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GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

EVALUATION OF SOLAR THERMAL AND PHOTOVOLTAIC ENERGY CONVERSION TECHNOLOGIES FOR SUSTAINABLE DEVELOPMENT

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Madrid

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ABSTRACT

The present work aims to propose a solution to the problems related to the current cost of electricity, which is influenced by current geopolitical issues, by leveraging the use of a renewable energy source, namely solar photovoltaic-thermal panels. Spain finds itself in a privileged position that allows for the adoption of such systems. However, it is essential to address environmental challenges, particularly concerning future waste management, and find an effective and environmentally respectful solution.

Key words: PVT Systems, hybrid systems, solar thermal energy, solar photovoltaic energy, efficiency.

1. Introduction

Due to the current geopolitical situation, the analysis of designs that allow the production of thermal and photovoltaic energy is particularly important, especially in applications for homes or small industries. This paper is focused on the search for the best option, in economic and operational terms, that can be a great help nowadays.

Thanks to the use of fossil fuels, society currently enjoys great privileges. From the 19th century, with the Industrial Revolution, the massive use of coal was imposed, a fundamental raw material to be able to use steam engines and it continued to be the main fuel source until almost the middle of the 20th century. From this moment, the use of oil and gas spread, making it essential to use new industrial innovations, such as the internal combustion engine used in vehicles and airplanes.

Today, the global economy is still largely based on coal, oil, and natural gas. Together they provide more than four fifths of the world's energy. We all know that the extractable supplies of these non-renewable energy sources are in decline, based on expert's research, oil reserves will be exhausted in 42 years; in 65 years natural gas and in 150 years coal reserves. (JAY_15)

At the same time, the economic and social costs, security risks, health, and environmental impacts of dependence on these fossil fuels continue to intensify.

For these reasons, both most energy experts and the public themselves accept that we will need to switch to energy sources that run out less easily and are not harmful to our health or the environment.

An alternative to reduce and stop the global energy crisis is the use of energy from the sun. This practice is linked to sustainable development since solar energy is inexhaustible and can be accessed practically from anywhere in the world.

Solar energy offers many advantages since we can obtain both electricity and thermal energy.

The efficiency of photovoltaic (PV) panels that exist on the market are between 10% to 25% depending on factors such as location, orientation, or weather conditions. Compared to the total solar energy, only a small portion of it is used in the form of electricity, and this efficiency is reduced when there is an increase in temperature in the PV cells.

The operation of solar thermal energy is through solar thermal collectors, which are devices that use the sun's energy to heat liquids, mainly water. To do this, the thermal solar panel absorbs the sun's rays and converts them into heat. The panel is connected to a storage tank that collects the thermal energy and from there it can be used.

There are two applications in a photovoltaic/thermal hybrid solar system, the first fundamental objective is to increase the performance of the photovoltaic panels, but also to take advantage of thermal energy for domestic uses through a cooling system.

Hybrid technology presents important advantages such as reduction of the surface area needed to generate the same energy as thermal and photovoltaic panels separately. Improvement of PV performance (being able to reach 89%), it is a clean technology, noise reduction, reduction of emissions per m2 compared to other separate solar technologies, as well as making it low maintenance.

To introduce a practical aspect to this work, a model is introduced for the analysis of implementing a hybrid PT system in a residential property located in Malaga, Spain. The property is a single-family dwelling occupied by 4 people.

2. Methodology

The methodology begins with a general study of the characteristics and behavior of hybrid systems in general. Based on this, an analysis of the project's location has been conducted, obtaining all the necessary data from the city of Malaga: irradiance, latitude, longitude, ambient temperature, network water temperature, etc.

Calculations have been performed according to the specifications mentioned in the technical requirements, both for low-temperature installations (solar thermal) and grid-connected installations (photovoltaic solar). Taking into account the requirements established in these documents, the selection of components has been carried out.

The photovoltaic solar installation features a photovoltaic array of 5 panels connected in series, each with a nominal power of 350 Wp. The selected inverter for the project is 2kW.

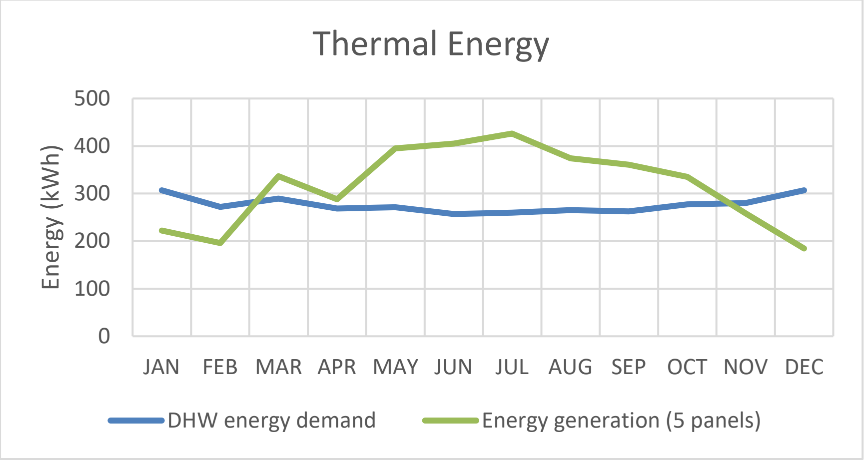
The system has been dimensioned with the aim of meeting the demand for domestic hot water and simultaneously powering electrical loads. To achieve this, the thermal energy generated by the panels throughout the year has been calculated and compared with the demand. While there are months when this generation is sufficient to meet the hot water consumption, there are other months when unfavorable weather conditions require the use of a resistance element to heat the storage tank. This resistance will be powered by the photovoltaic generation.

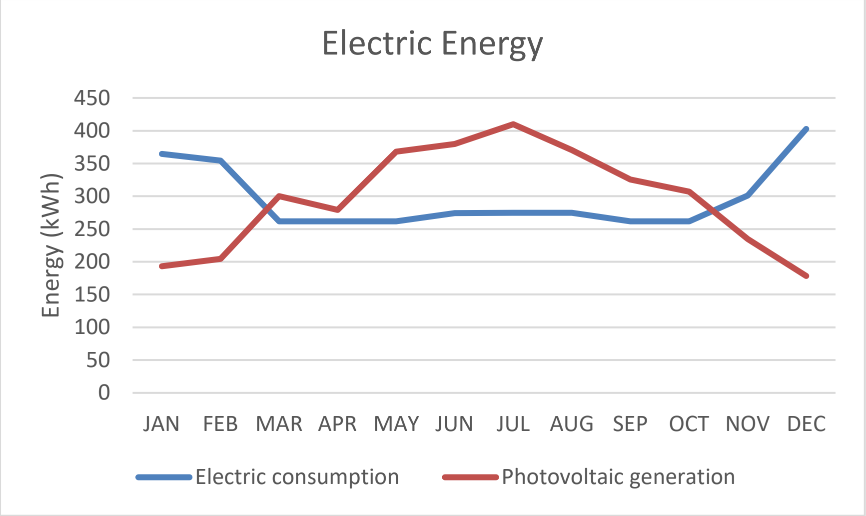
Next, the electrical generation portion that will be consumed by the household loads has been calculated. In months when panel generation is not sufficient, electricity will be drawn from the grid. Similarly, when generation exceeds consumption, the surplus will be injected back into the grid, resulting in savings.

The following sections analyze the economic viability and environmental impact of the project.

3. Results

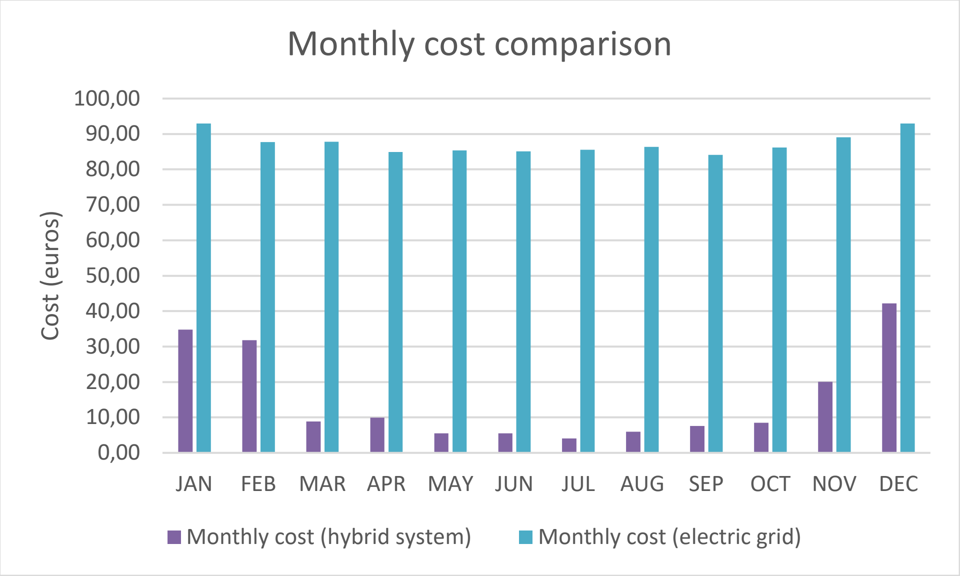
The obtained results of the study are presented below. The following two figures compare the thermal and electrical energy consumption (blue) with the energy generated by the system in different months of the year.



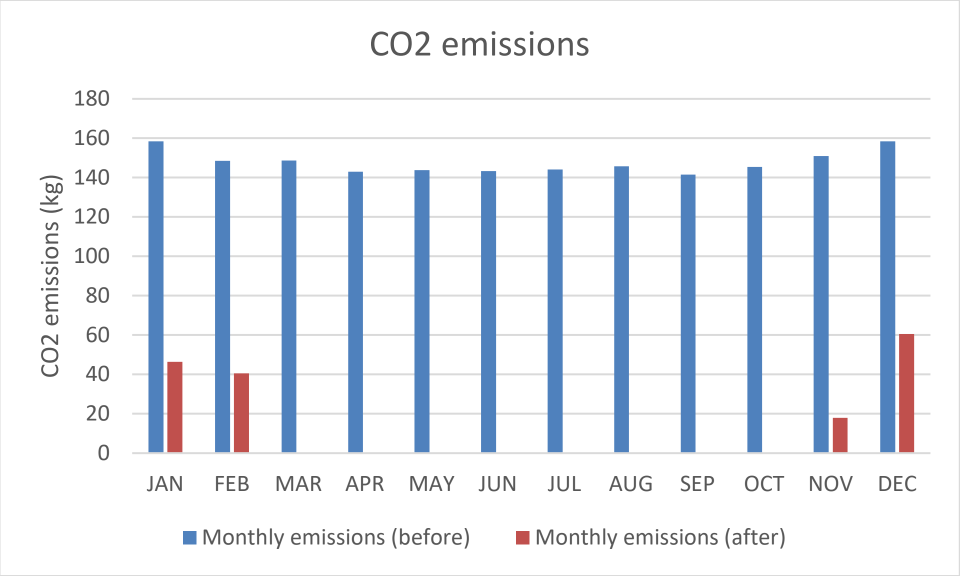


Based on the economic analysis conducted, it can be concluded that a solar installation of these characteristics is economically viable. Over a 15-year period, the Net Present Value (NPV) will have a positive value of €2483.83, and the Internal Rate of Return (IRR) of 13.21% is significantly higher than the 7% discount rate considered for this installation. Therefore, it can be affirmed that the installation is financially profitable.

In the following figure, the costs associated with grid electricity consumption before and after installation are shown.



Although the initial investment may be considered high for an average family of four in Spain, the long-term results justify carrying out the installation. Additionally, such installations have a beneficial impact on the environment, as demonstrated by the significant reduction in CO2 emissions that a single family can achieve, as shown below.



EVALUACIÓN DE LAS TECNOLOGÍAS DE CONVERSIÓN DE ENERGÍA SOLAR TÉRMICA Y FOTOVOLTAICA PARA EL DESARROLLO SOSTENIBLE

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RESUMEN DEL PROYECTO

El presente trabajo trata de proponer una solución a los problemas relacionados con el actual coste de la energía eléctrica, debido a los problemas geopolíticos actuales, basado en el uso de una fuente de energía renovable, los paneles solares fotovoltaicos-térmicos. España se encuentra en una situación privilegiada que permitiría el uso de este tipo de sistemas. No obstante, se tienen que abordar los problemas medioambientales, fundamentalmente en relación con los futuros residuos, y darles una solución eficaz y respetuosa con el medioambiente.

Palabras clave: **Sistemas solares fotovoltaicos-térmicos, sistemas híbridos, sistema solar térmico, sistema solar fotovoltaico, eficiencia**

1. Introducción

Debido a la situación geopolítica actual, el análisis de diseños que permitan la producción de energía térmica y fotovoltaica es especialmente importante, especialmente en aplicaciones para hogares o pequeñas industrias. Este trabajo se centra en la búsqueda de la mejor opción, en términos económicos y operativos, que pueda ser de gran ayuda en la actualidad.

