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Technical-economic analysis for ON/OFF GRID solar photovoltaic system design

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ABSTRACT

This manuscript presents a detailed techno-economic analysis of a hybrid solar photovoltaic (PV) system designed to operate in both grid-connected (ON GRID) and stand-alone (OFF GRID) modes. The study focuses on the Leonardo Da Vinci academic building at Universidad de Los Llanos, located in Villavicencio, Colombia, in the tropical Orinoquía region. Using local solar irradiance, temperature data, and real load profiles from the facility, the system was modeled to assess performance under true operating conditions. A key part of the system design involved a detailed shadow analysis to identify potential obstructions and optimize solar access. This step significantly improved the accuracy of energy yield predictions and contributed to long-term system reliability. Additionally, regression-based methods were used to determine optimal panel tilt angles and refine system sizing based on peak sun hours. Both ON GRID and OFF GRID configurations were evaluated in terms of energy output, levelized cost of electricity (LCOE), net present value (NPV), and internal rate of return (IRR). Results show that ON GRID systems are financially advantageous in urban environments with net metering, while OFF GRID systems are critical for ensuring energy autonomy in remote or underserved areas. The findings provide practical insights for the deployment of hybrid PV systems in institutional settings across equatorial regions.

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1. INTRODUCTION

Electricity consumption is a fundamental driver of development across all economic sectors [1], [2]. For decades, electricity generation has relied predominantly on fossil fuels [3]. However, the intensive use of non-renewable energy sources has resulted in the emission of significant quantities of pollutants into the atmosphere, accelerating global warming and causing severe environmental degradation [4].

According to the mining and energy planning unit (UPME), renewable energy sources currently account for approximately 20% of global electricity consumption, and this share is expected to increase substantially in the coming decade. Nonetheless, the International Energy Agency (IEA) reports that modern civilization remains approximately 80% dependent on fossil fuels, primarily diesel, and that rising levels of industrialization are leading to increased population density and energy demand-most of which continues to be supplied by non-renewable sources [5], [6]. This highlights the urgent need to transition toward cleaner and more sustainable energy technologies [7], such as wind, tidal, geothermal, biomass, and solar power [8], in order to reduce the global carbon footprint and mitigate greenhouse gas emissions [9].

In Colombia, hydropower represents the primary source of electricity due to the country's abundant water resources [10]. However, fossil fuels such as oil, natural gas, and coal, which are gradually being depleted, constitute the second most important energy source [4]. A promising alternative for diversifying Colombia's energy matrix is the implementation of solar photovoltaic (PV) systems [11], particularly because the country benefits from stable solar irradiance levels throughout the year due to its equatorial location [12].

In this context, numerous studies have emphasized the importance of optimizing the tilt angle of solar panels to maximize energy capture throughout the year. Accurate modeling of solar radiation on inclined surfaces, using regression analysis and isotropic or anisotropic models, has been shown to significantly improve system efficiency and reliability [13]-[16]. These approaches are especially relevant for systems deployed in regions with high solar potential, such as Villavicencio in the Orinoquía region.

Consequently, this study aims to carry out a detailed techno-economic analysis of a hybrid ON GRID and OFF GRID solar PV system designed specifically for the Leonardo Da Vinci academic building at Universidad de Los Llanos. The following sections present the methodology, simulation models, and economic evaluation criteria used in the system design and analysis.

Solar PV systems are typically categorized into four types: direct, isolated, grid-connected (interconnected), and hybrid systems. Direct systems consist of a PV array, an inverter, and the connected load, and do not store energy; their operation is directly dependent on instantaneous solar radiation. Isolated systems are commonly deployed in remote areas without grid access and include PV panels, inverters, and storage systems such as battery banks or other energy buffering technologies [17].

Grid-connected systems operate in parallel with the public electricity network. These systems are based on self-consumption of generated energy, with any surplus injected into the grid through a bidirectional meter, eliminating the need for energy storage. Their architecture includes PV panels, a grid-tied inverter, the main distribution board, and the metering system [18].

Hybrid systems combine the advantages of both isolated and grid-connected systems. They allow for both energy storage and surplus injection into the grid, thereby offering backup functionality while reducing dependency on the grid and lowering variable energy costs. This type of system typically includes PV panels, a charge controller, battery storage, a hybrid inverter, bidirectional metering, and load distribution panels [19].

The system proposed in this study utilizes hybrid PV technology due to its superior performance in balancing self-consumption, grid interaction, and energy reliability. A key component of this design is the hybrid inverter, which enables surplus energy injection into the grid and ensures continuous power supply during outages. It allows efficient use of stored energy during nighttime or grid failure scenarios [20]. Additionally, the system incorporates a maximum power point tracker (MPPT), which continuously adjusts operating parameters to extract the maximum possible power from the solar array under varying conditions [21].

In Colombia, renewable energy projects aligned with sustainability goals benefit from legal and financial incentives established under Law 1715 of 2014, which promotes the development and integration of non-conventional energy sources [22]. Compliance with registration and technical standards is required to access these incentives, and the system described herein is designed in accordance with these regulatory frameworks.

