therefore,

$$P_{\text{PV}} = 120 \times 585 = 70{,}200 \text{ Wp} = 70.2 \text{ kWp} \tag{2}$$

Thus, the total installed capacity of the photovoltaic system is **70.2 kWp**. This value is used in the estimation of the generated energy presented below and in the selection of the inverter.
The PV array is integrated with a lithium-ion battery bank designed to operate at a depth of discharge (DOD) of 80%. The detailed sizing of the storage system is presented in Section 5.2.2. The selected batteries are designed for approximately 800 cycles at 80% DOD, contributing to the continuity and stability of the power supply throughout the system's operating life.

2. PV module configuration: The photovoltaic modules are arranged in 15 strings, with 8 modules connected in series in each string. This configuration facilitates installation and maintenance while providing an appropriate electrical arrangement for energy collection and inverter operation.
The estimated area required for the photovoltaic array is approximately:

$$A_{\text{PV}} \approx 328 \text{ m}^2 \tag{3}$$

This area includes the physical footprint of the modules as well as the additional spacing required for ventilation, access, and maintenance activities.

3. Estimated daily energy generation: The average daily energy generated by the photovoltaic system is estimated using the following expression:

$$E_{\text{PV,daily}} = P_{\text{PV}} \times H_{\text{solar}} \times \eta_{\text{sys}} \tag{4}$$

where:

- $P_{\text{PV}} = 70.2$ kWp is the installed photovoltaic capacity.
- $H_{\text{solar}} = 5.5$ kWh/m^2/day is the average daily solar irradiation.
- $\eta_{\text{sys}} = 0.80$ is the assumed overall system efficiency.

Therefore,

$$E_{\text{PV,daily}} = 70.2 \times 5.5 \times 0.80 = 308.88 \text{ kWh/day} \tag{5}$$

The estimated daily generation exceeds the base energy demand of 273.97 kWh/day. The resulting energy margin is:

$$E_{\text{margin}} = 308.88 - 273.97 = 34.91 \text{ kWh/day} \tag{6}$$

This additional energy margin provides greater flexibility to accommodate temporary variations in electricity consumption and periods of lower solar irradiation.
Nevertheless, this calculation represents a preliminary estimate based on average daily values. The actual annual performance of the photovoltaic system, including seasonal variations, system losses, battery operation, and periods of energy deficit or surplus, is evaluated through the PVsyst simulation presented in Section 5.3.

5.2.2. Storage System

The storage system is essential to ensure that the energy generated during the day is available for use at night and in periods of low solar irradiation. The updated design seeks to cover 100% of the projected daily demand, with a storage capacity adjusted to 337.5 kWh, also providing additional margin for variations in consumption or emergencies.

- Battery selection: Tesla Powerwall 2 batteries, recognized for their high capacity and reliability, with a nominal capacity of 13.5 kWh per unit, were selected. These batteries stand out for their energy efficiency and scalable design, ideal for projects with high demand such as the ESBUC.

- Calculation of the number of batteries: The number of batteries required was calculated considering the total capacity needed to cover the projected daily demand and the additional margin. The calculation is as follows:

$$\text{Number of batteries} = \frac{\text{Total Capacity}}{\text{Capacity per battery}} = \frac{337.5}{13.5} = 25 \text{ batteries}$$

When rounding to the nearest integer, 25 batteries are required to meet the goal of covering 100% of the base daily demand.

5.2.3. Conversion System

The conversion system is essential to transform the energy generated by the photovoltaic modules, in direct current (DC), into alternating current (AC), which is necessary for the operation of the electrical equipment of the ESBUC facilities.

1. Inverter capacity: The selected inverter capacity rating is 70 kW, in line with the installed capacity of the solar modules (70.2 kWp). This design ensures that the system can efficiently handle the energy generated, maintaining a continuous and stable supply even during peak generation.
2. System efficiency: the inverter guarantees an efficiency of 95%-97%, minimizing energy losses during the conversion process and ensuring that the energy delivered is sufficient to cover the energy demand of the facilities.
3. Compatibility and reliability: the selection of the inverter was made considering its compatibility with the configuration of the photovoltaic system and its ability to operate in optimal conditions throughout the year, even in periods of higher solar radiation.

The capacity of the inverter and its integration with solar modules allows to reduce conversion losses, increasing the energy availability for the continuous operation of essential equipment. This approach not only strengthens energy autonomy, but also contributes to the reduction of dependence on conventional energy sources.

