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VISIÓN ELECTRÓNICA

A CASE-STUDY VISION

Energy use of roofs in residential buildings

Aprovechamiento energético de cubiertas en edificios residenciales

Luz Aída Castiblanco Forero [1], *Germán López Martínez* [2]

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ABSTRACT

To promote the energy transition and reduce the carbon footprint, a methodology for the design of photovoltaic solar systems in residential buildings is shown, through a case study taking advantage of the roofs of the building, to promote the self-generation of the partial or total energy demand of the common areas. Eight stages are contemplated, including: first, the determination of the energy demand of the building; second, the solar energy assessment of the sector using software such as Nasa Power, JRC European Commission, etc.; third, the comparison of these two data to define the percentage of energy demand to be covered; fourth, the preliminary selection of equipment adjusted to the requirement to be supplied; fifth, the availability of deck spaces for installation; sixth, the identification of the percentage of the energy requirement to be covered, considering aspects such as the generation of power peaks which it is recommended to exclude from the system, to give greater stability to it; seventh, the detail design; and eighth, the technical-economic evaluation of the solar system, to determine its economic viability. A case study is presented, where up to 80% of the demand can be covered and a projection of the return on investment and viability of the proposal.

RESUMEN

Con el fin de promover la transición energética y disminuir la huella de carbono, se muestra una metodología de diseño de sistemas solares fotovoltaicos en edificios residenciales, edificios de oficinas, centros comerciales, centros de salud y centros educativos aprovechando las cubiertas de estos, impulsando la auto generación para la demanda energética parcial o total de las zonas comunes. Se contemplan ocho etapas que incluyen: primero, la determinación de la demanda energética de la edificación; segundo, la valoración energética solar del sector mediante software como Nasa Power, JRC European Comission, etc.; tercero, la comparación de estos dos datos para definir el porcentaje de demanda energética a cubrir; cuarto, la selección preliminar de equipos ajustados al requerimiento a suplir; quinto, la disponibilidad de espacios de cubiertas para instalación; sexto, la identificación del porcentaje del requerimiento de energía a cubrir considerando aspectos como la generación de picos de potencia los cuales se recomienda excluir del sistema,

1 Electromechanical Engineering, Escuela Tecnológica Instituto Técnico Central. E-mail: lacastiblancof@itc.edu.co
2 PhD in Electrical Engineering, Universidad Distrital Francisco José de Caldas. Master's degree in mechanical engineering, Universidad de Los Andes. Specialist in technology education, Mechanical Engineer. Professor, Escuela Tecnológica Instituto Técnico Central. E-mail: galopezm@udistrital.edu.co

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para darle mayor estabilidad al mismo; séptimo, el diseño de detalle; y octavo, la evaluación técnico-económica del sistema solar para determinar su viabilidad económica. Posteriormente, se presenta un caso de estudio que evidencia que se puede cubrir hasta un 80% de la demanda y una proyección del retorno de la inversión y la viabilidad de la propuesta.

1. Introduction

Many residential complexes in Colombia and most rural areas have roofs that represent up to 90% of the total land area. The high levels of solar radiation in rural areas make solar electricity generation systems a viable option for many homes. This technology offers the possibility of achieving access to electricity for the most remote places and savings in the cost of electricity. It also provides the opportunity to generate additional income that can be used to finance the same project. However, this potential is not currently being fully exploited by construction companies and developers in new construction projects.

The UPME's report, "Integration of Renewable Energies," indicates that Colombia has an average irradiance of 4.5 kW-h/m²/d, which surpasses countries such as Germany (3.0 kWh/m²/d). In terms of W-h/m²/d, Colombia currently has higher rates of photovoltaic generation than countries such as Germany and Italy, which have average rates of 3.9 kWh/m²/d [1].

2. Methodology

This methodology entails a series of steps designed to efficiently determine the energy use of roofs of horizontal properties in particular, residential complexes and shopping or business centers.