In this research we hope to achieve technical-economic study of the design of an ON GRID and OFF GRID solar PV system for the "Leonardo Da Vinci" building at the Universidad de los Llanos, in Villavicencio city, Department of Meta, Colombia. This article is divided into four sections, the introduction with an exposition of the state of the art and the objective of this work. The methodology, where the characteristics of the study and design is exposed. The results ands discussion, where the system, simulations, costs, characteristics are shown, and finally the conclusions are reached.

2. METHOD

This section outlines the methodological framework used to define the technical specifications of the photovoltaic system (PVS). The procedure begins with a comprehensive shading analysis, followed by the detailed system design, including the configuration of its components, panel orientation, and installation positioning. The case study is centered on the Leonardo Da Vinci building at the Universidad de los Llanos, located in the Barcelona campus. The exact geographical coordinates are 4.0747225° N latitude and -73.5862024° W longitude. The building comprises two levels: The ground floor contains six classrooms and a surrounding perimeter corridor. The second floor includes seven classrooms, also bordered by a perimeter corridor.

To enhance system resilience and operational flexibility, the PVS was designed as two independent subsystems-one per floor-allowing distributed load management and redundancy in energy supply. The system design accounts for the specific load profiles of each floor. Figures 1 and 2 illustrate the architectural and structural model of the building developed in SketchUp, which was used to simulate shading effects and optimize solar panel placement and orientation.

Figure 1. Layout and structural configuration of the Leonardo Da Vinci Building

Figure 2. Design overview of the Leonardo Da Vinci Building at Universidad de Los Llanos

Climatic conditions have a direct impact on the efficiency and long-term performance of PV systems, particularly in tropical environments like Villavicencio. To better understand these effects, Figure 3 illustrates the daily maximum and minimum temperatures recorded throughout 2021. These values are important for estimating temperature-related losses in PV modules [23]. The graph shows warmer periods from January to April and again from November to December, with peak temperatures reaching around 31 °C. Cooler months, such as June through August, show a slight drop, with highs around 29 °C. Despite these fluctuations, the average ambient temperature remains relatively consistent at about 25 °C throughout the year [24].

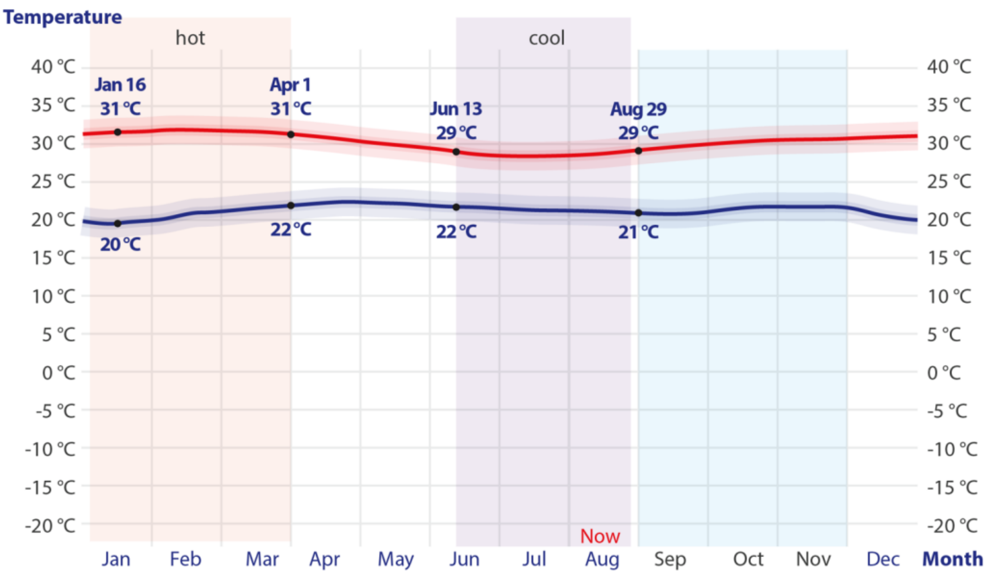

Figure 3. Average maximum and minimum temperatures in Villavicencio, Colombia, Source: ©WeatherSpark.com

To complement this, Figure 4 provides a detailed view of the average hourly temperature over the course of the year. It uses a heatmap to represent how temperature varies by time of day and month. The data show that the temperature typically ranges from 24 °C to 29 °C between 8:30 AM and 6:00 PM-prime hours for solar production. The hottest time of day, particularly from January to April and November to December, occurs between noon and 4:00 PM, when temperatures can climb up to 35 °C [24].

Solar access is also influenced by cloud cover, which affects the amount of sunlight reaching the PV panels. As shown in Figure 5, the clearest skies are observed between June and October, with August being the least cloudy month, averaging 38% cloud cover. In contrast, the cloudiest periods occur in March-April and November-December, when up to 80% of the sky is typically covered. Although cloudiness varies significantly across the year, long-term energy output can still be estimated with reasonable accuracy by averaging seasonal trends [24].