5.2.4. Electrical Distribution System

The electrical distribution system ensures that the energy generated and stored is efficiently delivered to ESBUC's consumption points. This system is designed to support the current PV system configuration and provide for possible future expansions. Its main components are:

Distribution Board:

1. Equipped with thermomagnetic and differential switches to protect electrical circuits and ensure operational safety.
2. Designed with sufficient capacity to handle the current generation of 308.88 kWh/day, integrating the energy supplied from the 337.5 kWh battery bank and the 70 kW inverter.
3. It includes reserve spaces for the integration of new loads, allowing the expansion of the system in case of future updates.

Wiring:

1. Selection of electrical conductors with the right gauge to minimize resistance losses and ensure efficient delivery of power from PV modules to inverter, batteries, and points of consumption.
2. It considers the distances between the different components of the system, ensuring compliance with technical standards and operational safety.

5.2.5. Monitoring and maintenance

1. Real-time monitoring: Installation of a system that allows monitoring the generation, storage and consumption of energy.
2. Preventive maintenance: Quarterly cleaning of modules and biannual review of connections.

3. Corrective maintenance: Immediate diagnosis and repair in case of failures.

This design not only ensures the safety of the system, but also allows for easy expansion in the future, integrating more solar modules or batteries as needed. Flexibility is a key aspect of the design, ensuring that it can adapt to the changing needs of the ESBUC.

To maximize the efficiency of the system, strategies were implemented to mitigate energy losses. Measures such as adequate ventilation to reduce thermal losses in the modules, the selection of homogeneous modules to minimize mismatch losses, and an optimization of the inclination and orientation to improve the capture of solar radiation were considered. These strategies ensure that the system operates as efficiently as possible and extend the life of the components.

The PVsyst V7.2.4 software played an essential role in the validation of the design, allowing the performance of the system to be simulated under various climatic and operating conditions. The simulations confirmed that the projected annual generation of the system would be sufficient to cover most of the facility's energy needs. In addition, the software made it possible to identify potential points for improvement in the design, such as the layout of the modules to minimize shading losses and the adjustment of the inverter parameters to maximize its efficiency.

5.3. Simulations of the operation of the solar photovoltaic electrical system with specialized software PVsyst V7.2.4.

The simulation of the solar photovoltaic electrical system designed for the ESBUC is essential to validate its performance under real conditions and ensure that it meets the projected energy demand. Using the specialized software PVsyst V7.2.4, the adjusted data of energy consumption, the solar resource available in Cartagena and the technical characteristics of the designed system were evaluated. The configuration used in the simulation is presented in Table 2; it allowed the identification of the energy behavior of the system and confirmed its technical and operational feasibility.

5.3.1. Simulation results

The energy balance of the photovoltaic system designed for the ESBUC is shown in Figure 1, where the different energy categories and their behaviour over the months are clearly distinguished. Unused energy (Lu), generated at times when the batteries are fully charged, averages 0.54 kWh/kWp/day. The losses associated with the photovoltaic (Lc) system, due to inefficiencies in collection and conversion, represent an average of 0.79 kWh/kWp/day. On the other hand, system losses related to battery storage and wiring (Ls) are calculated at 0.39 kWh/kWp/day. Finally, the power actually delivered to the user (Wr) remains stable throughout the year, ensuring a constant and reliable supply.

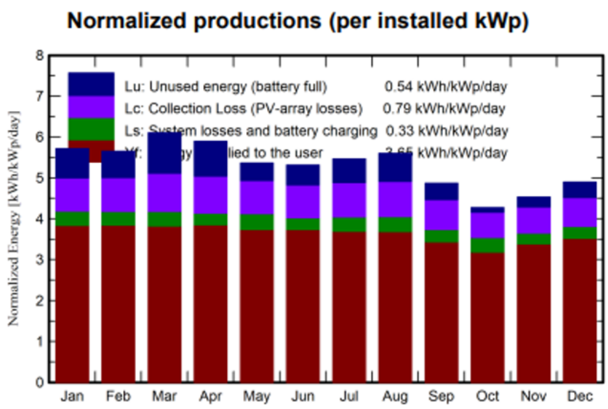


Figure 1. Standardized Production by Installed Capacity (kWp)
Source: The authors.

Figure 2 shows the Performance Ratio (PR) and illustrates the efficiency of the photovoltaic system and the solar fraction (SF) throughout the year. The PR, which measures the ratio between the energy actually

Table 2. *Simulation Configuration Parameters in PVsyst V7.2.4*
Source: The authors.