Gracias al uso de combustibles fósiles, la sociedad disfruta actualmente de grandes privilegios. Desde el siglo XIX, con la Revolución Industrial, se impuso el uso masivo del carbón, materia prima fundamental para poder utilizar motores de vapor, y continuó siendo la principal fuente de combustible hasta casi mediados del siglo XX. A partir de ese momento, se extendió el uso del petróleo y el gas, siendo esenciales para utilizar nuevas innovaciones industriales, como el motor de combustión interna utilizado en vehículos y aviones.

Hoy en día, la economía mundial todavía se basa en gran medida en el carbón, el petróleo y el gas natural. Juntos, proporcionan más de cuatro quintas partes de la energía mundial. Todos sabemos que las reservas extraíbles de estas fuentes de energía no renovables están en declive, según investigaciones de expertos, las reservas de petróleo se agotarán en 42 años; en 65 años el gas natural y en 150 años las reservas de carbón. (JAY_15)

Al mismo tiempo, los costos económicos y sociales, los riesgos de seguridad, los impactos en la salud y el medio ambiente debido a la dependencia de estos combustibles fósiles continúan intensificándose.

Por estas razones, tanto la mayoría de los expertos en energía como el público en general aceptan que tendremos que cambiar a fuentes de energía que se agoten con menos facilidad y no sean perjudiciales para nuestra salud o el medio ambiente.

Una alternativa para reducir y detener la crisis energética global es el uso de la energía solar. Esta práctica está vinculada al desarrollo sostenible, ya que la energía solar es inagotable y se puede acceder prácticamente desde cualquier lugar del mundo.

La energía solar ofrece muchas ventajas, ya que podemos obtener tanto electricidad como energía térmica.

La eficiencia de los paneles fotovoltaicos (PV) que existen en el mercado oscila entre el 10% y el 25%, dependiendo de factores como la ubicación, la orientación o las condiciones meteorológicas. En comparación con la energía solar total, solo una pequeña parte se utiliza en forma de electricidad, y esta eficiencia se reduce cuando hay un aumento de la temperatura en las células fotovoltaicas.

El funcionamiento de la energía solar térmica se realiza a través de colectores solares térmicos, que son dispositivos que utilizan la energía del sol para calentar líquidos, principalmente agua. Para hacer esto, el panel solar térmico absorbe los rayos del sol y los convierte en calor. El panel está conectado a un tanque de almacenamiento que recoge la energía térmica y desde allí se puede utilizar.

Existen dos aplicaciones en un sistema solar híbrido fotovoltaico/térmico, el primer objetivo fundamental es aumentar el rendimiento de los paneles fotovoltaicos, pero también aprovechar la energía térmica para usos domésticos a través de un sistema de enfriamiento.

La tecnología híbrida presenta ventajas importantes, como la reducción de la superficie necesaria para generar la misma energía que los paneles térmicos y fotovoltaicos por separado. Mejora del rendimiento fotovoltaico (pudiendo llegar al 89%), es una tecnología limpia, reducción de ruido, reducción de emisiones por m2 en comparación con otras tecnologías solares separadas, así como un bajo mantenimiento.

Para introducir una vertiente práctica a este trabajo, se introduce un modelo para el análisis de la implementación de un sistema híbrido PT en una propiedad residencial ubicada en Málaga, España. La propiedad es una vivienda unifamiliar ocupada por 4 personas.

2. Metodología

Se ha partido de un estudio general de las características y comportamiento de los sistemas híbridos en general. A partir del mismo, se ha realizado un análisis del emplazamiento del proyecto, obteniendo todos los datos necesarios de la ciudad de Málaga: Irradiancia, latitud, longitud, temperatura ambiente, temperatura agua de red, etc.

Se han realizado cálculos de acuerdo con las especificaciones mencionadas en los requisitos técnicos, tanto para instalaciones de baja temperatura (solar térmica) como para instalaciones conectadas a la red (solar fotovoltaica). Teniendo en cuenta los requisitos establecidos en estos documentos, se ha llevado a cabo la selección de componentes.

La instalación solar fotovoltaica cuenta con una matriz fotovoltaica de 5 paneles conectados en serie, cada uno con una potencia nominal de 350 Wp. El inversor seleccionado para el proyecto es de 2 kW.

El sistema se ha dimensionado con el objetivo de satisfacer la demanda de agua caliente doméstica y alimentar simultáneamente las cargas eléctricas. Para lograr esto, se ha calculado la energía térmica generada por los paneles a lo largo del año y se ha comparado con la demanda. Si bien hay meses en los que esta generación es suficiente para cubrir el consumo de agua caliente, hay otros meses en los que las condiciones climáticas desfavorables requieren el uso de un elemento de resistencia para calentar el tanque de almacenamiento. Esta resistencia será alimentada por la generación fotovoltaica.

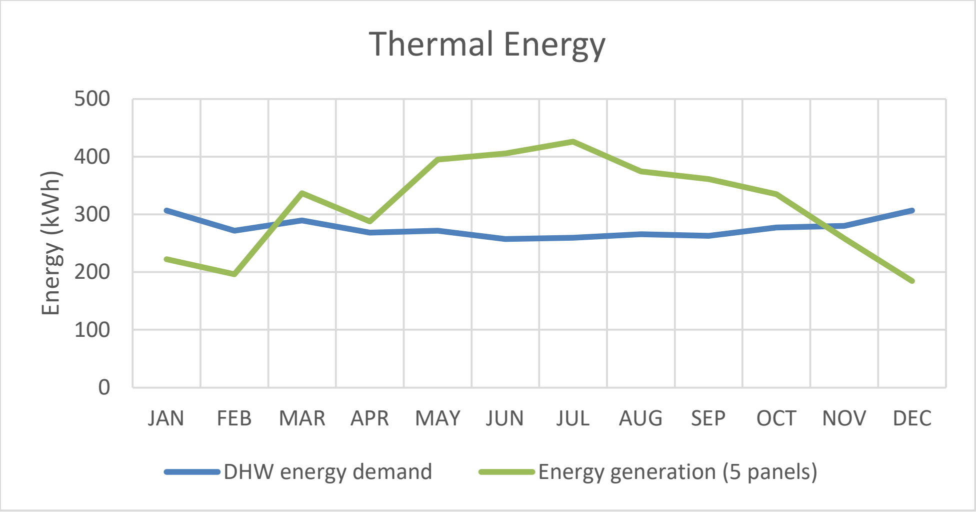
A continuación, se ha calculado la parte de generación eléctrica que será consumida por las cargas domésticas. En los meses en los que la generación de los paneles no es suficiente, se tomará electricidad de la red. De manera similar, cuando la generación supere el consumo, el excedente se inyectará de vuelta a la red, lo que resultará en ahorros.

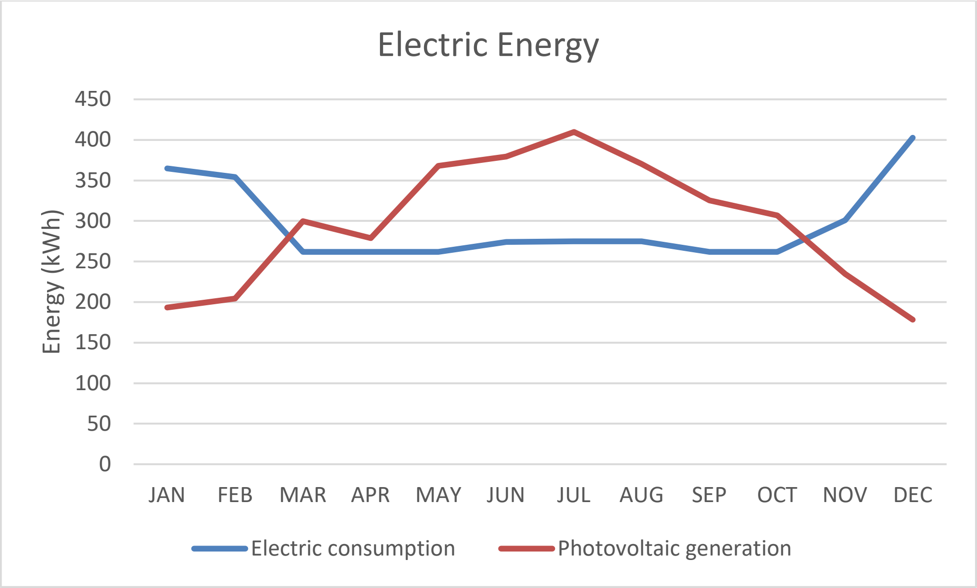
Las secciones siguientes analizan la viabilidad económica y el impacto ambiental del proyecto.

4. Resultados

The obtained results of the study are presented below. The following two figures compare the thermal and electrical energy consumption (blue) with the energy generated by the system in different months of the year.

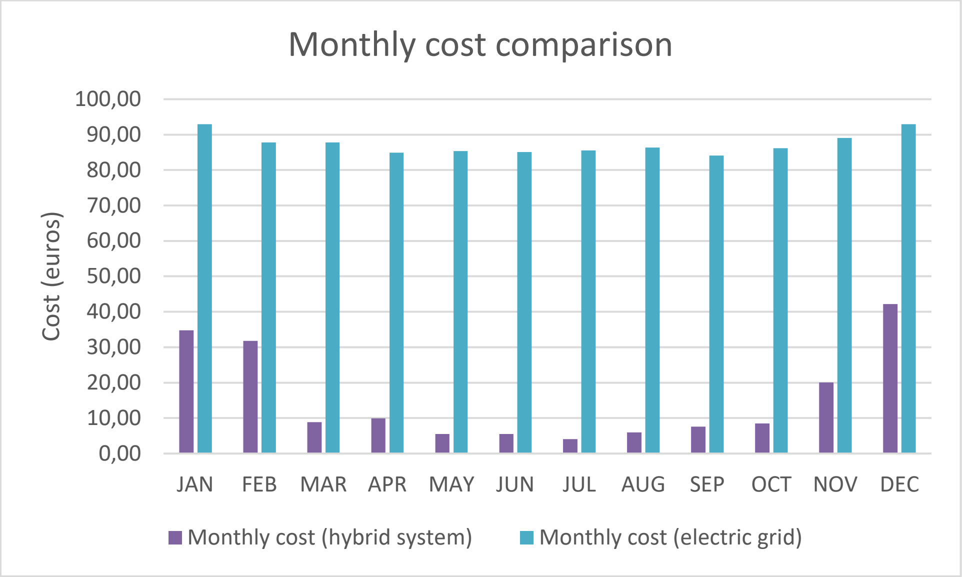
A continuación, se muestran los resultados obtenidos en el estudio. En las siguientes dos figuras se comparan los consumos de energía térmica y eléctrica (azul) con la energía que es capaz de generar el sistema en los diferentes meses del año.



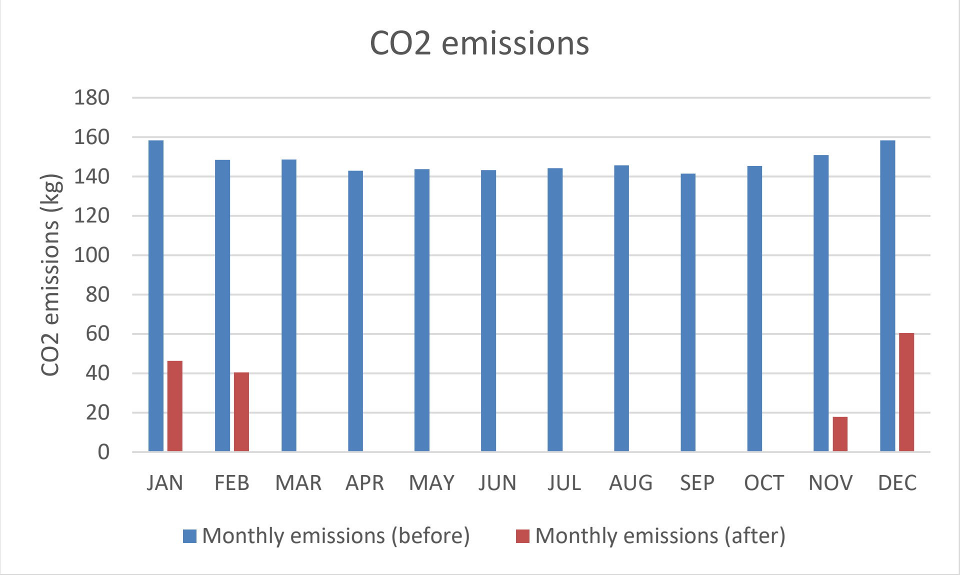


Basándose en el análisis económico realizado, se puede concluir que una instalación solar de estas características es económicamente viable. Durante un período de 15 años, el Valor Actual Neto (VAN) tendrá un valor positivo de €2483.83, y la Tasa Interna de Retorno (TIR) del 13.21% es significativamente mayor que la tasa de descuento del 7% considerada para esta instalación. Por lo tanto, se puede afirmar que la instalación es rentable desde el punto de vista financiero.