Rainfall is another environmental factor to consider in system planning and reliability. Figure 6 shows the probability of precipitation throughout the year. March and December are the wettest months, each with a rainfall probability exceeding 43%. The driest months are generally January through March and December, with the lowest probability, just 15, occurring on January 16. These patterns are useful when assessing potential disruptions and planning maintenance windows [24].

Figure 7 illustrates the variation in incident solar energy in Villavicencio throughout the year 2021. The orange line represents the daily average of shortwave solar radiation received at ground level, measured in kilowatt-hours per square meter (kWh/m²). The highest irradiance levels occur between August 15 and September 30, when values consistently exceed 5.9 kWh/m², marking the brightest period of the year. The peak day is September 13, with an average irradiance of 6.1 kWh/m². In contrast, the lowest irradiance levels are observed between October 28 and December 10, when values drop below 5.2 kWh/m², corresponding to the darkest period. The lowest point is recorded on November 15, with an average of 5.0 kWh/m² [24].

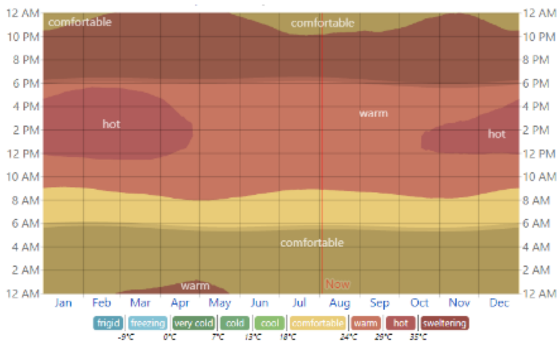

Figure 4. Average hourly temperature in Villavicencio, source: © WeatherSpark.com

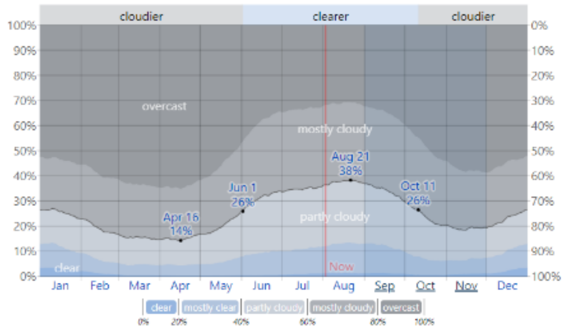

Figure 5. Average cloud cover percentage in Villavicencio, Source: © WeatherSpark.com

Figure 6. Daily precipitation probability in Villavicencio, source: © WeatherSpark.com

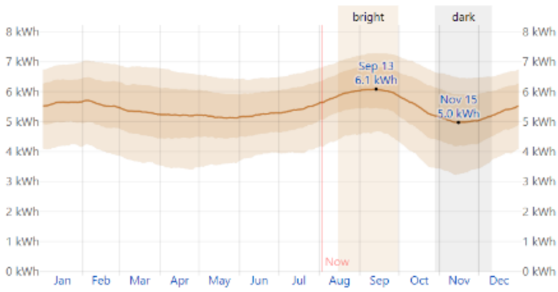

Figure 7. Daily energy probability in Villavicencio, source: © WeatherSpark.com

This seasonal profile of solar radiation, together with Villavicencio's relatively stable climate and moderate temperature fluctuations, supports the feasibility of implementing a PVS in the region. The consistent solar resource availability throughout the year reinforces the suitability of this location for reliable and efficient solar energy generation.

2.1. Potential energy use

Based on IDEAM's long-term analysis, sunshine data was collected from the Universidad de Los Llanos weather station in Villavicencio, using 24 years of historical records. As shown in Table 1, the average daily sunshine duration is 4.5 hours [25]-[27]. For the purposes of system design, this value was rounded to 5 hours of effective sunlight per day, ensuring a practical and conservative estimate for PV performance.

Table 1. Monthly averages of sunshine. Source: IDEAM Atlas

Average monthly sunshine	
Station	Unillanos / Villavicencio, Meta
Elevation (m.a.s.l.)	340
Years of Information	24
Months	Average value of sun hours per day
January	5.8
February	5.3
March	3.5
April	3.5
May/June/July	3.8
August	4.2
September	4.7
October	4.9
November	5
December	5.5
Anual average	4.5

Figure 8 shows the monthly average solar brightness in Villavicencio, while Figure 9 provides a broader view of solar radiation across Colombia. Figure 10 focuses again on Villavicencio, displaying the monthly average solar radiation levels. According to IDEAM's Solar Atlas, the Meta region receives between 4.5 and 5.0 kWh/m² per day of solar radiation. This information is essential for estimating the surface area needed to meet the energy demands of the Leonardo Da Vinci building through solar power.