Energy demand configuration	**Daily and annual consumption:** Base daily consumption: 273.97 kWh/day. Projected annual consumption: 99,999.05 kWh/year.	**Consumption patterns:** Charging was defined as constant during the 24 hours, representing critical equipment such as lighting, refrigerators and auxiliary systems.
Solar Resource Configuration	**Geographical location:** Latitude: 10.42°N, Longitude: −75.55°W, Altitude: 9 m. Average solar irradiation: 5.5 kWh/m^2/day (Meteonorm historical data).	**Configuration of the Modules:** Inclination: 10°. Orientation: South (azimuth 0°). Shading: Shadow-free installation to maximize efficiency.
PV System Configuration	**Installed capacity:** Total rated power: 70.2 kWp. Selected modules: 120 units of 585 Wp each, organized in 15 strings of 8 modules in series.	**Total area of the modules:** Approximately 328 m^2, considering space for ventilation and maintenance.
Battery Bank Configuration	**Storage capacity:** It must cover 100% of the daily demand, equivalent to 273.97 kWh, with an additional margin that ensures the flexibility of the system in the face of variations in consumption or energy generation. Model: Tesla Powerwall 2, with a nominal capacity of 13.5 kWh per unit. No. of batteries: 25 batteries, providing a total capacity of 337.5 kWh.	**Operation parameters:** State of charge (SOC): minimum 10%, maximum 90%, ensuring efficient use of batteries and extending battery life. Storage efficiency: 95%, which minimizes losses during the loading and unloading process.
Inverter Configuration	**Rated Capacity:** 70 kW, enough to handle the energy generated and cover peaks in demand.	**Technology and Efficiency:** MPPT (Maximum Power Point Tracking) Technology: Optimizes the conversion of direct current (DC) to alternating current (AC), maximizing energy capture in all solar irradiation conditions. Minimum efficiency: 95%–97%, depending on operating conditions. This range ensures that most of the energy generated is used, minimizing losses during conversion.

harnessed and the maximum potential energy of the system, remains at an annual average of 68.8%, reflecting a typical performance for the region considering factors such as thermal and conversion losses. The designed photovoltaic system generates an annual surplus of 13,758 kWh, as a result of the high generation capacity compared to the projected demand; This surplus cannot be used in its entirety due to the saturation of the battery bank in periods of maximum generation. The solar fraction (SF) stands at 93.5%, which reflects an operating deficit of 6.5%: in annual aggregate terms, generation exceeds demand, but the time lag between generation and consumption prevents the use of all the energy produced.

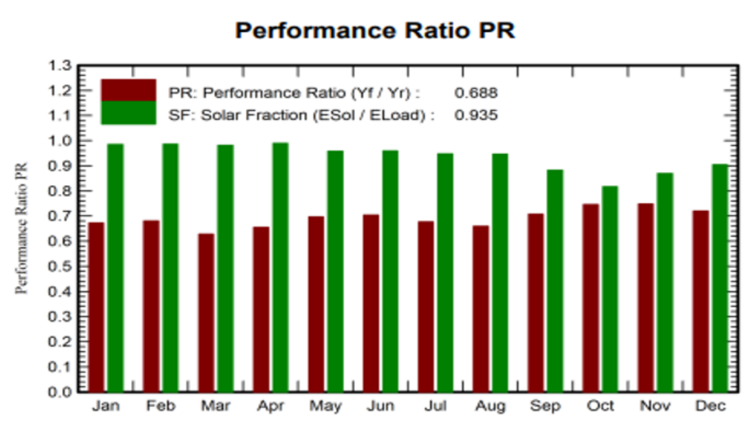


Figure 2. Performance Ratio and Solar Fraction (SF)
Source: The authors.

The analysis of the graphs confirms that the photovoltaic system designed for the ESBUC is capable of covering most of the annual energy demand with efficient and sustained performance. The energy balance highlights an annual generation of 111,354 kWh, of which 93,494 kWh are used to cover the needs of the facilities, while the surplus of 13,758 kWh offers opportunities for expansion or integration with the electricity grid. The solar fraction of 93.53% reflects that the system relies primarily on photovoltaics, minimizing the use of external sources. On the other hand, the average Performance Ratio (PR) of 68.77% remains within the typical values for the region, considering thermal, storage and cabling losses. Table 3 discusses each key variable.