En la siguiente figura se muestran los costes debidos al consumo de la red eléctrica antes y después de la instalación.



Aunque la inversión inicial pueda considerarse alta para una familia promedio de cuatro personas en España, los resultados a largo plazo justifican llevar a cabo la instalación. Además, este tipo de instalaciones tienen un impacto beneficioso en el medio ambiente, como se demuestra por la reducción significativa de las emisiones de CO2 que una sola familia puede lograr, como se muestra a continuación.



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CHAPTER 1: INTRODUCTION

1- Problem Statement

Currently, electricity generation systems using photovoltaic panels have an efficiency ranging from 15% to 25%, which is not very efficient. This means that only a small portion of the captured radiation is actually used to generate energy, as most of it is lost in the form of heat. Furthermore, as temperature increases, efficiency decreases at a rate of approximately 0.4% per degree Celsius. This is because when the temperature of photovoltaic cells increases, the current also increases while the voltage decreases. This phenomenon can be observed in the following image.

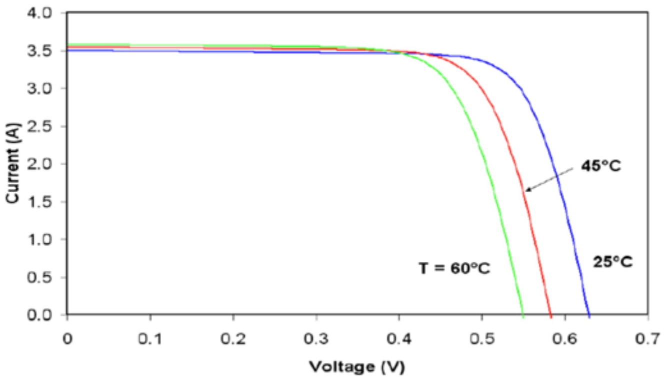


Figure 1: Effect of temperature on the current-voltage characteristics of a solar cell (HABE11)

In short, the overall effect is that with temperature increases, the power output of the system will decrease. Additionally, due to thermal stress, there is a risk of permanent structural damage. However, installing a photovoltaic-thermal solar energy system requires the inclusion of two independent equipment. This implies that more available surface area will be needed to carry out both installations.

The manufacture of photovoltaic cells employs temperature-sensitive materials, which is why increasing temperature leads to a decrease in electrical efficiency. To address this issue, the idea is to channel and utilize this thermal energy that causes the temperature increase in the cells. This would result in an increase in system efficiency.

This project aims to provide a viable solution to the problems presented.

The simultaneous production of electrical and thermal energy is known as cogeneration. This simultaneous production means that both energies can be used at the same time, which implies that the power plant should be located close to the consumption sites. This energy production system is very different from conventional electric power plants that take place in independent thermal power plants. In this generation process, heat is released but is eliminated in the environment instead of being utilized.

Cogeneration can be described as a method that serves to obtain a more efficient system, as it allows saving on electricity transmission lines and distribution. In addition, losses in the lines are lower. This technique offers numerous advantages, such as saving primary energy and emissions, improving the quality of the supply, and reducing losses through transport.

Firstly, the efficiency of the system will improve significantly thanks to cogeneration, as it will allow the efficiency value to be above 90%. It can save up to 50% of primary energy compared to traditional energy supply. In terms of power, these cogeneration systems are capable of covering part of the demand from users thanks to the residual heat of the equipment, which can operate for more than 8300 hours per year. On the other hand, there is also a decrease in CO2 gases and polluting emissions. Another positive aspect of cogeneration is that these systems are easy to integrate into thermal and electrical installations, and work on demand. The maintenance of these systems is simple; however, a moderate investment is required, but it is quickly amortized with energy cost savings.

CHAPTER 1: TECHNOLOGIES DESCRIPTION

The purpose of the project is:

1. To investigate and understand the renewable energy sector and how it can be applied in a residential setting for self-consumption.
2. To assess the economic viability of the project and provide justification for each decision made.
3. To study and comprehend the theoretical aspects of various renewable energy installations suitable for this type of project.
4. To analyze the project's profitability by calculating the payback period, Net Present Value (NPV), Internal Rate of Return (IRR), and other relevant indicators, to determine whether it is appropriate to proceed with the project or if it should be discarded.
5. To consider and evaluate the positive impacts that the installation of renewable energy sources has on the environment.
6. To select the necessary components for the project, taking into account the different alternatives available in the market.

CHAPTER 2. SOLAR PHOTOVOLTAIC INSTALLATION

A photovoltaic system produces electrical energy directly from solar radiation. The photovoltaic modules are responsible for converting the radiation into electricity. This energy is produced by the photovoltaic effect in the form of direct current (DC).

This DC current generated can be stored or injected into the grid as DC or transformed into alternating current (AC). To store energy, the installations have batteries, which allows the energy to be used at any time, not just when the system is operating. It is important to note that solar radiation is not available at all times.

Generally, these installations also have an inverter, which transforms the DC current into AC. In this way, this energy can be used by commercial electrical equipment, as well as electrical installations that distribute electricity.

Another component of solar photovoltaic installations is the charge controller. Its function is essential, as it is responsible for controlling the proper functioning of the system by preventing overcharging and discharging of the battery. In case of detection of any malfunction, it provides visual alarms. In this way, efficient use is achieved, and the useful life of the equipment is extended. The following figure shows a diagram of this type of installation, taking into account that there may be variations.

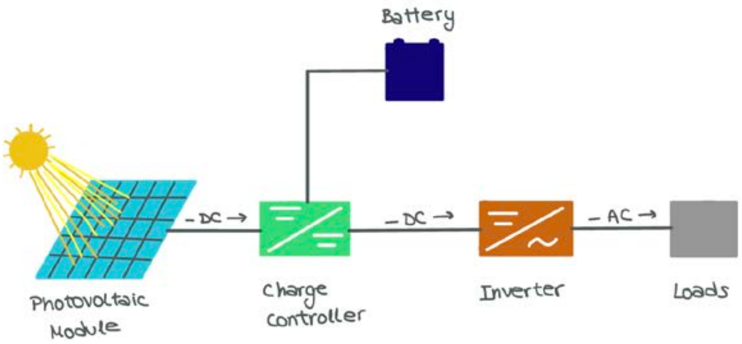


Figure 2: Photovoltaic System

2.1 Photovoltaic cell

The photovoltaic cells are responsible for transforming solar radiation into electrical energy. During this process, the electrons surrounding the nucleus of semiconductor material atoms absorb photons of light. The electrons are excited by these photons, causing their energy state to increase. Next, the flow of electric current takes place as the excited electrons become charge carriers.

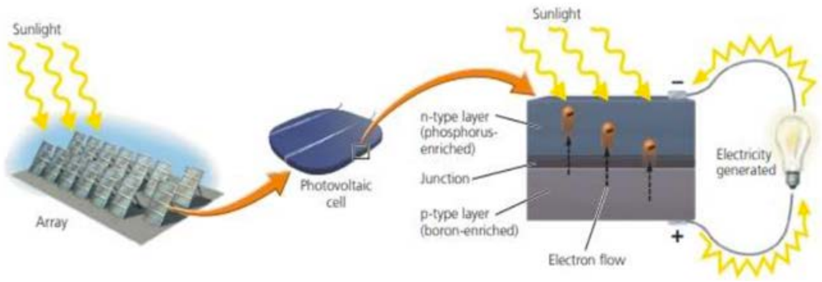


Figure 3: A photovoltaic (PV) cell converts sunlight into electrical energy. (JAY_19)

When solar panels are exposed to light, the electrons in the atoms move from the p-type layer (enriched with boron) to the n- type layer (enriched with phosphorus). Electrical current flows from the n-type layer back to the p-type layer through the wiring. This direct current is converted to alternating current to produce electricity.

2.2 Solar cell parameters to determine efficiency.

To determine the performance of solar cells, the maximum power, short-circuit current intensity, open circuit voltage, and fill factor are mainly used as parameters. These parameters are determined from the I-V characteristic curve. This curve represents all possible operating points of current and voltage and varies according to environmental conditions and panel state.

In the I-V curve graph, it can be observed that the intensity will have its maximum value when the voltage is zero, however, when the voltage is maximum, the current is equal to zero. These values are known as open-circuit voltage (Voc) and short-circuit current (Isc). Depending on the solar radiation and the area of the cells, the short-circuit current may vary, and the open-circuit voltage also varies depending on the semiconductor material, lighting, and temperature. If the temperature increases, the value of the open-circuit voltage decreases.

From this graph, the maximum power point (MPP) can also be obtained, which is obtained by calculating the voltage multiplied by the intensity.

$$Pmax = Vmp * Imp$$

Vmp stands for voltage at maximum power point and Imp stands for current at this point. The maximum power (Pmax) is the maximum power delivered by the device.

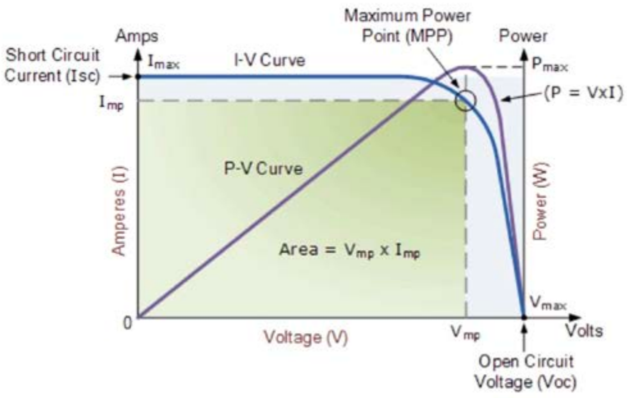


Figure 4: Current-voltage characteristic of a typical solar panel (JAAF18)

The fill factor (FF) is the rectangular area under the curve at the maximum power point and indicates how efficient the panel is. The system will be in optimal conditions when the FF has a value similar to the short-circuit current and open-circuit voltage, since when these values are not close, it will not be as efficient.

With the information provided by the I-V curve, a study can be made of the daily power produced by the panel. It is also possible to analyze how the operating state varies throughout the day and thus know the peak hours.

The daily power can be estimated by multiplying the panel's maximum power and the peak hours. The conversion efficiency is calculated as the ratio of the maximum generated power to the incident power on the solar cell.

$$\eta = \frac{Pmax}{Pin}$$

Currently, the conversion efficiency of photovoltaic cells produced on an industrial scale is not very high, ranging between 12% and 18%. Depending on the semiconductor material, it is possible to achieve a theoretical maximum efficiency close to 25%, but this efficiency corresponds only to a narrow range of the light spectrum.

It is true that in general, photovoltaic cells using monocrystalline semiconductors tend to have higher efficiency than cells using polycrystalline semiconductor. This is because monocrystalline materials have a more uniform crystal structure, which allows them to have a better ability to absorb light and convert it into electricity. Additionally, monocrystalline materials have fewer crystallization defects, which reduces energy loss and increases cell efficiency.

However, polycrystalline silicon solar cells are less expensive to produce than monocrystalline silicon solar cells, and their efficiency is increasing due to improvements in manufacturing technology and material quality. Therefore, although monocrystalline solar cells may have slightly higher efficiency than polycrystalline solar cells, the choice of solar cell type will depend on the specific requirements of the application and the cost-benefit desired.

2.3 Typical characteristics of solar cells

Typical characteristics of solar cells include the active surface area, the anti-reflective material, the geometric shape and dimensions, and the conversion efficiency. The active surface area is the portion of the total area of the photovoltaic cell that participates in the process of converting sunlight into electricity. In the past, the connection to the semiconductor material was made with small metal traces on the part of the cell exposed to radiation, which reduced the active surface area and, consequently, decreased efficiency.

To increase the active area without increasing the total surface area, cells can now be constructed so that the connection between the p-type and n-type layers of the semiconductor is on the back of the cell.

It is essential that the surface of the semiconductor be treated to prevent losses. This surface is exposed to solar radiation and tends to reflect part of the incident light, reducing the amount of energy captured by the cell. To avoid significant losses, an anti-reflective coating is deposited on the surface.

The manufacturing method of photovoltaic cells influences the geometric shape of the cell. The circular shape of solar cells was used in the early models because the materials used to make the cells were produced in the form of disks. Currently, solar cells are made in different shapes and sizes, and the square shape has become more common due to its ease of handling and assembly in solar modules. The corners can be rounded or have 90º angles, depending on the manufacturing process and the specific design of the cell.

Regarding thickness, most solar cells available on the market have a thickness of around 0.3 mm. However, the thickness can vary depending on the cell technology and the manufacturer. The surface area of the cell can also vary depending on the specific design of the cell and the application requirements. (ROCI11)

2.4 Equivalent circuit of a solar cell

The equivalent circuit of a solar cell is typically described using two widely used models to account for the non-linear I-V curve relationship: the single diode model and the two-diode model.