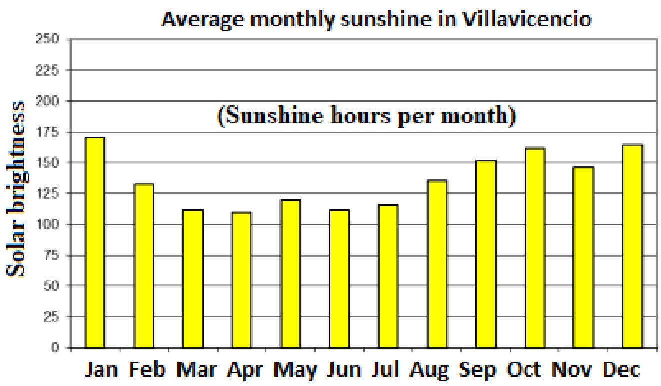

Figure 8. Monthly distribution of solar brightness in Villavicencio. Source: IDEAM Atlas

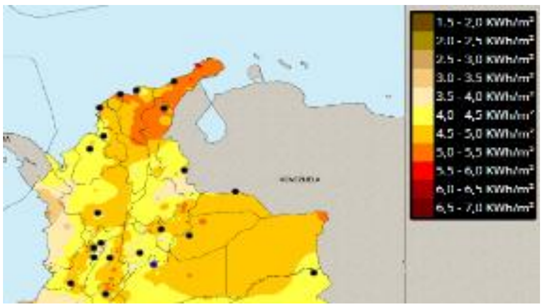

Figure 9. Average solar radiation in Villavicencio, source: IDEAM Atlas

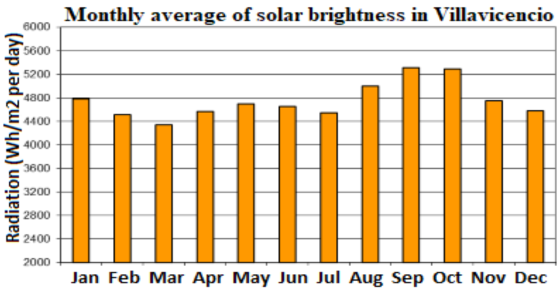

Figure 10. Monthly average of solar radiation in Villavicencio, source: IDEAM Atlas

2.2. Orientation and angle of inclination

To capture the maximum amount of solar radiation, PV panels should be oriented toward the equator. In the case of Villavicencio, Colombia, this means facing the panels south, along a northwest-southeast axis. Based on the building's location, this is the most effective direction for energy production [28]-[30]. The roof of the Leonardo Da Vinci building has a fixed slope of approximately 20°. Therefore, the solar panels will be installed directly on the roof, following its natural angle. This installation method simplifies mounting and ensures a good balance between energy performance and structural practicality. Figure 11 shows the proposed panel layout [31], [32].

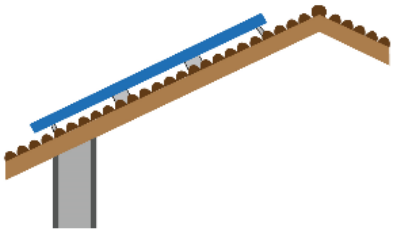

Figure 11. Case overlapping solar panel

2.3. Hybrid PV solar design

The building has two floors, each made up of classrooms and a perimeter corridor. To improve reliability and energy management, each floor is equipped with its own independent hybrid PV system. This setup allows for better control of the energy needs per floor and provides system redundancy. The hybrid system was chosen to support both ON GRID and OFF GRID modes, ensuring continuous power even if the grid fails. The next section describes the formulas and design criteria used to size the PV systems for both floors.

The installed power and the daily consumption in kWh of each classroom are calculated independently for each floor using the following equations. First, in (1), the installed power P_{inst} is determined by multiplying the equipment loads by the number of equipment n, of type i, by their consumption P_{disp}. Once the daily consumption of the loads per classroom, E, is obtained, the total daily consumption sum is calculated [33]. Subsequently, the daily (given in kWh/day) and monthly energy consumed per classroom is determined as shown in (2). The same procedure is performed for the lighting of the perimeter corridor.

Previously, according to the IDEAM study, it was decided to work with 5 hours of solar brightness, and each classroom's peak power was calculated. Therefore, the total peak power (kWp) is calculated per classroom's peak value as shown in (3). Note: All consumption values are oversized by 10% to give the system some slack.

$$P_{inst}(W) = \sum_{i=1}^{m} n_i \, P_{available}(W) \tag{1}$$

$$E(kWh/day) = P_{inst}(W) * \frac{Hours/day}{1000} \tag{2}$$

$$P_{peak}(kWp) = \frac{Consumption\left(\frac{kWh}{day}\right)}{Hours\ of\ brigthness\ solar} \tag{3}$$

$$E_{1year}(kWh) = E_T(kWh) * 1.02 \tag{4}$$

$$E_{2year}(kWh) = E_{1year}(kWh) * 1.02 \tag{5}$$

With the current value of total monthly consumption, the energy demand is projected to grow by 2% every two years for four years. With this, it is intended to give more load to the system. See (4) and (5). Therefore, the current total monthly consumption value corresponds to the four-year energy projection. With this projection value, the design power is calculated, considering that the calculated power corresponds to 75% as shown in (6).