The phases are outlined below:

- The first step is to determine the energy demand of the building. This is followed
- By a solar energy valuation of the sector, which can be carried out using software such as NASA Power or the JRC European Commission.
- A comparison of the two data sets is then conducted to define the percentage of energy demand that is to be covered.
- Following this, a preliminary selection of equipment is made, with the aim of ensuring that it is adjusted to the requirements that are to be supplied.
- The availability of deck spaces for installation is then considered.
- The percentage of the energy requirement that is to be covered is identified, with consideration given to aspects such as the generation of power peaks. It is recommended that these are excluded from the system, to give greater stability to it [2].

2.1. Determination of the energy demand of the building

To ascertain the energy demand of the building, it is essential to determine the average energy consumption in the areas where the system is to be implemented. This data can be obtained from the billing records of the network operator that supplies the service. In the case study, a total of nine common areas were identified, each containing an electric meter which includes the entire lighting system, in addition to two elevators and the injection and ejector pumps. A study of the time of use of luminaires, elevators and pumps over a fourteen-day period was conducted. This resulted in the estimated daily percentage use of electricity, which yielded the following values: 35%, 15%, and 50%, respectively [3]. For the purposes of calculation, the data obtained is contrasted with the record of monthly consumption billing over a period of one year. Particular attention is paid to the areas that will be subject to substitution with the photovoltaic solar system, which serves to confirm the accuracy of the assumed demand data. An alternative approach is to ascertain the electrical plans and installations, thereby verifying the loads or installed power, and to conduct an inventory of the equipment that is to be included in the system, should access to such information be available [4].

2.2. Solar energy valuation of the sector where the building is located

A number of applications are available which provide real-time data on irradiance and solar radiation. These can be used to determine the solar hours, which indicate the optimal inclination for solar panels in order to maximize energy generation. Examples of such applications include NASA POWER, JRC PVGIS, Valentin, and others. This information is crucial for the effective design of solar systems and the optimization of their performance, which can have a substantial impact on the generation of clean and sustainable energy [5].

2.3. Comparison of collected information

Once the usable amount of radiation for energy generation has been defined, the requisite energy supply is calculated. The peak solar hours (PSH), the irradiance captured during this period, the angle of inclination at which the equipment or panels can be installed, and other pertinent factors are then evaluated. A summary table is then constructed, in which the data collected in the preceding stages are recorded for subsequent application in the sizing of the proposed solar system.

2.4. Preliminary selection of equipment adjusted to the requirement to be supplied

Once the relevant aspects have been defined, including the radiation of the area, the peak solar hours, the demand to be supplied, and the areas available for installation, the next step is to identify the components or equipment that offer the greatest efficiency and effectiveness in energy generation. It is also essential to determine whether the system will be autonomous or connected to the grid [6].

2.5. Availability of deck spaces for installation

They can represent an extensive area where the installation of clean and renewable energy generators from solar radiation is feasible. It is imperative that this step is undertaken with accurate and detailed information about the property and its covering in place. This can be accomplished by examining architectural floor plans, if available, as they provide precise data regarding the dimensions and orientation of the roofs. Furthermore, the utilisation of aerial surveys, whether through satellite images or drones, enables the acquisition of a more comprehensive and up-to-date representation of the layout, along with potential obstacles or shadows that may impact the efficiency of solar panels.

It should be noted that the available areas do not necessarily offer the space required for the installations of photovoltaic equipment, an aspect that must be taken into account if it is proposed to supply the entire energy demand of the construction, in case this situation arises, it will be necessary to specify what maximun percentage of the energy of the energy requirement could be covered [7].

2.6. Percentage of the energy requirement to be covered

To ascertain the percentage of demand to be covered, as previously discussed, a balance must be struck between the available area, the energy need, the budget, and the return on investment time. Accordingly, in the case study, it is determined that only the percentage corresponding to the lighting of the social areas will be addressed, as including all the demand would necessitate the consideration of factors such as the generation of power peaks for equipment such as pumps and lifts. These have been observed to have particularly high and transient electrical demands that occur at specific times of the day [8].