2.4.1 Single diode model

The single diode model is the simplest way to describe the behavior of a solar cell. The equivalent circuit of the single diode model consists of a current source in parallel with an ideal diode formed by a PN junction, along with other components that emulate losses. The series resistance represents the resistance of the diode and thermal losses, and the shunt resistance represents leakage currents due to manufacturing defects in the structure. The model is shown in the following figure.

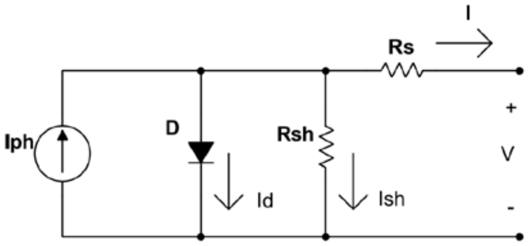


Figure 5: Single diode model

Under solar radiation conditions, the intensity I is calculated as a function of the remaining intensities. Iph represents the photocurrent generated by the cell, Id is the current that flows through the diode, and Ish is the current that flows through the shunt resistance.

$$I = Iph - Id - Ish$$

The photogenerated current can be calculated with the formula shown below, where ki is the short-circuit current of the cell at 25°C and 1000 W/m2 with a value of 0.0032 A, T is the operating temperature of the cell in °K, and G is the solar irradiation in W/m2.

$$Iph = [Isc + Ki * (T - 298.15)] * G/1000$$

The current flowing through the diode depends on factors such as the reverse saturation current (Io), which in turn depends on the temperature.

$$Id = Io * (e^{\frac{q*(V+I*Rs)}{n*K*Ns*T}} - 1)$$

“q” is the charge of the electron that has a value of 1.6e-19C.

“n” is the linearity factor of the diode.

“K” is the Boltzmann constant which is equal to 1.3805e-23 J/K.

"Ns" is the number of cells connected in series.

Finally, the current flowing through the shunt resistance is represented in the following equation.

$$Ish = \frac{V + I * Rs}{Rsh}$$

The ideal model of a diode does not account for losses due to recombination in the depletion region. In a real solar cell, recombination can be significant, especially at low voltages. Therefore, to accurately model a solar cell, it is necessary to consider losses due to recombination.

In addition, the ideal model of a diode only considers the diffusion phenomenon and adjusts the ideality factor to n=1. However, in a real solar cell, there are other processes that can affect the current, such as recombination in the front contact region, absorption in the active layer, and reflection on the back surface. Therefore, to accurately model a solar cell, it is necessary to consider these processes and use more sophisticated models that take these considerations into account. (GUST20)

2.4.2 Two-diode model

The two-diode model is a commonly used equivalent circuit to represent the behavior of a solar cell. This model consists of two diodes in parallel with a current source. Each of the diodes represents a different depletion region in the solar cell, which allows for the consideration of losses due to recombination in both regions. The first diode is located in the depletion region near the front contact of the cell, while the second diode is located in the depletion region near the back surface of the cell.

The current source represents the current generated by the solar cell when exposed to sunlight. This current can flow through either of the diodes and will be distributed between them based on their individual electrical characteristics.

In theory, the behavior of a solar cell can be described ideally by using a current source connected in parallel with a rectifying diode. However, in practice, it is necessary to include another diode that controls the recombination current in the space-charge region, as well as a shunt resistance in parallel with the source that represents the short-circuit current near the cell terminals due to semiconductor impurities and non-idealities. Additionally, the metal contacts of the cell and the resistance of the material are represented by a resistance connected in series with the shunt cell elements, as shown in the figure below. In summary, to accurately represent the behavior of a solar cell, it is necessary to use a model that takes into account the non-idealities and recombination losses that occur in the cell.

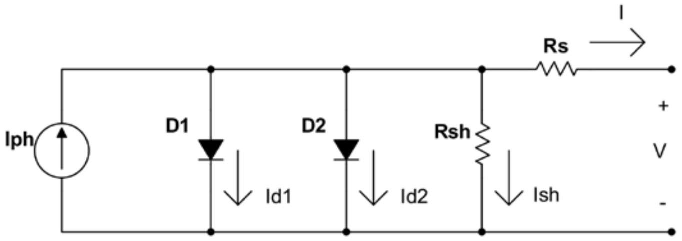


Figure 6: Two-diode model

It is recommended that the series resistance has a very small value and that the shunt resistance has a much higher value. "I" is the current flowing through the cell and can be calculated using the following equation:

$$I = I_{ph} - I_{D1} - I_{D2} - I_{sh}$$

Where, I_{ph} is the photocurrent generated by the source, I_{D1} and I_{D2} are the currents flowing through the diodes, and I_{sh} is the current flowing through the shunt resistance. Using the Shockley equation, the value of the currents flowing through the diodes can be estimated.

$$I_{D1} = I_{SD1} * [e^{\frac{q*(V_L+I_L*R_S)}{n1*K*T}} - 1].$$

$$I_{D2} = I_{SD2} * [e^{\frac{q*(V_L+I_L*R_S)}{n2*K*T}} - 1].$$

" I_{SD1}" represents the diffusion current.

"I_{SD2}" represents the saturation current.

"V_L" is the terminal voltage.

"n1 and n2" are the ideality factors of the diffusion and recombination diode respectively.

"k" is Stefan Boltzmann's constant.

"T" is the absolute temperature in Kelvin of the solar cell.

"q" represents the charge of the electron.

Finally, the current times the shunt current is determined by this equation.

$$I_{sh} = \frac{V_L + I_L * R_S}{n2 * K * T}$$

This model, which includes two diodes in parallel and a current source, is considered more accurate for low solar irradiation values and allows for simulations under dynamic temperature conditions in a solar cell. This is because the model takes into account the non-idealities and losses due to recombination that occur in the cell, which can significantly affect its performance under different conditions.

Research related to semiconductor theory and PN junction physics in diodes has shown that the behavior of solar cells is more complex than what can be represented by a single diode in parallel with a current source. In particular, it has been shown that the two-diode model can more accurately explain the nonlinear behavior of the current-voltage curve of a solar cell, as well as the dependence of cell efficiency on temperature and solar irradiance. In summary, the two-diode model is considered a valuable tool for simulating the behavior of solar cells under different conditions, which is essential for the research and development of more efficient solar technologies. (GUST20)

2.5 Off grid and On grid Systems

<u>Off-grid Systems</u>

Off-grid systems are recommended for situations where consumption is not very high, in which case it is not worth assuming the cost of connecting to the grid. They are also the ideal option for systems located in hard-to-reach areas where connection to the grid is complicated. The main characteristic is that these systems are usually equipped with energy storage systems, as they are not connected to the grid.

During the operating period, during active solar radiation hours, an energy storage system must be available for the energy that is not consumed, which will be provided to the load when the available energy is reduced. These systems must be dimensioned with a configuration that allows the feeding of the load and the recharge of the accumulation batteries during the hours of insolation.

Photovoltaic modules, the charge controller, the inverter, and the accumulation batteries are the basic components of isolated systems. Photovoltaic modules produce the energy that will be stored in the batteries, while the load is simultaneously supplied through the charge controller.

Figure 7: Off-grid system (source: Solar Power World)

A set of rechargeable batteries forms the storage system. The system sizing is done with the aim of ensuring that the electrical load has sufficient feeding autonomy. Therefore, the batteries must have a low self-discharge rate, long lifespan, low maintenance, and a high number of charge-discharge cycles.

On-grid Systems

The main advantage of this type of system is its reliability, since in case of failure it has the possibility of alternative power supply. These systems usually do not have storage systems, since the energy that is not consumed by the loads during working periods is injected into the power grid. The function of grid-connected systems is therefore to introduce the largest possible amount of energy into the grid. A measuring system will also be included to account for the generated production.

The photovoltaic modules, the inverter for grid connection, an exchange device with the power grid, and the bidirectional energy meter make up a grid-connected photovoltaic system.

Figure 8: On-grid system (source: FAVPNG)

To power the system, the inverter is a fundamental component. The inverter is a device that transforms the direct current produced by the modules, which typically have a voltage of 12V, 24V or 48V, into alternating current, usually 220V. Inverters have an electronic device that allows maximum power to be obtained, adapting the production characteristics of the photovoltaic panels to the requirements of the load.

2.6 Connection between collectors.

2.6.1 Parallel connection

The connection of the solar panels must be taken into account, since it will affect the efficiency of the system. The different options available and the advantages and disadvantages of each of them are described below.

Depending on the active power desired by the consumption, there are different ways to connect several solar panels to obtain electricity.

Wiring solar panels in parallel involves connecting the positive terminals of each panel and wiring the negative terminals of each panel. They are then connected to the charge controller or inverter of the solar system. When solar panels are connected in parallel, they all share the same voltage.

The main advantage of the parallel configuration is reliability. In the event that one or more solar panels are affected by shading or other damage caused during manufacturing or during the life cycle of the system. The performance of other solar panels in the array is not affected because the wiring connection makes all panels independent of the others.

However, there are some disadvantages to this type of connection. Low voltages cause higher current values, which translates into higher electrical losses, since energy losses are directly related to the squared current value. Therefore, this leads to a lower efficiency performance of the solar PV system.

In addition, it is not recommended to increase the current as it will imply that the temperature of the circuit is higher and can cause safety problems. As the current increases, it also causes an increase in wire gauges in order to have better capacities and to be able to withstand higher ampere values.

In short, the choice of the installation in parallel connection implies that the costs of the installation increase, since a larger size of the cables and an increase in their length are required to be able to make the connection.

This type of connection is recommended for small systems and is intended to supply low loads.

2.6.2 Series connection

The other type of connection is in series and is made by connecting the positive terminal of each panel to the negative terminal of the next panel until the final panel is connected to the charge controller or inverter.

In series connection, the current flowing through all the panels is the same while the voltages are divided. The set of solar panels connected in series is known as a string.

To obtain a certain power if the voltages are lower the currents will be higher. The series connection has the characteristic that this configuration increases the voltage values with each panel added and, therefore, the overall current provided by the system will be less.

Therefore, with this connection savings are achieved because smaller lengths and sizes will be needed in the wiring. In addition, greater efficiency will be obtained.

However, the main disadvantage of this configuration is the low reliability of the system when connected in series. Since the entire system is connected by a single cable, if the cable fails, the entire system will be affected. When one of the solar panels in the string is shaded, either by a tree or a cloud, the overall performance and efficiency of the system suffers. Shading can even become a bigger problem in this configuration because a shaded part creates resistance in the current flow.

Taking into account the problems that this type of connection presents, methods can be applied to solve the problems. For example, the problem of efficiency could be improved with the implementation of a microinverter that will serve to make each panel independent from the other. In this way, the highest possible efficiency can be achieved. Thanks to the microinverter, in the event that a panel is affected by shadow, it will not affect the output power.

The second option is to purchase solar panels with a bypass diode. The goal is for the diode to act as a wall that blocks or isolates the shaded area of the panel to prevent efficiency losses from the rest of the same panel and, therefore, from the entire power system.

Unfortunately, the reliability issue cannot be resolved, as it is an intrinsic property of the connection itself.

In addition to serial and parallel configurations, connections can be made that combine both.

2.7 Classification of solar cells

Thanks to technological development, solar cells can be classified into three main generations. First-generation or conventional cells refer to crystalline silicon solar cells, which are the most common and widely used today. These cells are made from high-purity semiconductor materials and are based on PN junction technology to convert solar energy into electricity. Second-generation cells are thin-film solar cells that use semiconductor materials different from silicon, such as cadmium telluride (CdTe) or copper indium gallium sulfide (CIGS). These cells are thinner and lighter than crystalline silicon cells, making them ideal for large-scale applications. Third-generation cells are concentrated light solar cells or multilayer cells that use multiple layers of semiconductor materials to capture a wider range of wavelengths of solar light. These cells are more efficient than first and second-generation cells and are primarily used in high-power applications such as large-scale electricity generation.

2.7.1 First generation cells

- Monocrystalline Silicon

Currently, silicon is the most commonly used compound in solar cell production. However, due to its expensive and complex manufacturing process, there is a search for more economical materials to replace it. The silicon production process involves the purification of the material, its melting and crystallization into round ingots. Then, thin wafers are cut from the round ingot to obtain individual solar cells, maximizing the surface of the material.

The most widely used manufacturing process to obtain monocrystalline silicon is known as the Czochralski method. This process involves the use of a monocrystalline silicon seed that is placed in contact with the surface of the molten silicon in a container. As the crystal seed is slowly withdrawn, the molten silicon begins to solidify and its atoms align with the seed's monocrystalline structure, extending along the monocrystalline structure.

Solar cells have a uniform tone that is usually blue or black, and in laboratory conditions, a performance of 19.1% has been achieved. However, in mass production, the efficiency varies between 10% and 13%.

Figure 9: Silicon Monocrystalline cell (Source: JENYS energy-saving)

- Polycrystalline Silicon

Polycrystalline solar cells are made from silicon of lower purity, which makes them more economical than monocrystalline cells. Although this often results in slightly lower efficiency, polycrystalline cell manufacturers argue that the cost advantages outweigh the losses in effectiveness.