A panel is selected for its power, efficiency, and USD/kW to determine the number of panels. This way in (7) determines the quantity of these panels.

$$P_{75}(Wp) = \frac{\frac{E_{2year}(kWh)}{30\ days}}{5\ hours\ sunshine} \tag{6}$$

$$P_{75}(Wp) = \frac{Maximum.Power.Panel*Panel.Qty}{1000} \tag{7}$$

Once the number of panels in the system is defined, the hybrid inverter is selected to be equivalent to 100% of the required peak power calculated in (3). The particularity of the selected inverter is that it contains two MPPT inputs, which allows for making an array of panels in series for each input. For the panel array, the following criteria are used, considering inverter characteristics:

- Peak power (Wp) < = Maximum power of the inverter.
- Open circuit voltage (Voc) < Maximum input voltage of the inverter.
- Maximum power voltage (Vmp) >= Inverter's operating voltage.
- Inverter short circuit current (Isc) MPP1 <= Inverter Isc MPP1.
- Short circuit current (Isc) MPP2 <= Isc MPP2 of the inverter.

Having defined the number of panels and inverters per floor, we calculate the number of batteries. For this purpose, the technical characteristics of the battery are used and the days of autonomy to support the backup power consumption are determined. In this case, a value of half a day is given.

According to the nominal battery charging voltage of the selected inverter and the calculated storage capacity, the ampere-hour (Ah) consumption required by design for autonomous operation is determined. The battery characteristics indicate the operating voltage and the Ah consumption. This data determines the number of batteries and the connection arrangement. See (8)-(11).

$$Cons.Days.Auton. = Cons.monthly * Days.Auton \quad (8)$$

$$Storage = \frac{Cons.Days.Auton}{Discharge\ Depth} \quad (9)$$

$$Cons.Days.Auton.(AH) = \frac{Storage}{Inverter\ Charge\ Voltage} \quad (10)$$

$$Number\ of\ Batteries = \frac{Cons.Days\ Auton.(AH)}{Battery\ Consumption\ (AH)} \quad (11)$$

3. RESULTS AND DISCUSSION

The following results are according to the solar PV system design for each classroom in the Leonardo Da Vinci building.

3.1. First floor

Table 2 shows the monthly, daily, and peak consumption for each classroom on the second floor, with an oversizing of 10% of the total consumption and the number of panels required for the solar PV system design. The total estimated monthly energy consumption for the second floor, including a projected 10% increase, is 1,590.6 kWh. Table 3 presents the detailed calculations based on anticipated growth, resulting in a final projected consumption of 1,654.8 kWh for the second floor.

With the consumption value of 1,654.8 kWh, the design power is calculated at 75%, i.e., 11.032 Wp. Then a projection is made at 100%, which gives a value of 14.70 Wp. For determining the design power, the solar panel's maximum power and the number of panels to be implemented in the PV system must be known. In selecting the solar panel, a LUXEN SOLAR model LNVH-590M, monocrystalline type, with a maximum power of 590 Wp. Therefore, the power value should be close to 14.70 Wp, i.e., 24 panels. Table 4 shows the values mentioned above.

Table 2. Total consumption of second floor classrooms

Floor 1	Monthly (kWh)	Daily (kWh/day)	Peak (kWp)
Classroom 1 – Network room	334	11	2.2
Classroom 2 - D	325	11	2.2
Classroom 3 - E	309	10	2
Classroom 4 – Production lab	248	8	1.6
Classroom 5 - GITECX	98	3	0.6
HALL	83	3	0.6
TOTAL	1,446	48	9.6
+10%	1,590.6	52.8	10.56
#Panels	24		

Table 3. 2% biennial growth for 4 years

FLOOR 1 - 2% biennial growth for 4 years		
Current	1590.6	kWh
2 years	1622.4	kWh
4 years	1654.8	kWh

Table 4. 100% design power

100% design power		
Peak (Wp)	%	Projection
11,032	75	
14,16	100	14,709333

Table 5 shows the characteristics of the INFINITISOLAR 3P-15 kW hybrid inverter. This inverter has an output power range of 15 kW, covering the 14.16 kW required. As the selected inverter has two MPPT inputs, 12 panels are distributed for each input. The following criteria mentioned in Table 6 must be met in this case.

Table 5. Hybrid inverter selection

Inverter characteristics			
Brand	Infinitisolar		
Model	Infinitisolar 3P 15 KW		
Maximum input power	22.5		kWp
Maximum input voltage	900		Vdc
Operation voltage	350		Vdc
Short-circuit current (MPP1/MPP2)	37.65	18.6	A
Rated power output	15		Kw
Maximum output current	21,7		A
Dimensions	219x650x820		mm

Table 6. Criteria to be met by hybrid inverter

Characteristics of the group of modules to be connected to the inverter by MPPT
Peak power Wp <= 22.5 kWp
Short circuit voltage Voc < 900 VDC
Maximum power voltaje Vmp >= 350 VDC
Short circuit current Isc (MPP1) <= 37.65 A
Short circuit current Isc (MPP2) <= 18.6 A

Table 7 show that 12 panels are placed in series in the first and second inlets, meeting the preselected criteria and with a power of 14160 W. Table 8 shows the calculated value of the storage capacity with half a day of autonomy required by the system (14160 W), i.e., 295 Ah@48 VDC. The selected battery is the KAISE brand, as shown in Table 9, with a consumption of 200 Ah. The number of batteries results in a parallel arrangement of 2 sets of 4 batteries in series. Therefore, we are providing 48 VDC with a consumption of 400 Ah.