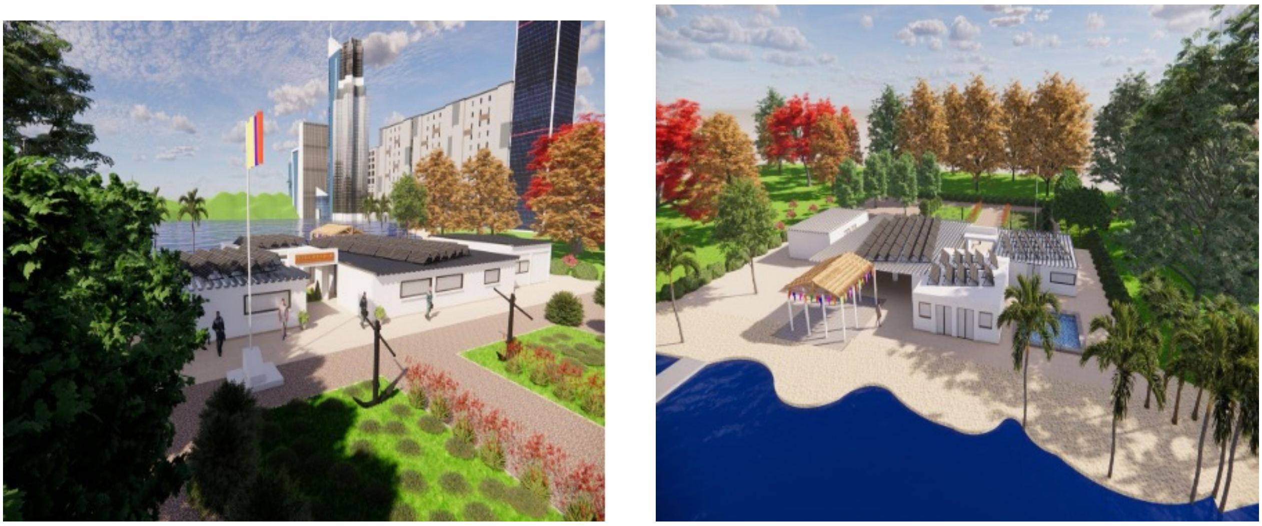
Table 3. *Key variables of the solar photovoltaic system*
Source: The authors.

Variable	**Analysis**
Global Solar Irradiance ($GlobHor$) and Corrected Efficiency ($GlobEff$)	The annual horizontal solar irradiance ($GlobHor$) is 1913.5 kWh/m^2, while the corrected irradiance ($GlobEff$), adjusted for losses due to angle of incidence and shadows, is 1890.6 kWh/m^2. This indicates a minimal loss in solar capture, which reflects an adequate optimization in the inclination and orientation of the modules. The months of greatest radiation are March, April and July, which coincides with greater energy generation.
Generated and Unused Energy	E_{Avail}: The total energy generated by the system is 111,354 kWh/year, enough to cover the projected demand of 99,960 kWh/year. E_{Unused}: However, 13,758 kWh/year is not used due to battery bank saturation, particularly in high-generation months such as March, April, and July. This shows an opportunity for optimization in storage capacity.
Missing Power (E_{Miss})	In some months, especially in October and November, the missing energy (E_{Miss}) increases significantly, reaching up to 1554 kWh in November. This is due to lower solar irradiation in these months and a constant consumption that is not fully covered by the system, generating a deficit of 6466 kWh/year, equivalent to 6.47% of the total demand.

Continued on next page

Variable	Analysis
Solar Fraction (*SolFrac*)	The average annual solar fraction is 93.5%, indicating that the PV system meets most of ESBUC's energy demand. In months such as January, February and March, the solar fraction reaches values above 98%, while in months with less irradiation, such as October and November, it decreases to values close to 82%.
Ratio of Energy Supplied (E_{User}) to Load (E_{Load})	The energy supplied to the user (E_{User}) amounts to 93,494 kWh/year, which represents an efficient use of the system. This corresponds to 93.5% of the energy needed (E_{Load}: 99,960 kWh/year). The small discrepancy is due to the inevitable losses in the system and the mismatch between generation and consumption.

The simulation confirms that the photovoltaic solar electricity system designed for the ESBUC covers 93.5% of the annual energy demand of the facilities. The adjustments made ensure long-term sustainability and operational efficiency, and ensure a positive environmental impact by reducing reliance on non-renewable sources. The losses identified are moderate and do not compromise the viability of the system, but rather pose opportunities to further optimize its performance. The two modeled system views are presented in Figure 3: Figure 3a shows the first simulation and Figure 3b shows the second.



(a) Simulation 1 **(b)** Simulation 2

Figure 3. ESBUC solar photovoltaic power system simulations.
Source: The authors.