The main visual distinction between monocrystalline and polycrystalline solar cells is that the latter have areas with different shades, in contrast to the uniform appearance of monocrystalline cells. In terms of efficiency, polycrystalline cells have a performance of 18% under laboratory conditions, while in mass production, this performance ranges from 10% to 12%.

Figure 10: Polycrystalline Silicon cell (Source: JENYS energy-saving)

- Amorphous silicon

Amorphous silicon is a type of silicon that lacks a crystalline structure, unlike the previous varieties. It is manufactured by depositing layers of the material under vacuum onto a surface of glass, plastic, or metal. Because these layers can have different sizes, amorphous silicon solar cells are usually continuous and occupy the entire surface of the module. However, one of the main problems of amorphous silicon is that its efficiency decreases after prolonged exposure to sunlight, although the material is very stable and has good behavior towards external agents such as humidity, temperature, and corrosion. After the first 100 hours of operation, a degradation in the current production occurs, which stabilizes over time and remains practically constant.

This non-crystalline form of silicon was discovered in 1974 and has a disordered atomic structure, which makes it less sensitive to temperature. Amorphous silicon thin-film technology is the most popular today, with efficiencies ranging from 5% to 7%, although double and triple junction designs can increase it up to 10%. Among the advantages of amorphous silicon photovoltaic cells are the following:

- High absorption of solar light, up to 40 times higher than monocrystalline silicon cells.
- Lower manufacturing costs compared to other photovoltaic cells based on silicon.

- They can be deposited on low-cost substrates such as steel, glass, or plastic.

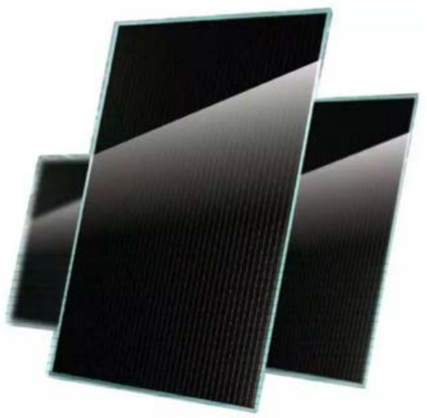


Figure 11: Amorphous silicon cell (Source: JENYS energy-saving)

2.7.2 Second generation cells

- Thin-film solar cell

Thin-film solar cells are a second-generation alternative to conventional solar cells, manufactured by depositing one or more thin layers of photovoltaic materials onto a substrate, such as glass, plastic, or metal. Various thin-film solar cell technologies are commercially available, including cadmium telluride (CdTe) and copper indium gallium diselenide.

Thin-film solar cells have a much thinner thickness than conventional first-generation crystalline silicon solar cells, which use wafers up to 200 µm thick. The thickness of the film ranges from a few nanometers (nm) to tens of micrometers (µm). Because of this, thin-film cells are lighter and more flexible than crystalline silicon cells. Additionally, thin-film solar cells are used in integrated photovoltaic construction and as a semitransparent photovoltaic glazing material that can be laminated onto windows.

Solar cells using thin-film polycrystalline silicon have been shown to achieve photovoltaic energy conversion efficiencies of over 19% through light trapping and optimal silicon thickness for back surface passivation. Currently available thin-film photovoltaic technologies have great potential for cost reduction in large volume production but still face challenges in achieving sufficient performance and superior quality to achieve efficiencies between 11% and 12.7%.

Cadmium telluride, known as CdTe, is a form of thin film that has some useful characteristics but also presents a toxicity problem. Although CdTe is less efficient than silicon, it is cheaper and can be used to make thin-film solar cells. Instead of using silicon, glass is coated with a thin layer of a crystalline cadmium-tellurium compound, which requires much less semiconductor material. This manufacturing process produces highly efficient (11-13%) solar panels at a lower cost, which could reduce the cost for consumers by 50%. Additionally, this technology does not require connection to the electrical grid, making it ideal for use in remote and isolated regions.

Figure 12: Thin-film solar cell (MARÍ20)

2.7.3 Third generation solar cells

- Gallium Arsenide (GaAs) solar cells

Gallium arsenide is a chemical compound formed from gallium and arsenic. Solar cells made with single-junction gallium arsenide have achieved photovoltaic conversion efficiencies greater than 25%. These cells are produced by epitaxially growing gallium arsenide on a monocrystalline substrate. Its main advantage is conversion efficiency, as its theoretical efficiency is nearly twice that of crystalline silicon.

Unlike conventional solar cells, thin-film gallium arsenide solar cells have advantages such as flexibility, lightweight, color and shape adaptability, as well as flexibility.

Conventional silicon solar cells lose their ability to function properly at temperatures above 200°C, however, gallium arsenide batteries have better thermal resistance. Experimental test results show that gallium arsenide batteries remain operational even at temperatures as high as 250°C.

The use of monocrystalline substrates to grow GaAs is a costly process, which is considered a disadvantage. Therefore, the main focus is on reducing the amount of material used, limiting its application to concentric PV/T systems that require less surface area and, therefore, less material. (MARÍ20)

2.8 Photovoltaic solar panel components

In the following image, the various components of a standard photovoltaic solar panel are depicted. The aluminum frame, tempered glass, encapsulant, solar cells, back sheet, and junction box are shown in the following figure.

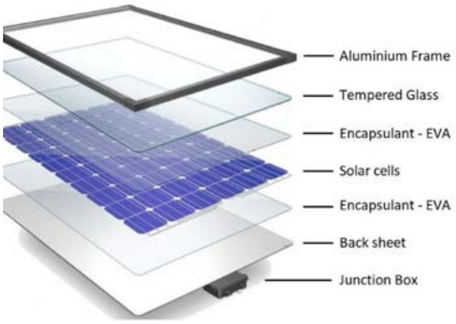


Figure 13: Photovoltaic solar panel (Source: Clean Energy Reviews)

Cross-linkable ethylene vinyl acetate (EVA) is the most widely used encapsulation material in the solar industry. The cells are laminated with EVA films under compression between them in a vacuum using a lamination machine. This process is carried out at temperatures up to 150°C. However, a drawback of EVA films is that they are not UV-resistant, so protective front glass is necessary for UV screening purposes.

Typically, a thin, opaque film known as Tedlar composite (Tedlar polyester Tedlar or TPT) is utilized as the backing layer. Tedlar refers to the brand name owned by Dupont for a film made of polyvinyl fluoride (PVF), polyethylene terephthalate (PET), or metal.

CHAPTER 3. SOLAR THERMAL INSTALLATION

A solar thermal installation is made up of different components. Firstly, the primary circuit, made up of collectors and the pipes that connect them. These give off heat that is captured by the secondary circuit. This is connected in series and is made up of the exchanger and a deposit that accumulates the energy obtained in the primary and transfers it to the accumulation system. Finally, the tertiary circuit, whose function is to transfer the energy accumulated in the accumulation system to the consumption circuit. This transfer is carried out thanks to an exchanger.

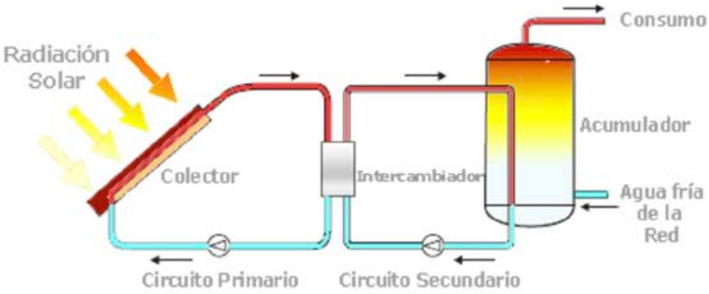


Figure 14: Thermal Installation Components (Source: Ener City, Energía Limpia)

The entire solar installation consists of the circuits described above. These circuits, in turn, are made up of different systems, which ensure the correct operation of the whole.

The solar collectors make up the collection system and its main function is to obtain thermal energy. This energy is obtained thanks to the energy that is captured through solar radiation. This collection system is made up of a set of collectors connected to each other. The reception of radiation is through a heat transfer liquid, which is usually water.

The exchange system transfers the heat between the fluid that circulates through the primary circuit and the water that circulates through the secondary. The heat exchanger heats the drinking water through the heat captured from solar radiation. It has the shape of a serpentine, since thus, it is possible to increase the contact surface and therefore be more efficient.

Thermal energy in the form of hot water is stored in the storage system. The cold water enters under the accumulator where it meets the exchanger, as it heats up it moves upwards, which is where it will come out. Hot water will now be available to be consumed. Internally it has a system to prevent the corrosive effect of hot water stored on the materials. On the outside it has a layer of insulating material to prevent heat loss and is covered by a material that protects the insulation from possible humidity and blows.

The distribution system is responsible for transporting hot water to the points of consumption.

To ensure that the installation works correctly, a control system is required. This equipment avoids subjecting the equipment to extreme conditions that could damage it or cause failure. In addition, thanks to the valves and pumps the performance is optimized. Normally, this system regulates the system through the operation of the circulation pump. This is activated when the water temperature at the outlet of the collectors is higher than that of the accumulator. To do this, it compares the inlet and outlet temperatures to the collector and the temperature of the accumulator.

Finally, a backup power system is essential, as it will allow additional power supply if the demand cannot be met. These systems depend on solar radiation and cannot guarantee the full supply of the demand at all times.

3.1 Solar collectors

Solar collectors are devices that are used to capture solar thermal energy through the sun's radiation and thus heat the water. Hot water can be used both at home and at an industrial level.

These devices must meet certain characteristics for the system to function correctly. These collectors are exposed outdoors, so they must be resistant to possible weather conditions, including high or low temperatures. They must be efficient, stable, and durable.

Solar collectors are made up of different elements. Below is a schematic of a flat solar panel:

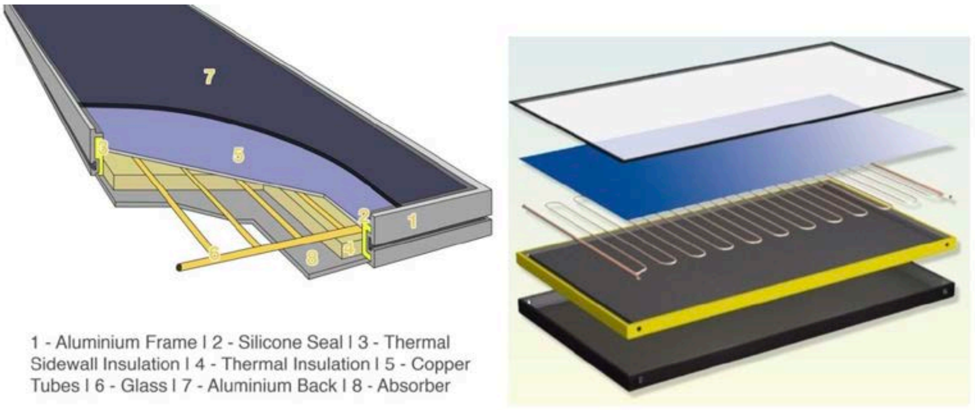


Figure 15: Flat solar panel (Source: Blog Mech)

The aluminum frame serves to protect all the elements that are inside from the outside.

Silicon Seal, this elastic silicone element makes it possible to maintain tightness inside the collector, protecting it from water when it rains. In addition, these joints must be resistant to high temperatures and mechanical loads.

The transparent cover protects the components of the sensor from the outside. In addition, it contributes to reducing losses since it works as a thermal insulator. Materials such as glass, which has a low iron content, are used. Most are made of glass instead of plastic covers since glass is a material that will better resist solar radiation or high temperatures. They also have greater thermal expansion, which is not recommended as it will not guarantee watertightness. For these reasons, the use of plastic materials is not recommended. Glass covers usually have a thickness of about 5 mm. They must have at least 3 or 4 mm since it is intended to be a resistant structure and prevent it from fracturing. In addition to reducing losses due to radiation and convection, it ensures the tightness of the collector, protecting the interior components against external agents such as rain, humidity or other, and thus avoiding their deterioration. Between the cover and the casing there are elastic joints to ensure that water does not enter the interior and absorb the different thermal expansion of the components.

Thermal insulation is an important component in photovoltaic and thermal solar collectors, since it helps to reduce heat losses from the system and, therefore, improves its efficiency. Thermal insulation is mainly used in solar thermal collectors to maintain the temperature of the hot fluid inside the system.

Thermal insulation is placed on the back and sides of the solar thermal collector to reduce heat loss to the outside. It can be made of different materials, such as expanded polystyrene (EPS), mineral wool, polyurethane foam, or fiberglass, among others. These materials have insulating properties that reduce the transmission of heat and prevent the heat of the fluid that circulates inside the solar collector from escaping.

They must be able to withstand high temperatures. The thickness can vary, on the back it ranges from 40-70 mm, on the side walls it is usually around 10 mm.