Table 7. MPP1 panel array

	Panels array (MPP1)		
	#PANELS	12	Condition
	Voc Array	612,24	OK
	Vmp Array	521,76	OK
Serie 1 and	Isc Array	14,57	OK
Serie 2	Wp Array	7080	OK

Table 8. Battery calculation

Battery bench calculation	
Monthly consumption	14,160
Days of autonomy	0.5
Depth of discharge	0.5
Consumption with days of autonomy	7,080
Storage	14,160
System	48
Ah	295

Table 9. Battery selection

Battery selection	
Voltage	12
Ah	200
Consumption	2,400
Parallel array	1,475
In series	4
In parallel	2
Brand	KAISE
Dimensions	52.2x24x21.87 cm

3.2. Second floor

Table 10 shows the monthly, daily, and peak consumption for each classroom on the second floor with an oversizing of 10% of the total consumption and the number of panels required by the SF design. The total monthly consumption calculated for the second floor plus the 10% of oversizing is 1,428.9 kWh. Table 11 shows the values calculated according to the biannual growth of 2% for 4 years. This results in a consumption of 1,486.7 kWh for the second floor. With the consumption value of 1,486.7 kWh, we calculate the design power at 75%, i.e., 9.91 Wp. Therefore, the power value at 100% should be close to 13.21 Wp. In this case, with 22 panels and a maximum power of 590 Wp, a value of 12.98 kWp is obtained, as shown in Table 12.

Table 10. Total consumption of second floor classrooms

Floor 2	Monthly (kWh)	Daily (kWh/day)	Peak (kWp)
Classroom 1 – DaVinci 205	47	2	0.4
Classroom 2 - ES	56	2	0.4
Classroom 3 - B	347	12	2.4
Classroom 4 – A	330	11	2.2
Classroom 5 – Office 1	105	4	0.8
Classroom 6 – Office 2	73	2	0.4
Classroom 7 - Lab	187	6	1.2
HALL	154	5	1
TOTAL	1,299	44	8.8
+10%	1,428.9	48.4	9.68

Table 11. 2% Biennial growth for 4 year

Floor 2 - 2% biennial growth for 4 years		
Current	1,428.9	kWh
2 years	1,457.5	kWh
4 years	1,486.7	kWh

Table 12. 100% design power

100% Design power		
Peak(kWp)	%	Projection
9.911	75%	
12.98	100%	13.215111

Table 6 outlines the technical specifications required for the inverter, which are met by the selected INFINITISOLAR 3P – 15 kW hybrid inverter. This model supports a maximum output power of 15 kW, adequately covering the system’s demand of 12.98 kW. Given that the inverter is equipped with two independent MPPT inputs, the PV array is divided accordingly, with 11 panels connected in series to each MPPT input. The design criteria for this configuration are detailed in Table 7. As confirmed in Tables 13 and 14, both the first and second MPPT inputs receive 11 panels in series, fully complying with the electrical and operational requirements specified for the system.

Table 13. MPP1 panel array

	#PANELS	11
Serie 3	Voc Array	561.22
	Vmp Array	478.28
	Isc Array	14.57
	Wp Array	6490

Table 14. MPP2 panel array

	#PANELS	11
Serie 4	Voc Array	561.22
	Vmp Array	478.28
	Isc Array	14.57
	Wp Array	6490

Table 15 shows the calculated value of the storage capacity with half a day of autonomy required by the system (12980 W), as well as the ampere-hour consumption (270 Ah) with the charging voltage required by the hybrid inverter system (48 VDC). The selected battery is the KAISE brand, with a consumption of 200 Ah, as shown in Table 16. The number of batteries required corresponds to a parallel arrangement of 2 sets of 4 batteries in series, providing 400Ah@48V.

Table 15. Battery calculation

Battery bench calculation	
Monthly consumption	12,980W
Days of autonomy	0,5
Depth of discharge	0,5
Consumption with days of autonomy	6,490
Storage	12,980
System	48VDC
Ah	270,41667

Table 16. Battery selection

Battery selection	
Voltage	12
Ah	200
Consumption	2,400
Parallel array	1.35
In series	4
In parallel	2
Brand	KAISE
Dimensions	52.2x24x21.87 cm

3.3. Shadow analysis simulation

Using the online software SketchUp, the behavior of the shadows on the study building is projected. It allows the evaluation of possible obstacles affecting the solar radiation output of the solar panels [34], [35]. Figure 12 shows the behavior of the day 15/04/2022 between 9:00 am and 3:00 pm, showing a feasible design to obtain energy between 5 and 6 hours during the day.