2.7. Detail design

A comprehensive design for the solar PV system entails the production of technical drawings, detailed schematics, and comprehensive operational documentation for the system's installation and subsequent functionality. The following steps are recommended for the comprehensive design of the solar PV system:

- Mounting design: Design the mounting system for solar panels on roofs, on the ground, or on other structures. The design must comply with local building codes and ensure the safety and stability of the system.
- Electrical Design: A diagram should be created which provides a comprehensive and detailed representation of the way the venue's solar panels, inverters, batteries (if used), and electrical distribution system will be connected. (Single line plans demonstrating compliance with NTC 2050 Art. 690 RETIE).
- Battery selection (if needed): If the system in question necessitates the incorporation of energy storage, it is then incumbent upon the designer to select the most appropriate batteries and to determine their capacity and location within the overall design.
- Wiring Design: Specify the gauge and type of wiring needed to connect all system components. Ensuring wiring meets electrical and safety standards.
- Technical Documentation: It is necessary to create comprehensive documentation that includes, the following elements: design drawings, equipment specifications, installation instructions, performance calculations, electrical diagrams, and other technical details.
- Regulatory compliance: Ensure that the design complies with local, regional, and national regulations and standards related to solar PV systems.
- Installation Plan: A comprehensive installation plan should be developed, which includes a detailed work sequence, a bill of materials, and instructions for the safe and efficient installation of the system.
- Functional tests: It is imperative that the system undergoes exhaustive testing to ascertain its optimal functionality prior to its official implementation. It is necessary to make the requisite adjustments and configurations to the components.
- Final documentation: The final documentation should include warranty information, user manuals, and any other details relevant to system owners or operators [9].

2.8. Technical-economic evaluation of the solar system and feasibility

The key takeaways from this evaluation are:

2.8.1. Technical aspects

In terms of technical aspects, the efficiency of the designed system is evaluated, its adequate sizing is determined, and its location and assembly are assessed to ensure access for the necessary and timely maintenance of the equipment. Additionally, energy compatibility is considered, which entails ensuring that the photovoltaic solar system is compatible and safe when connected to the grid, in accordance with Colombian regulations for these facilities and in coordination with the network operator of the sector. Furthermore, the costs of the installation are evaluated to ensure consistency with its efficiency [10].

2.8.2. Economic aspects

The efficiency of the designed system is evaluated, proper sizing is determined, and its location and installation are studied to ensure access for necessary and timely maintenance of the equipment. In addition, energy compatibility is considered, which includes ensuring that the photovoltaic solar system is compatible and safe when connected to the grid, in accordance with Colombian regulations. Finally, the cost of the installation will be the basis for the determination of the viability of the project.

3. Case Study

The Solera PH residential complex is in the municipality of Madrid Cundinamarca, in the province of Sabana Occidente, approximately 25 kilometers from Bogotá. It consists of six two-story buildings with a total of 624 residential units and occupies an area of 15 hectares. The total area of the complex is 15,096.90 square meters, of which approximately 14% (6,948 square meters) are the roofs of the buildings and the social and common areas [11].

3.1. Determination of energy demand.

As shown in Table 1, the information used to determine the energy requirements for the Solera apartment complex represents the energy service bill for a period between the years 2021 and 2022.

As can be seen, the months with the most representative consumption correspond to March and July (2022), and the areas with the highest consumption are the pumps and Tower 6, which at the time of the analysis had more inhabitants than the other towers, being one of the first to be delivered to its owners. The final average shows a daily consumption of 297.63 kWh, a value that serves as a reference for the calculations and sizing of the system [12].

3.2. Solar energy valuation of the sector where the building is located

The Solera PH residential complex is located at latitude 4.733 and longitude -74.267. Based on data from the Solar Atlas and sources like NASA POWER, this area receives an annual irradiance of 1299

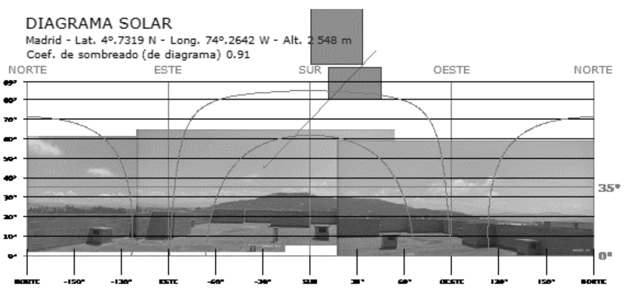
Table 1. Energy consumption of Solera PH common areas.