The absorber plate is the component that is responsible for converting solar radiation into internal energy of the fluid that circulates through the tubes. These tubes should not be too far apart, it is recommended that they maintain a distance around 100mm. It is very important that these tubes are located close to each other to optimize the operation of the system. Copper or aluminum is usually used to make the absorbers since these materials have very good thermal conductivity. They are usually thin and have a high absorbance coating. Selective coatings are currently used and are a decisive factor in the objective of reducing thermal losses.

The plate is based on a metallic plate surface that incorporates the metallic pipes through which the working fluid circulates, usually joined by welding. Copper is the material that is usually used for the manufacture of the absorber. Other materials such as aluminum or steel can also be used. The pipes are also made of copper since it has a good thermal conductivity and is very resistant to corrosion. It is very important that the thermal contact between the pipes and the absorber so that the heat transfer is good.

Another factor that will allow optimizing the performance of the system is the surface treatment of the absorber. This will determine its ability to absorb radiation and emit radiation, depending on this the absorptance and emissivity factors are established.

You can find treatments with black paint or selective treatments. With black paint you can obtain a high absorptance, but also a high emissivity, this makes them a good option with high performance if the temperature is not very high. Most of the time, specific solar paints that withstand working temperatures are used, they have binders since they will prevent them from degrading and have greater durability.

The use of selective treatments aims to keep the absorptance high, but at the same time to reduce the emissivity of the absorber. There are many selective heat treatments. Electroplating of black chromium applied on copper has been used for a long time, it can also be applied on a layer of nickel. Currently, selective treatments obtained by pulverization, physical or chemical deposition processes are used. These treatments improve high temperature performance compared to black treatments and will reduce radiation losses. (MINI10)

3.2 Types of absorbers

The hydraulic circuit of the absorber must facilitate the transfer of heat since the fluid that circulates inside must evacuate the heat from the collector. To achieve this, it is important to meet certain characteristics. For example, that the contact surface is as large as possible, also that the fluid that circulates inside is in a permanent regime helps to ensure good heat transmission. It is also very important that the flow in the circuit is constant to optimize performance.

There is a wide variety of absorbers, including those made of copper tubes in a harp or serpentine arrangement. The arrangement of these is decided keeping in mind the objectives that are to be achieved, which are that the heat transfer is as high as possible, so that the circulating fluid absorbs a high amount of heat, but also that the costs of the materials and manufacturing are not very high. For this reason, although increasing the contact surface also increases heat transfer, a balance must be sought to optimize the system. Taking all these factors into account, in most cases, the distance between the tubes is usually around 100 mm.

Hydraulic circuits consisting of parallel pipes that are joined to two pipes at the ends are known as absorbers with harp configuration. The following figure shows this distribution.

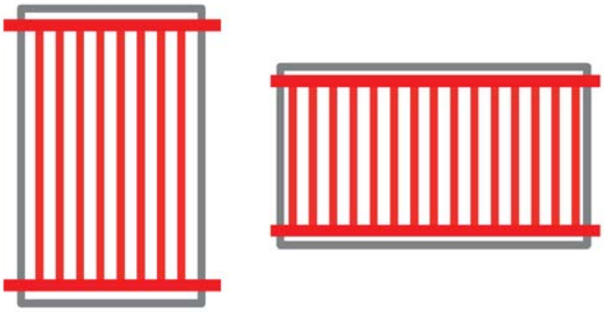


Figure 16: Harp pipe solar absorbers (Source: coolproject.es)

This configuration has quite low losses since the fluid enters through the distributor and circulates through all the parallel pipes. It is very important in this type of circuit to ensure that the flow that circulates through all the pipes is the same to optimize the performance of the system. If it is not designed properly there will be pressure losses in the parallel pipes and in the distribution pipes. This is because the distribution of the flow that circulates through the pipes depends on the losses. For this reason, these circuits are also applied in the manufacture of other systems, where the loss of charge is as low as possible. There are also 2 types of configurations for harp-type absorbers. There is the possibility of mounting longitudinally or transversally.

The other type of absorber is formed by a hydraulic circuit made up of a single serpentine-shaped pipe that runs through the entire absorber, known as the serpentine configuration. Its schematic can be seen in the following figure.

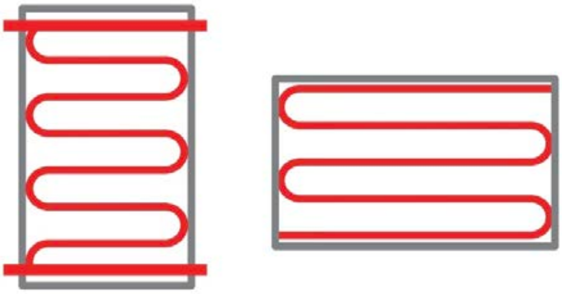


Figure 17: Serpentine pipe solar absorbers (Source: coolproject.es)

In these circuits there is the possibility that the outlet of the coil is directly outside or that it has distributor tubes so that the interconnection between the collectors is easier. The advantage this configuration has over other types of hydraulic circuits is that since the fluid circulates through a single pipe, there are no hydraulic imbalance problems.

However, the head loss for coil-type absorbers will be higher. This is a consequence of the fact that, for the same flow regime, the flow that circulates through a single pipe of the serpentine type is greater than that which circulates through the grid configuration, where the total flow is distributed among the many pipes placed in parallel.

In addition, it must be considered that in coil-type absorbers there are sudden changes in the direction of the flowing fluid. As a conclusion, the load loss will be higher, so there are applications in which its use is not recommended. (MINI10)

There are other types of absorbers, although the harp and serpentine type are the most used. For example, the hydraulic circuit can also be made with sheets of aluminum or stainless steel, known as roll-bond.

The term "roll-bond" refers to a manufacturing process in which two metallic materials are joined using a hot rolling technique. This process is used to produce hybrid solar panels that combine the characteristics of photovoltaic and thermal solar panels. (RICC21)

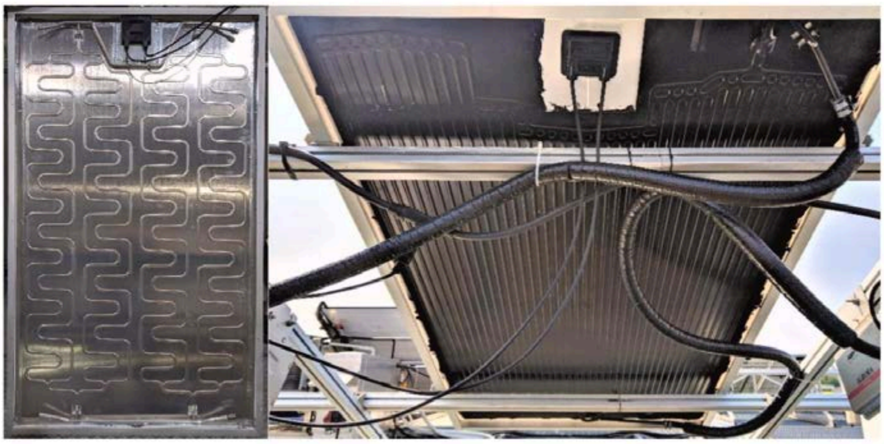


Figure 18: Roll-bond configuration (source: SolarTech^{LAB})

3.3 Connection between the collectors

The series connection between the collectors that make up the system will allow the fluid to progressively increase its temperature as it passes from one collector to the next. In the following image you can see this configuration.

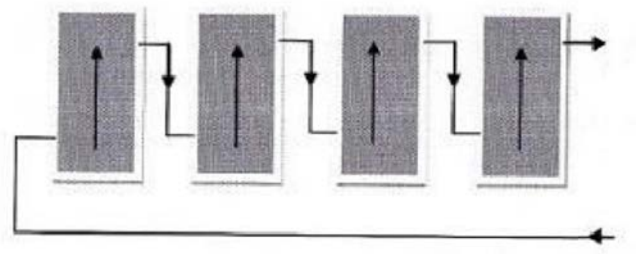


Figure 19: Series connection (Source: ingmecanica.com/tutorial/)

This configuration is not recommended since the final collectors work at very low performance. This is due to the fact that as the temperature of the fluid increases as it passes from one collector to the next, the thermal gradient that can be reached decreases as the fluid approaches the outlet of the collector.

For this reason, this type of connection is not recommended. In the case in which very high temperatures are to be obtained, it is advisable to use other types of equipment such as medium and high temperature solar thermal collectors to obtain better results.

In the case of wanting to use the serial connection, no more than three collectors should be connected so that the efficiency drops excessively.

Parallel connection is normally used. If you want to avoid the installation of flow balancing valves, the connection in parallel with inverted return is recommended. The following image shows this configuration.

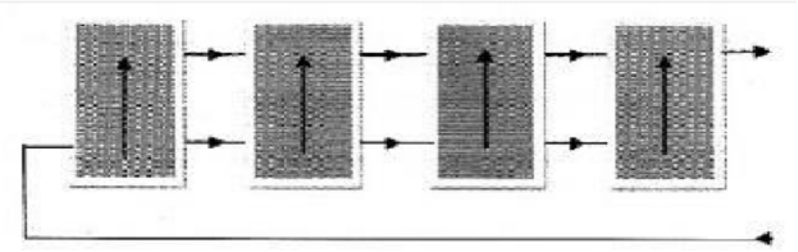


Figure 20: Parallel connection with inverted return (Source: ingmecanica.com/tutorial/)

When necessary, the collectors can be arranged in several rows, each row also being connected in parallel. In these installations, it is recommended to install shut-off valves at the inlet and outlet of each battery of collectors, so that they can be isolated for maintenance or replacement work.

In some situations when this type of connection cannot be installed, a connection in parallel with the external pipe and balanced with a valve can be used. In this case, the connection of the collectors can be made in parallel according to this configuration.

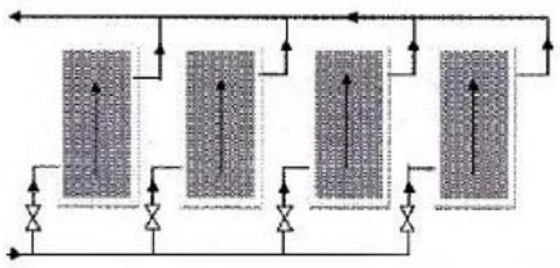


Figure 21: Parallel connection by external pipe and valve (Source: ingmecanica.com/tutorial/)

In cases where this configuration is used, it is not recommended to connect more than 10 collectors in parallel in the same series. If more are connected in the series, there is a risk that the collectors in the center receive less flow than those at the ends.

3.4 Natural and forced circulation.

Solar thermal systems utilize different circulation methods to transfer the heat captured by solar panels to the hot water storage and distribution system. The two main methods are natural circulation and forced circulation.

Natural circulation is a passive system that takes advantage of the density differences of the heat transfer fluid in the system. The fluid is heated in the solar panels due to solar radiation and, as it becomes lighter, it tends to rise to the top of the system. As the hot fluid ascends, the cooler water in the storage system descends to take its place. This continuous process of natural convection allows for heat transfer without the need for additional pumps or controllers. Natural circulation is commonly used in low-temperature solar thermal systems, such as domestic water heating systems.

On the other hand, forced circulation utilizes pumps and controllers to actively drive the heat transfer fluid through the system. The pumps are responsible for moving the fluid from the solar panels to the storage and distribution system. This forced circulation provides greater control and efficiency in heat transfer, especially in larger systems or when higher thermal performance is required. Forced circulation systems typically include sensors and controllers to monitor and regulate the temperature and flow of the fluid.

The choice between natural circulation and forced circulation depends on various factors such as system size, geographical location, temperature requirements, and desired efficiency. It is important to consider the specific project characteristics and system requirements when selecting the appropriate circulation type.

3.5 Operating principle.

Transmissive selectivity and absorption-emission selectivity are the 2 properties on which the operation of solar collectors is based.

The first property, transitive selectivity, is possessed by those materials that have high transmittance at short wavelengths, it varies from 0.2 to 3 µm. In addition, the transmittance at long wavelengths, from 10 to 14 µm, is low. These waves are emitted at the temperature of the absorber plate. This phenomenon is known as the greenhouse effect as shown in the following image.

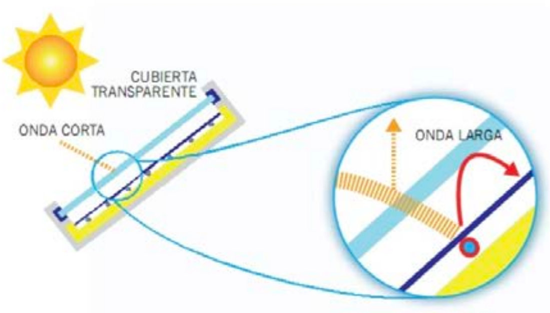


Figure 22: Greenhouse effect in a solar collector. (Source: coolproject.es)

The following graph allows to analyze the transmittance of a glass and the approximate distribution of the energy in each wavelength. Of special interest is the study of radiation from the sun, 60000K, and radiation from the absorber, 400K.