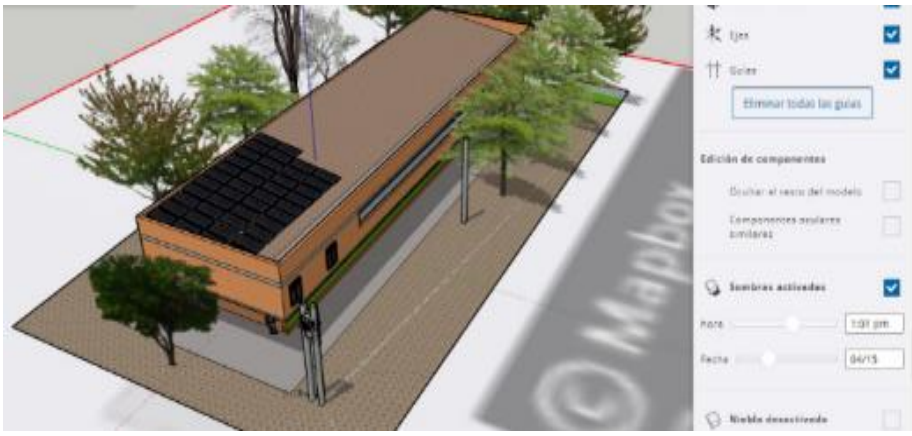

Figure 12. Shadow analysis using SketchUp

3.4. Wiring diagrams

The electrical wiring diagrams for the proposed hybrid PV system are presented below. Figure 13 illustrates the configuration of Series 1 and Series 2, connected to the MPP1 and MPP2 inputs of the 15 kW hybrid inverter assigned to the second floor. This series arrangement delivers a total DC input power of 14,160 W. Figure 14 shows the battery bank configuration connected to the load input of the same 15 kW inverter. The battery system is designed to operate at 48 VDC with a storage capacity of 400 Ah, ensuring adequate backup for essential loads. In addition, Figure 15 displays the second set of PV strings—Series 3 and Series 4—also connected to the MPP1 and MPP2 inputs of another 15 kW hybrid inverter. This array provides a total input power of 12,980 W, completing the second-floor system design. Figure 16 shows the second-floor design corresponding to a battery array with a hybrid inverter of 15 kW. The array gives a battery DC bus of 48 VDC at 400 Ah. The proposed solar PV system is shown in Figure 17.