6. Discussion

The analysis of the photovoltaic system designed for the ESBUC reflects a sustainable, efficient and technically feasible energy solution, validated through accurate and adjusted simulations. Key findings are presented below:

- Design validation: the simulation results confirm that the PV system designed for the ESBUC generates a total annual energy of 111,354 kWh/year, higher than the projected energy demand (99,999.05 kWh/year according to the equipment inventory and 99,960 kWh/year in the load modeled in PVsyst). This favorable annual balance is not equivalent, however, to 100% coverage: the solar fraction (SF), which measures the proportion of demand effectively covered by the solar energy used, is 93.5%, with an operating deficit of 6.5% (6,466 kWh/year) concentrated in periods of low generation or high demand.

The difference is explained by the time lag between generation and consumption and by the saturation of the battery bank, which prevents the use of 13,758 kWh/year of the energy generated.
- Energy efficiency: the system maintains an average Performance Ratio (PR) of 68.8%, which is within the typical values considering thermal, storage and cabling losses.
- Identification of opportunities for improvement: Although the design covers most of the projected energy demand, areas for improvement are identified: Increasing the capacity of the battery bank could reduce losses of unused energy (E_Unused) and maximize the use of the surplus generated. Integrating surplus energy into the electricity grid could represent an additional source of revenue for ESBUC and better management of the energy balance. Analyze the behavior of the system during the months with less solar irradiation (October and November) to implement adjustments that reduce the energy deficit.

As recommendations aimed at optimizing the performance and future projection of the photovoltaic system designed for the National Navy Diving School, it is highlighted that the aspects that should be prioritized are the optimization of the battery bank, in order to reduce energy deficits in periods of low irradiation and take advantage more efficiently of the surpluses generated in months of high solar production. thus strengthening institutional energy autonomy. The management of surplus energy is also seen as an important opportunity. This can be through its use in new areas of the institution or by connecting it to the electricity grid, which allows technical, economic and regulatory issues to be explored [9]. Likewise, the potential of intelligent monitoring and the use of digital technologies, including advanced control systems and artificial intelligence, to improve operational efficiency and decision-making is highlighted. Finally, the relevance of the educational, economic and replicable impact of the project is emphasized, both for training in sustainability and for its adaptation in other public institutions, consolidating it as a comprehensive model of sustainable energy management.

7. Conclusions

The design of the photovoltaic system proposed for the National Navy Diving School demonstrates the technical, environmental and operational feasibility of supplying 110 V equipment through solar energy, consolidating itself as a sustainable alternative to the use of conventional sources. The results show that an installed capacity of 70.2 kWp allows to cover approximately 93.5% of the annual energy demand, with an estimated generation of 111,354 kWh/year, which confirms that well-sized photovoltaic systems can reliably meet institutional energy needs.

Likewise, the study highlights the relevance of incorporating specialized simulation tools, such as PVsyst, to validate energy performance and estimate system losses, which are within acceptable ranges for this type of technology. From an environmental perspective, the partial replacement of conventional electricity with solar energy implies a significant reduction in CO_2 emissions, which directly contributes to the sustainability objectives of the National Navy and is aligned with its energy transition policy [1].

Finally, the project's findings suggest practical applications that can be replicated in other naval dependencies and open future lines of research aimed at optimizing energy storage, integration with the electricity grid and the combination of complementary renewable sources. Taken together, the study shows that rigorous technical planning and the use of renewable energy constitute a solid basis for strengthening energy self-sufficiency and sustainable public management.

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Authors' Biography

Katherine María Prada Sánchez is an Environmental Engineer, a Specialist in Environmental Education, and a candidate for a Master's degree in Engineering with an emphasis on Civil and Environmental Engineering. She teaches environmental management and project formulation and has experience developing formative research projects and advising undergraduate degree projects at the Diving and Salvage School of the Naval Petty Officer Academy "ARC Barranquilla".

Fernando de Jesús Aricapa Palacio is an Environmental Engineer with a Master's degree in Engineering, with an emphasis on Civil and Environmental Engineering. He is the Director of the Engineering and Industrial Environmental Technology programs at Fundación Universitaria Tecnológico Comfenalco.

MA1 Sergio Pacheco Guzmán is a technologist in the Colombian National Navy with training in electromechanics and experience in the maintenance, operation, and diagnosis of electrical and electromechanical systems and equipment. He is also a technologist in maritime and river diving and salvage and has completed Coast Guard and Surface Warfare courses, developing the skills required to work in operational and maritime environments. He is affiliated with the Naval Petty Officer Academy of the Colombian National Navy.