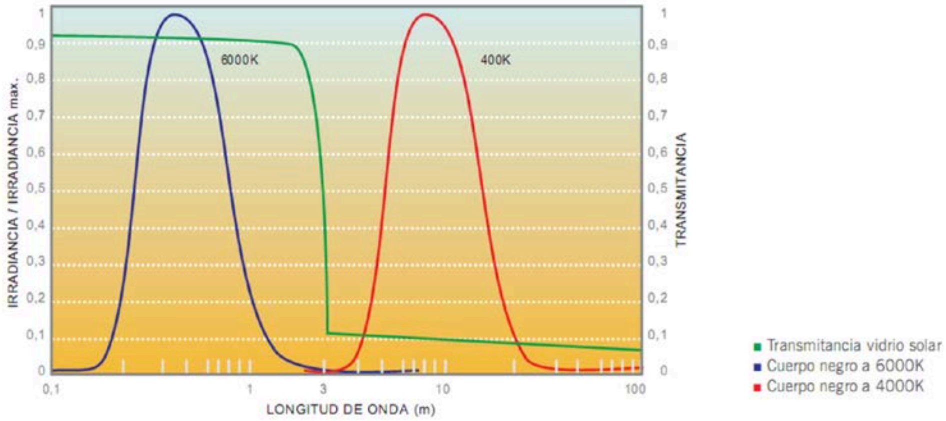


Figure 23: Spectral distribution of radiation and transmissivity of glass (Source: coolproject.es)

The second property that determines the operation of solar collectors is the absorption-emission selectivity. In the case of short wavelengths of solar radiation incident on the collector, the absorptance value is high (α). In addition, the emissivity at long wavelengths emitted by the absorber is of a low value (ε).

In conclusion, certain characteristics are sought in solar collectors so that the efficiency is the best possible. Firstly, that the transmittance is high, that is, that it can absorb the greatest amount of solar radiation. It must also have a low emissivity, it is not enough that it simply be able to absorb as much solar radiation as possible, but also emit as little as possible, known as low longwave transmittance.

Next, the energy flow in a solar collector can be analyzed:

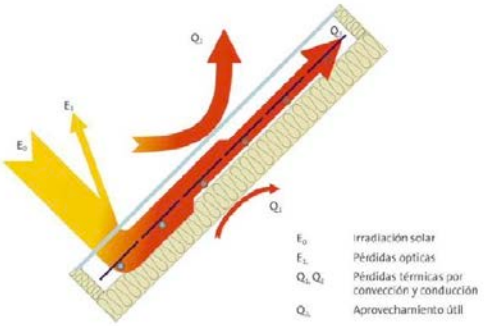


Figure 24: Energy flows in a collector (Source: coolproject.es)

A distinction is made between optical and thermal losses. The optical losses will depend on the type of glass with which the solar collector is made and can vary between 4 and 6% of the incident irradiance, these losses are caused by reflectivity. Thermal losses (Q1 and Q2) occur mostly on the front face, where the transparent cover is located, and account for around 80% of the total losses. The rest of the losses take place on the back face or on the sides, it will depend on the thermal insulation that the system has, also on the temperature or the wind outside.

3.6 Efficiency

The performance of a thermal photovoltaic solar panel (PVT) is influenced by several factors.

First, the amount of solar energy that the PVT panel receives is key, so the intensity and duration of sunlight is a factor that will largely determine the performance of the system. An analysis must be done to study the best possible location where the panels can be installed, looking for places with high solar radiation.

The efficiency of the solar panel depends on the efficiency of the photovoltaic solar cells. This factor determines the amount of electrical energy that can be generated from solar energy. The higher the efficiency of the panel, the greater the amount of electrical power that can be generated.

The design and quality of the PVT panel also influence its performance. A well-optimized design can improve solar energy collection and heat transfer, while high-quality panels can have a longer lifespan and offer better performance in the long run.

The ambient temperature is directly related to the performance of the system since the efficiency of photovoltaic solar cells is reduced with high temperatures. An efficient cooling system can help keep the temperature of the solar cells within an optimal range for best performance.

The working liquid used in the PVT panel cooling system must have good thermal properties and corrosion resistance. In addition, the amount of working liquid used must be adequate to ensure optimal heat exchange in the panel.

Also, the orientation and inclination of the panel can influence the amount of solar radiation it receives. In general, PVT panels work best when facing south and having a slope that matches the local latitude.

The equation of the performance of a solar thermal collector is expressed as:

$$\eta_{collector} = \frac{\dot{q}_{useful}}{\dot{q}_{total}} = \frac{\dot{q}_{useful}}{IA} = \alpha - U\,\frac{(T_{collector} - T_{ambient})}{I}$$

α = absorptivity factor

U = termal conductivity between the collector and ambient [$WK^{-1}m^{-2}$]

I = solar flux [Wm^{-2}]

$T_{collector}$ = collector temperature [K]

$T_{ambient}$ = ambient temperature [K]

As reflected in the above formula, the system performance is the quotient of net and total heat. In usable heat it is calculated as the difference between the heat absorbed by the collector, which depends on the absorptance factor (α), and the heat losses.

The total energy captured by the panels is calculated as:

I = solar flux [Wm^{-2}]

A = area of collector [m^2]

On the one hand, from all the radiation that falls on the plate, the absorber is not able to capture everything.

The absorption factor refers to the fraction of solar radiation that is absorbed by a solar panel. Solar panels are designed to absorb as much solar radiation as possible and convert it into usable electrical energy. The absorption factor depends on several factors, such as the type of material used in the solar panel, the structure of the panel, and the wavelength of the incident solar radiation.

On the other hand, solar radiation emission refers to the amount of solar radiation that is emitted by a solar panel. When a solar panel absorbs solar radiation, part of this energy is converted into usable electrical energy, while another part is emitted in the form of thermal radiation. The amount of solar radiation emitted depends on the amount of solar radiation absorbed and the thermal properties of the solar panel.

In general, solar panels are designed to maximize the absorption factor and minimize the emission of solar radiation, so that they can generate the greatest possible amount of electrical energy from incident solar radiation.

Therefore, taking these factors into account, the following formulas are defined to calculate the energy absorbed and the losses.

$$\dot{q}_{loss} = AU(T_{collector} - T_{ambient})$$

Using these two expressions, the usable energy can be calculated as:

$$\dot{q}_{useful} = A\left(I\alpha - U(T_{collector} - T_{ambient})\right) = \dot{m}c_P(T_{out} - T_{in})$$

Looking at the performance equation, it shows that the higher the fluid inlet temperature, the lower the performance. The opposite occurs when the irradiance increases and the fluid inlet temperature decreases.

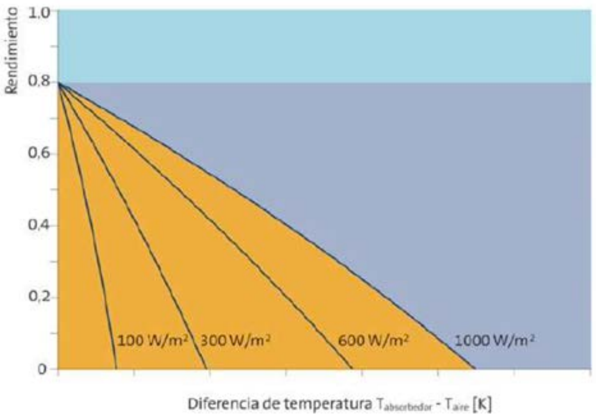


Figure 25: Performance variation with irradiance and temperature

CHAPTER 4. HYBRID SYSTEMS

The continuous development of hybrid panel technologies, coupled with their integration into facilities that require low- to medium-temperature electricity and heat, as well as the constant increase in energy prices, has led to a steady growth of this technology and its implementation in real-world applications. While this technology is efficient, integration into different types of installations and storage requirements remain the biggest obstacle it faces. Factors such as regulations and the time lag between generation and consumption influence sizing and the need for thermal and electrical storage, and their proper combination can be a key factor in their market development.

Currently, due to the reduction in costs of photovoltaic technology and advancements in hybrid panels, it is possible to achieve greater energy efficiency through trigeneration systems. This technology is gaining a foothold in an important market niche, shared with photovoltaic and particularly thermal systems. Hybrid panels have the advantage of generating more energy than separate thermal or photovoltaic panels and are particularly suitable for cases where space is limited.

4.1 Classification

There are different ways to classify PVT collectors based on various criteria, both in their photovoltaic and thermal parts. In the thermal part, there is a greater variety of criteria to classify them.

To differentiate the hybrid collectors, different types are distinguished depending on the part that generates electrical energy, i.e., the photovoltaic cells. We can distinguish between monocrystalline, polycrystalline, and thin-film silicon plates, including all subgroups of the latter. Monocrystalline and polycrystalline silicon plates are the most common and popular in PVT technology, as well as in traditional photovoltaics.

From a thermal standpoint, a distinction in solar thermal collectors can be made between concentrated and non-concentrated collectors. Furthermore, various types of systems can be differentiated based on the working fluid employed, whether it entails natural or forced circulation, or whether the input is singular or multiple. Additionally, different types of hybrid systems exist, contingent upon the presence of glazing on the collector or the inclusion of a thermal absorber.

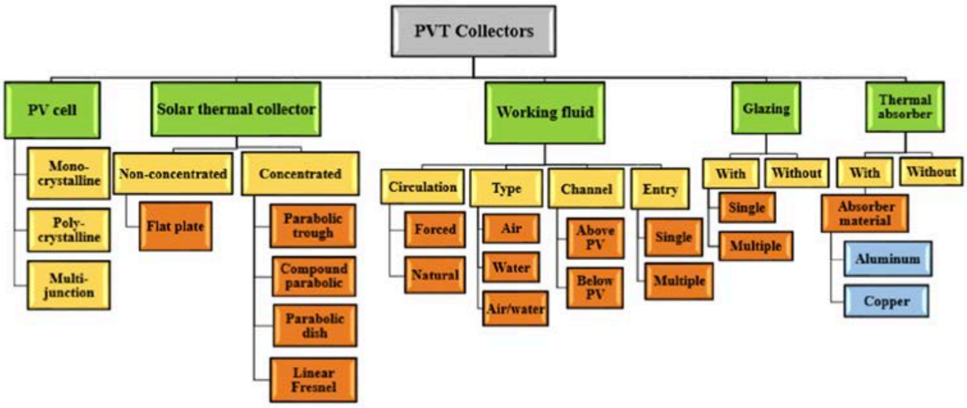


Figure 26: Classification of PVT solar collectors (ALVA21)

4.2 Operation, components, and efficiency

In a photovoltaic cell, most of the solar radiation that it absorbs is converted into heat, which causes the temperature of the cell to increase, thereby reducing its electrical efficiency. To solve this problem, the solar cells can be cooled by a fluid flow, either a gas or a liquid, to decrease their temperature and improve their efficiency. Additionally, the heat extracted by the coolant can be utilized to fulfill another demand such as providing hot water or space heating, allowing the possibility of obtaining a useful thermal output from PV systems. The desire to improve electrical efficiency and provide heat has driven the development of hybrid PV concepts. These hybrid photovoltaic/thermal (PVT) systems are holistic solar energy solutions that combine a PV module for generating electricity with a heat exchanger arrangement and a coolant circuit containing a heat transfer fluid for heat provision.

Typically, the primary objective of a hybrid PVT system is to maximize its electrical output, and therefore, the heat transfer unit's operating conditions are optimized to enhance its electrical performance. To achieve this, the cooling fluid in the heat transfer circuit is maintained at low temperatures to prevent a decline in the PV cell's electrical efficiency, which would otherwise be undesirable. However, this low-temperature limitation on the heat transfer fluid's exit from the collector impedes its potential use for heating purposes, which requires higher outlet fluid temperatures. If the system were designed to provide higher outlet fluid temperatures for heating applications, the PV cell's electrical efficiency would suffer. As a result, a trade-off is required to balance the electrical and thermal performance of hybrid PVT systems based on the end-users' specific requirements.

The following is a diagram of the different components that make up a hybrid solar system.

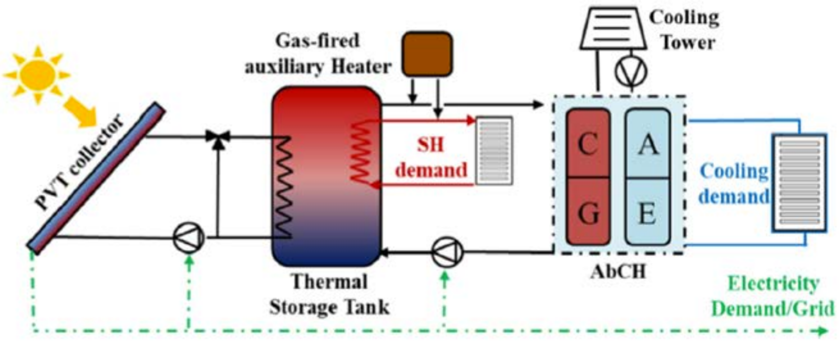


Figure 27: Space cooling/heating PVT system (AMAL20)

Finally, the efficiency of the hybrid system is the sum of the efficiency of the photovoltaic cells and the heat exchanger, i.e., the sum of the thermal and electrical efficiency.

$$\eta = \eta_E + \eta_T$$

4.3 Dependent factors

4.3.1 Sun

The sun is located in the center of the solar system, it is the closest star to the earth, it constitutes the maximum source of electromagnetic energy that maintains life on the planet.