DAYS	PUMBS LOBBY AND SOCIAL ROOM		TO1 SOCIAL ROOM		TO Y TO2		TO3		TO4 Y TO5		TO4 Y TO5		TO6		BCI		Total daily demand kWh
	MONTHLY	DAILY	MONTHLY	DAILY	MONTHLY	DAILY	MONTHLY	DAILY	MONTHLY	DAILY	MONTHLY	DAILY	MONTHLY	DAILY	MONTHLY	DAILY	
29	4000	137,93	0	0	802	27,66	800	27,59	830	28,62	844	29,10	982	33,86	0	0	284,76
33	4720	143,03	0	0	904	27,39	940	28,48	910	27,58	1001	30,33	1122	34,00	0	0	290,82
30	4320	144,00	0	0	841	28,03	870	29,00	752	25,07	854	28,47	1035	34,50	0	0	289,07
30	4400	146,67	0	0	824	27,47	825	27,50	842	28,07	747	24,90	1035	34,50	0	0	289,10
29	4640	160,00	0	0	891	30,72	887	30,59	971	33,48	878	30,28	1140	39,31	0	0	324,38
29	4320	148,97	0	0	790	27,24	827	28,52	855	29,48	835	28,79	1085	37,41	0	0	300,41
30	4320	144,00	0	0	822	27,40	785	26,17	815	27,17	887	29,57	1095	36,50	0	0	290,80
28	4160	148,57	0	0	771	27,54	755	26,96	758	27,07	796	28,43	1116	39,86	0	0	298,43
33	5200	157,58	0	0	922	27,94	878	26,61	945	28,64	1023	31,00	1291	39,12	0	0	310,88
271	40080,0	1330,74	0,00	0,00	7567,0	251,4	7567,0	251,4	7678,0	255,2	7865,0	260,9	9901,0	329,1	0,00	0,00	2678,64
	4453	147,86	0	0	840,78	27,93	840,78	27,93	853	28,35	874	28,99	1100	36,56	0	0	297,63

Source: Own based on OR Enel - Codensa turnover.

kWh/m2, with an average of 3.6 hours of sun per day. The recommended tilt angle for solar panels is 23° at 0° azimuth. Being close to the equator, Madrid Cundinamarca experiences direct solar radiation, with a shading coefficient of 0.9, indicating minimal shading (Upme-Ideam, 2014). Figure 1 shows the specific irradiance levels for the residential complex in the Solera PH case study, essential data for the design of the solar system presented in this report, and this information is used to calculate the solar system in this document. [13]

Figure 1. Solar diagram Solera PH.



Source: Own design based on Solarius PV software.

3.3. Comparison of collected information

Table 2 shows the collected information that is the basis for the sizing of the photovoltaic solar system. It is important to clarify that for this specific case only the lighting demand is considered.

Table 2. Information Collected.

Item	Value
Annual irradiance	1299 kWh/m2
HSP	3,6
Angle tilt panels	23°
Total daily energy demand	297.63 kWh
Energy demand for lighting	104 kWh

Source: own from Atlas Solar [3].

Table 3 shows the breakdown of energy consumption in relation to the demand for pumps, elevators and lighting. The energy demand for lighting corresponds to 107 kWh of real data and was estimated at 120 kWh of energy, since the occupancy rate of the common areas was 89% during the survey; Over time, the occupancy rate gradually increased to 95% and has remained stable.

Table 3 shows the percentage of energy demand, where the pumps have the highest percentage of consumption, which is 50%, and the lighting, which is the aspect that is going to be supplied, has 35%.

Table 1. Installed power vs consumption years 2021-2022.