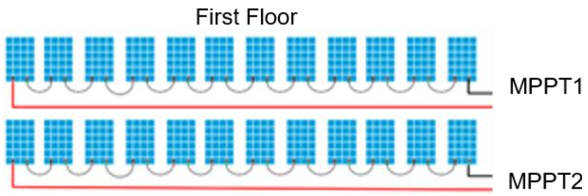

Figure 13. Series 1 and 2 array of solar panels. Inverter No. 1

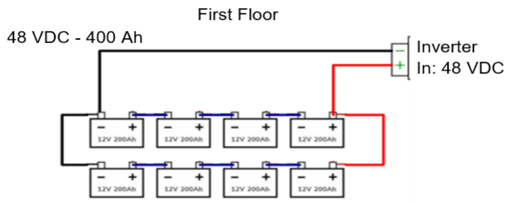

Figure 14. Battery arrangement for inverter #1

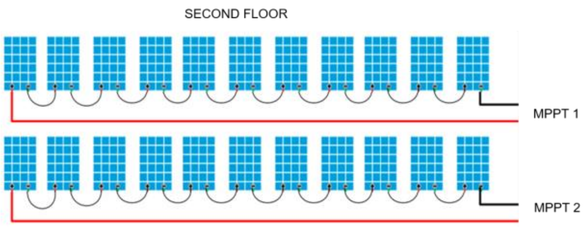

Figure 15. Series 3 and 4 array of solar panel

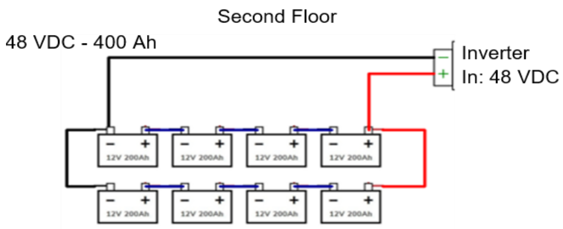

Figure 16. Battery arrangement for inverter #2

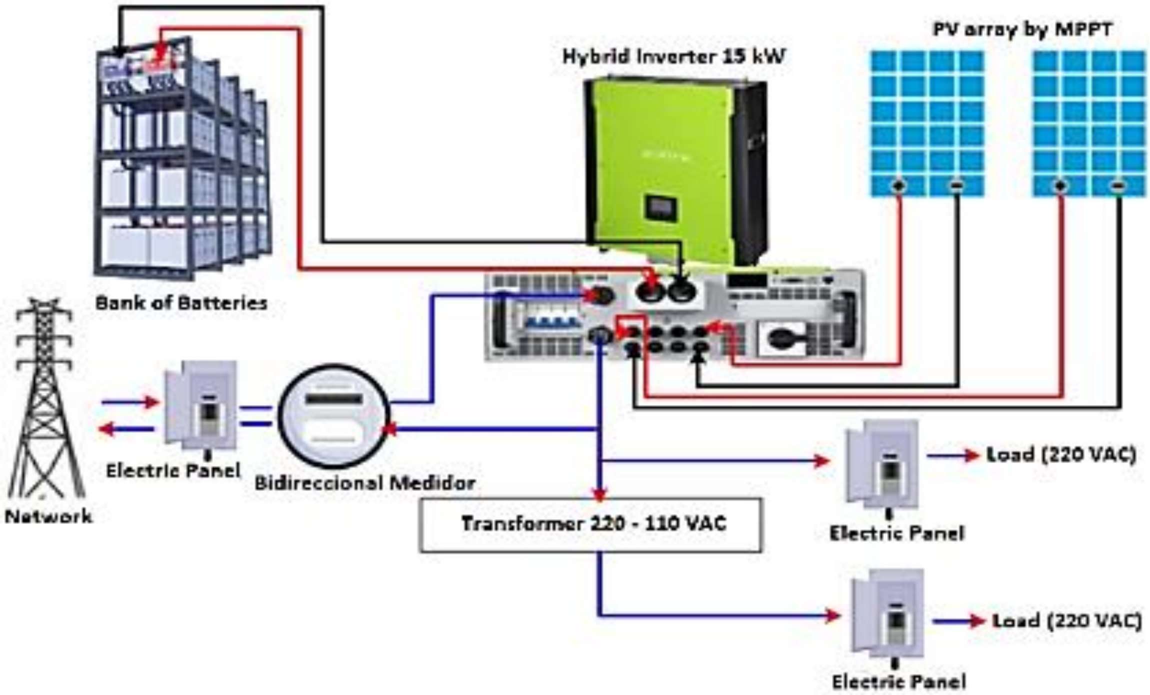

Figure 17. Hybrid SPV connection diagram

3.5. Budget and bill of materials

According to the design's needs, the project's economic aspects are reflected. Therefore, it demonstrates its cost and economic recovery in the long term. In Table 17. The total cost of the design is COP $101,094,100; it is USD $25,300.

Table 17. Bill of materials and costs

Component	Quantity (Floor 1)	Quantity (Floor 2)	Unit value ($)	Total (Floor 1) ($)	Total (Floor 2) ($)	Overall total ($)
Solar Panel (Luxen Solar)	24	22	1,062,000	25,488,000	23,364,000	48,852,000
Inverter Infinitisolar 3P 15 KW	1	1	9,800,000	9,800,000	9,800,000	19,600,000
Batteries KAISE 12 V-200 Ah	8	8	1,299,000	10,392,000	10,392,000	20,784,000
Tube Cunduit 1"x3m	5	5	13,100	65,500	65,500	131,000
Elbow 1"	5	5	1,900	9,500	9,500	19,000
Bidirectional Three-phase meter LY-SM300	1	0	1,061,480	1,061,480		1,061,480
Cable 10AWG Black (meters)	16	16	4,390	70,240	70,240	140,480
Cable 10AWG Red (meters)	35	35	4.390	153.650	153.650	307.300
Straight connectors MC4	50	46	8.990	449.500	413.540	863.040
Transformer 220/110 Vac SOLIS 30 A	1	1	3.817.900	3.817.900	3.817.900	7.635.800
Metal Clamp 1"	20	20	900	18.000	18.000	36.000
Accessories (Screws, fasteners, straps)	1	1	150.000	150.000	150.000	300.000
Battery conectors	8	8	4.000	32.000	32.000	64.000
Battery Rack	1	1	150.000	150.000	150.000	300.000
Labor	1	1	500.000	500.000	500.000	1.000.000
			Total			101.094.100

4. CONCLUSION

The technical and economic analysis conducted in this study confirms the feasibility of implementing a hybrid solar PV system for the Leonardo Da Vinci building at Universidad de Los Llanos, located in Villavicencio, Colombia, The assessment incorporated 24 years of historical meteorological data, detailed climate behavior from the year 2021, shading analysis, and simulation-based modeling, The results highlight the region's favorable solar potential, with average daily solar radiation between 4.5 and 5.0 kWh/m² and consistent sunshine hours throughout the year, making the site highly suitable for solar energy generation.

The design process considered both ON GRID and OFF GRID operational modes to ensure flexibility, energy autonomy, and resilience. A hybrid inverter was selected to support both configurations, allowing the system to operate seamlessly with or without grid availability. Essential electrical loads were identified, excluding high-consumption equipment such as air conditioners to maintain system efficiency and economic viability. Load distribution, system sizing, tilt angle optimization, and shadow analysis were key factors in defining the final design.

Although the initial investment is relatively high, the projected return on investment is expected within 4 to 5 years, supported by reduced electricity consumption and national incentives provided under Law 1715 of 2014. This study provides a scalable and replicable model for institutions in equatorial regions seeking energy independence through hybrid solar PV systems, and supports Colombia's transition to a cleaner, more sustainable energy matrix.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

Not applicable as it requires the involvement of personnel from outside the work team, no sensitive information was handled.

ETHICAL APPROVAL

Not applicable in the research.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [J.E.M.B.], upon reasonable request.

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