EQUIPMENT	INSTALLED POWER			DEMAND		
PUMPS	181	KVA	53%	148	kW/h	50%
ELEVATORS	56	KVA	16%	46	kW/h	15%
LIGHTING	107	KVA	31%	104	kW/h	35%
TOTAL	344	KVA	100%	298	kW/h	100%

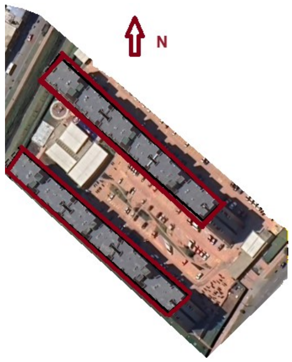
Source: Own based on Enel-Codensa invoicing.

3.4. Preliminary selection of equipment adjusted to the requirement to be supplied

To select the equipment, the data previously collected in the previous sections is taken, considering the availability of space on the roofs of the buildings. To do this, a photographic study of the roofs is carried out and then they are analyzed with reference to the plans provided by the complex administration. In addition, satellite images provided by NASA through Google Earth are used, as can be seen in Figure 2; these spaces are outlined in red. [14]

Figure 2 illustrates the portion of the roof structure pertaining to the six double towers, comprising 13 floors with a collective surface area of 15,090 m².

Figure 2. Satellite photo of Solera PH roofs.



Source: own.

The following information has been extracted from: https://earth.google.com/web/@4.73131005,-74.28147822,2544.49314969a,524.37584867d,35y,87.68238871h,0t,0r

The data in Tables 2, 3 and 4 will be used to determine the most appropriate equipment for the sizing of the solar system.

It is important to consider the recommendations made in Phase 1, which suggest proposing a grid connected system to achieve a shorter payback period [15].

Table 2. Data to calculate Photovoltaic generation power.

Variable	Value
Monthly Irradiance**	110.51 kWh/m2
Panel tilt angle	23°
Safety factor	1,5***
Expected consumption	120 kWh

Source: Own from [5].

** Ideam

Then, the following calculations are made, with the equations:

$$Average\ daily\ consumption = L_{dm} = 120\,\frac{kWh}{day}\ (1)$$

$$\min i\,mum\ daily\ irradiation\ received = 3{,}68\,\frac{Wh}{m^2}\,per\ day\ (2)$$

$$onthly\ received\ irradiance = 110{,}54\,\frac{kWh}{m^2}\,Mounth\ (3)$$

$$Total\ system\ power\ rating = ▯\{F\_\{SG\} \cdot L\_\{dm\}\}\{\^\{Irradiance\}\} = ▯\{1{,}5 \cdot 120.000W\}\{3.68\ W\} = 48.913\ Wp$$

Where: FSG=Safety factor. Ldm = Monthly demand. HSP= Peak Solar Time

Table 5 presents the principal data for the sizing of the solar system.

Table 3. On Grid System Sizing.

On Grid System Sizing	
Total daily demand required Wh/day	Article 120.000
Solar irradiation Madrid Cundi W/m²/day	3.683
Work performance	0,85
Power of the Wp Module	545
Safety factor	1,5
Photolvotaic Power Wp	48.913
Total Solar Panels Reference 545W JA Solar Mono PERC	90
Unit area of module^{m2}	2,58
Area total requerida m²	237,36
Unit weight of the module kg	27,8
Total weight of modules system kg	2.495,02

Source: Own from [16].

Table 5 llustrates the requisite equipment selected for the sizing of the system. It indicates that, for a peak power of 48.913 Wp, 90 panels of 545 W monocrystalline can be utilized.

3.5. Availability of deck spaces for installation

Upon analysis of the floor plans provided by the administration and subsequently ratified by satellite, according to Figure 2, Table 6 identifies the distribution of the spaces of the common areas, as well as any potential available areas for the installation of the proposed photovoltaic solar system.

Table 4. Distribution of common areas Solera PH Residential Complex.

AREA	m²	%
DECKS 6 TOWERS	4.948,00	33%
SOCIAL ZONE	715,17	5%
GOAL	294,71	2%
CAR PARK	9.132,12	61%
TOTAL	Question 15.090.00	100%

Source: Own based on floor plans provided by the Solera administration.

As the proposed system is connected to the grid, there is no need to define storage equipment, batteries and charge controllers. However, it is necessary to define the current inverters in order to ensure they meet the previously outlined requirements. The selection of suitable inverter equipment for the efficient operation of the system is presented below, with the following equations used for this purpose.

$$Operating\ power = \frac{Inversor\ power}{0{,}96} \quad (6)$$

$$Operating\ power = \frac{10000}{0{,}96} = 10417W \quad (7)$$

$$Number\ of\ investors = \frac{Rated\ system\ power}{Inverterd\ rated\ power} \quad (8)$$

$$Number\ of\ investors = \frac{48913\ W}{10417\ W} \quad (9)$$

As evidenced in the results obtained from the equations, it is necessary to use 5 inverters with arrays of 18 panels each. Thus, the investor registered in table 7 is selected.

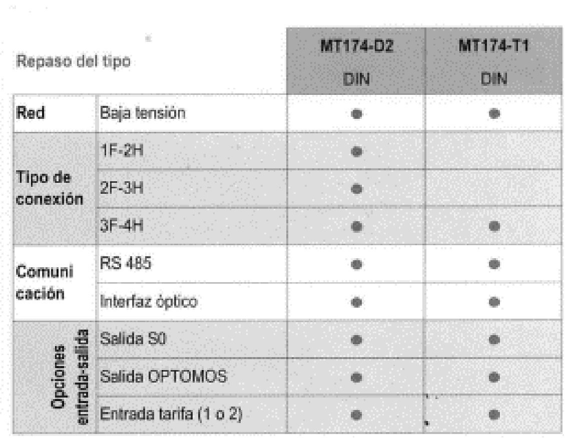
Table 5. Solar System Inverter Selection

System Power Rating (W)	**Question 48.913**
Minimum Inverter Power (W)	**10.000**
Number of Inifini Solar Three Phase On Grid Inverter Inverters	**5**

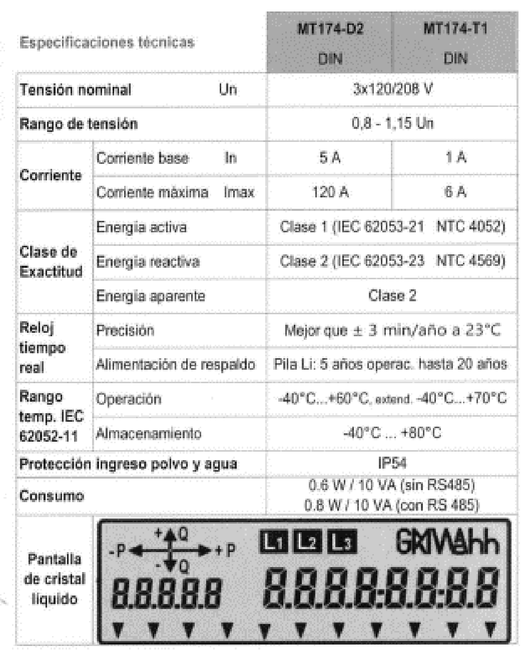
Source: Own

Another piece of equipment necessary for the operation of the system is the bidirectional meter that has the following characteristics:

Table 6. Features Bidirectional meter.



Repaso del tipo		MT174-D2 DIN	MT174-T1 DIN
Red	Baja tensión	●	●
Tipo de conexión	1F-2H	●	
	2F-3H	●	
	3F-4H	●	●
Comunicación	RS 485	●	●
	Interfaz óptico	●	●
Opciones entrada-salida	Salida S0	●	●
	Salida OPTOMOS	●	●
	Entrada tarifa (1 o 2)	●	●



Especificaciones técnicas		MT174-D2 DIN	MT174-T1 DIN
Tensión nominal	Un	3x120/208 V	
Rango de tensión		0,8 - 1,15 Un	
Corriente	Corriente base In	5 A	1 A
	Corriente máxima Imax	120 A	6 A
Clase de Exactitud	Energia activa	Clase 1 (IEC 62053-21 NTC 4052)	
	Energia reactiva	Clase 2 (IEC 62053-23 NTC 4569)	
	Energia aparente	Clase 2	
Reloj tiempo real	Precisión	Mejor que ± 3 min/año a 23°C	
	Alimentación de respaldo	Pila Li: 5 años operac. hasta 20 años	
Rango temp. IEC 62052-11	Operación	-40°C...+60°C, extend. -40°C...+70°C	
	Almacenamiento	-40°C ... +80°C	
Protección ingreso polvo y agua		IP54	
Consumo		0.6 W / 10 VA (sin RS485) 0.8 W / 10 VA (con RS 485)	
Pantalla de cristal liquido	-P +Q -Q +P L1 L2 L3 GkWAhh 8.8.8.8.8 8.8.8.8:8.8:8.8		

Source: Meter Catalog [7].

3.6. Percentage of the energy requirement to be covered.

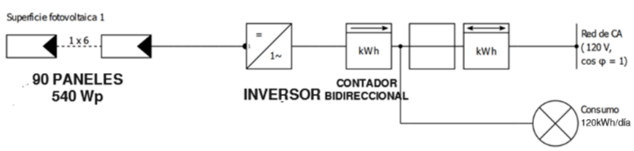
A review of the data collected in the preceding phases indicates that the lighting requirements for the common areas of the Solera PH co-ownership can be met through the installation of the necessary equipment, given the available energy production capacity and the area in which the equipment can be installed.

- Demand: 120 kWh/day
- Peak system power: 48.9 kWp
- Panels Utilization Area:225 m2
- Coverage percentage: 100%

3.7. Detail design

Figure 3 shows a standard diagram for grid-connected systems.

Figure 3. Standard Single Line Diagram for Solar PV System



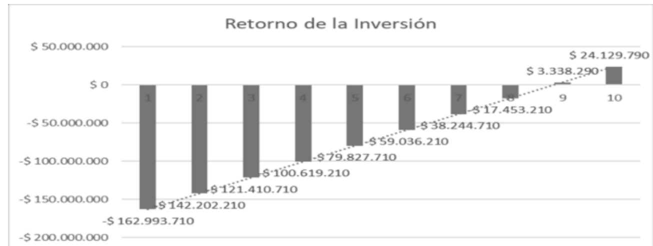
Source: Own based on PvSyst software.

Figure 3 shows the design of the proposed system, indicating the parameters of the equipment required for the installation. This assembly is in the design and planning stage, so the calculation of conductors and on-site implementation is part of the installation when it is executed.

3.7. Technical-economic evaluation of the solar system and results.

In this phase, the evaluation of the data collected is concluded, and the viability of the project can be defined by determining that the total cost of the system to cover 100% of the demand is $235,819,850. This figure is projected to yield energy surpluses of 30% and a nine-year return on the initial investment, as illustrated in Figure 4.

Figure 4. Return on Investment.



Source. Own.

Table 9. specifies the investment and maintenance costs of the system projected over nine years.

Table 7. Solar photovoltaic system costs.

INITIAL INVESTMENT COST	**$ 235.819.850**
ANNUAL MAINTENANCE	**$ 2.496.000**
SELF-GENERATION SAVINGS 2%	**$ 20.250.000**
SALE EXEDENTS 30%	**$ 3.037.500**

Source: own.

4. Conclusions and recommendations

It is feasible to supply 100% of the energy demand for the lighting of the common areas and the corresponding pumps and lifts are not included as they are alternating current equipment that have characteristics of starting power requirements that require, in the start-up phase, some power peaks that the system is not able to supply and is covered by the supply from the network.

The project is transversal to its location because, as shown in the town of Sabana Occidente, which is cold climate, it has sufficient solar radiation to supply the demand for light energy for horizontal properties through solar systems.

This type of project is viable for application in the lighting part because it presents a return on investment in half the useful life of the photovoltaic generation equipment, its maintenance is at a low cost annually.

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