The sun is the origin of most renewable energy because it causes the heating of the earth and produces geothermal energy; the heating of the waters by means of the sun induces the formation of the water cycle and thus hydraulic energy. These phenomena generate a pressure differential that gives rise to the winds that are the source of wind energy and in the same way thanks to this great star that is the main actor for the phenomenon of photosynthesis of plants which are the basis of biomass energy.

Solar radiation is the set of electromagnetic waves which go in all directions and originate from the solar source through a nuclear fusion process that emits them without the need for a material or physical medium. Its unit of measure is the irradiation W/m2 and the amount of solar radiation that reaches the earth's surface is directly proportional to the height above sea level.

To have the highest possible efficiency in the system, it is desired to have the highest possible radiation. The movement of the Earth around the Sun is an astronomical phenomenon known as Earth's orbit. It takes the Earth approximately 365.25 days to complete one orbit around the Sun, which is known as a solar year. During its orbit, the Earth moves in an ellipse around the Sun, with the Sun at one of the foci of the ellipse. This cycle can be seen in the figure below.

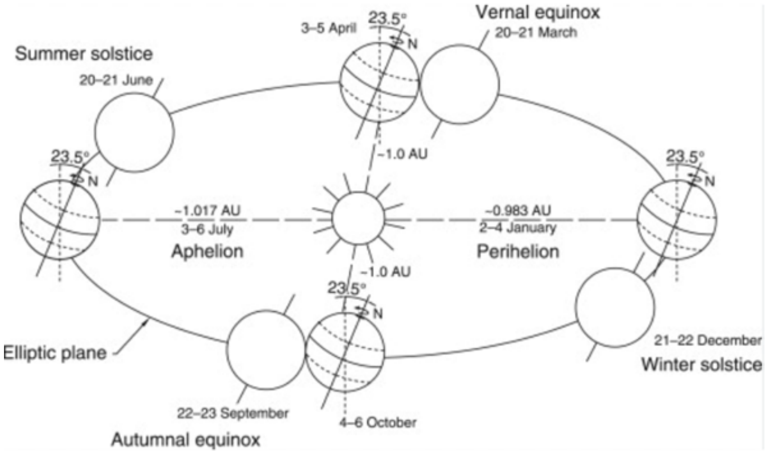


Figure 28: The Earth´s Orbit (ALI_12)

The position of the Sun in the sky varies throughout the day and throughout the year due to the rotation of the Earth on its own axis and the tilt of the Earth's axis in relation to the plane of its orbit around the Sun. of the Sun in the sky also varies depending on the observer's geographic location on Earth.

During the day, the Sun moves from east to west in the sky due to the Earth's rotation on its own axis. At solar noon, when the Sun is at its highest point in the sky, its position is directly due south in the northern hemisphere and directly due north in the southern hemisphere. After solar noon, the Sun begins to move west and sets over the horizon at sunset.

The tilt of the Earth in relation to the plane of its orbit around the Sun also affects the position of the Sun in the sky and the incidence of solar radiation on the Earth. At the summer solstice in the Northern Hemisphere, the Earth's tilt causes the Sun to be at its highest point in the sky during the day and the amount of solar radiation incident on the Northern Hemisphere to be maximum. At the winter solstice in the Northern Hemisphere, the Sun is at its lowest point in the sky during the day and the amount of solar radiation incident on the Northern Hemisphere is minimal.

The solar declination is the angle formed between the plane of the equator and the line that goes from the center of the sun to the center of the Earth and varies between +-23.45º. The following image shows the representation of the solar declination and how it varies during the months of the year.

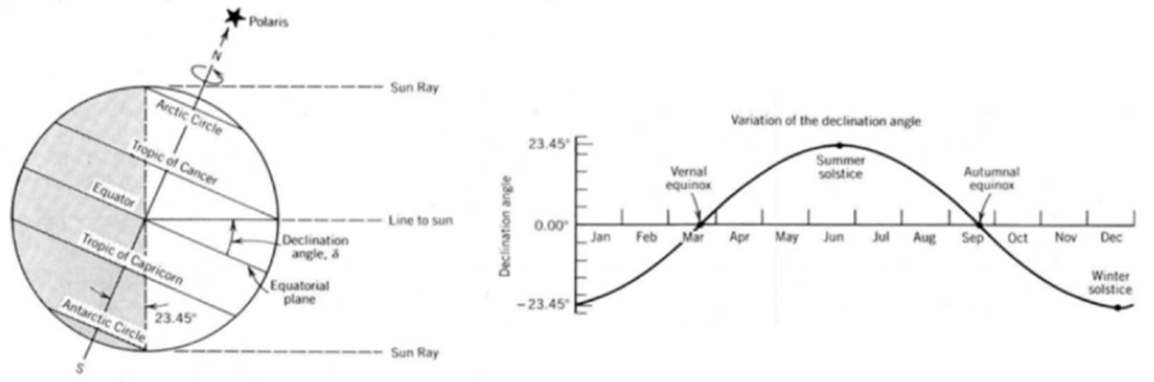


Figure 29: Solar declination angle (FELI14)

This analysis of the solar incidence on the surface is very useful to establish the location of the solar panels in order to be as efficient as possible.

4.3.2 Angle of incidence

The angle of incidence of solar radiation on a solar panel is a key factor in the amount of useful energy that can be obtained.

When solar radiation hits the surface of the solar panel perpendicularly, it is said to be at an angle of 0 degrees. In this case, solar radiation is fully absorbed and converted into electrical energy with maximum efficiency. However, as the angle of incidence increases, the amount of solar radiation that is absorbed and converted to electrical energy decreases.

The amount of energy due to direct radiation that can be captured by a surface that is exposed to the sun's rays depends on the angle between the surface and the sun's rays.

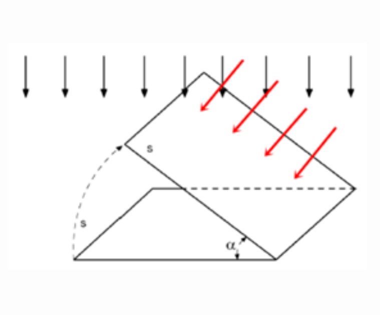


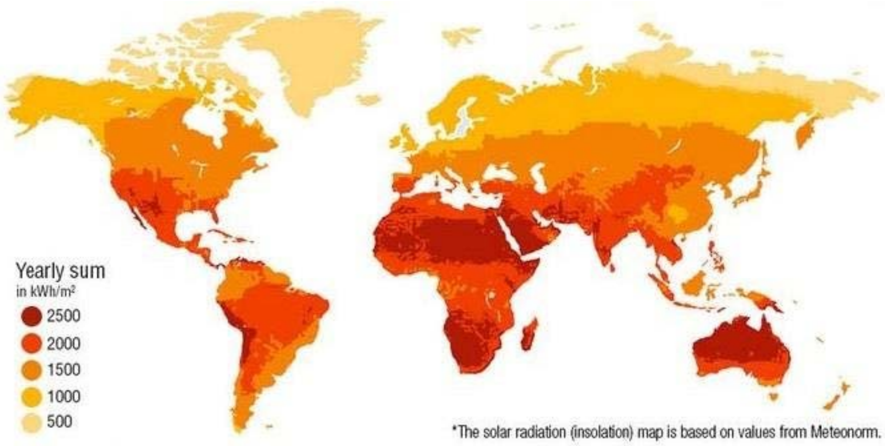
Figure 30: Solar radiation on an inclined surface (Source: Magazine Point by Axle Themes, Espectro solar)

If “I” is established as the intensity on a solar panel that is perpendicular to the incident rays. The intensity on a surface inclined α degrees will be equal to I*cosα.

Therefore, to maximize electrical power output from a solar panel, it is important that it be installed at an angle that allows the greatest amount of solar radiation to strike the panel surface perpendicularly. The optimal installation angle depends on geographic location and factors such as time of day, season of the year, and weather conditions.

The use of the Sun's energy is conditioned by the intensity of radiation received on Earth. The radiation varies according to the latitude of the place, the time of day, the atmospheric and climatic conditions. The metric unit used for radiation is W/m2, which expresses the amount of energy that reaches an area of one square meter.

Below are images showing the radiation that reach different regions.



*The solar radiation (insolation) map is based on values from Meteonorm.

Figure 31: Solar radiation map (Source: Alchemie Limited Inc)

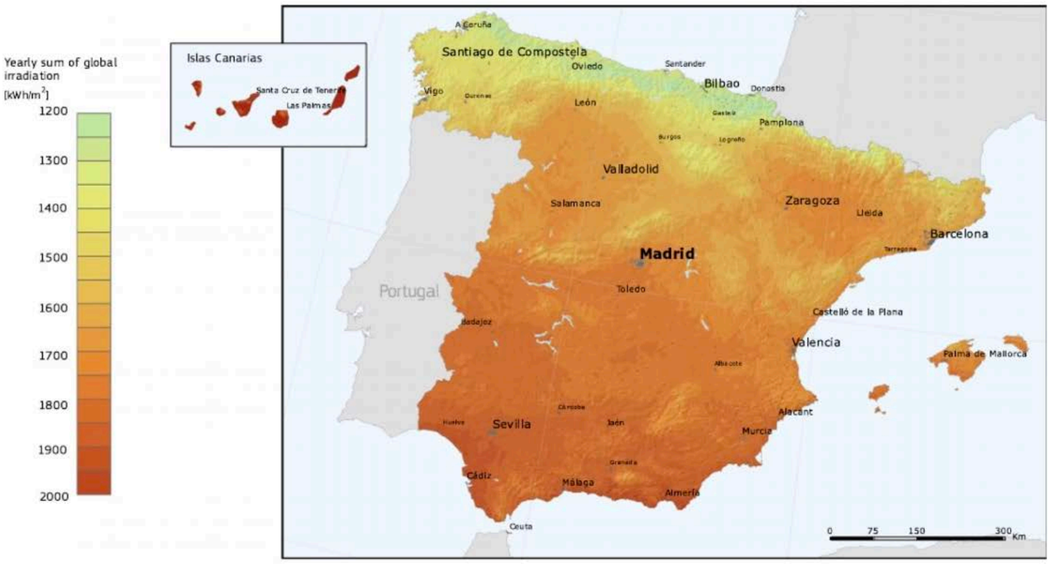


Figure 32: Horizontal global irradiation in Spain (Source: PVGIS© European Union)

4.3.3 Separation between collectors

Another important parameter to optimize the performance of the system is the separation distance between the collectors. This distance can be calculated with the formula shown below:

$$d = k * h$$

K is a factor that will depend on the latitude of the place.

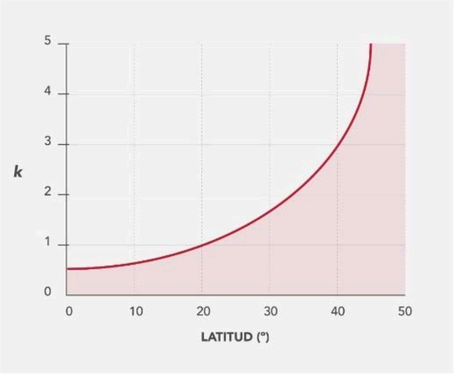
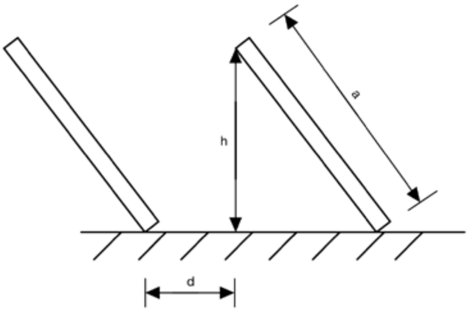


Figure 33. Latitude K Curve Plot (Source: TechnoSun)

The value "h" represents the height that the panel reaches. It can be calculated in a simple way, since the value "a" is known, known as the height of the collector, and the angle that the panel forms with the horizontal of the ground. The value of "h" can be obtained by multiplying "a" by the sine of the angle.



CHAPTER 5. CASE STUDY

5.1 Evaluation of the solar source

The following section will discuss the analysis of implementing a hybrid PT system in a residential property located in Malaga, Spain. The property is a single-family dwelling occupied by 4 people.

It is very important to consider the exact location to obtain the data related to the radiation and temperature values in the place. In the next chart, this information has been placed using the NASA source.

Coordinates:

- Longitude: -4.4º
- Latitude: 37º

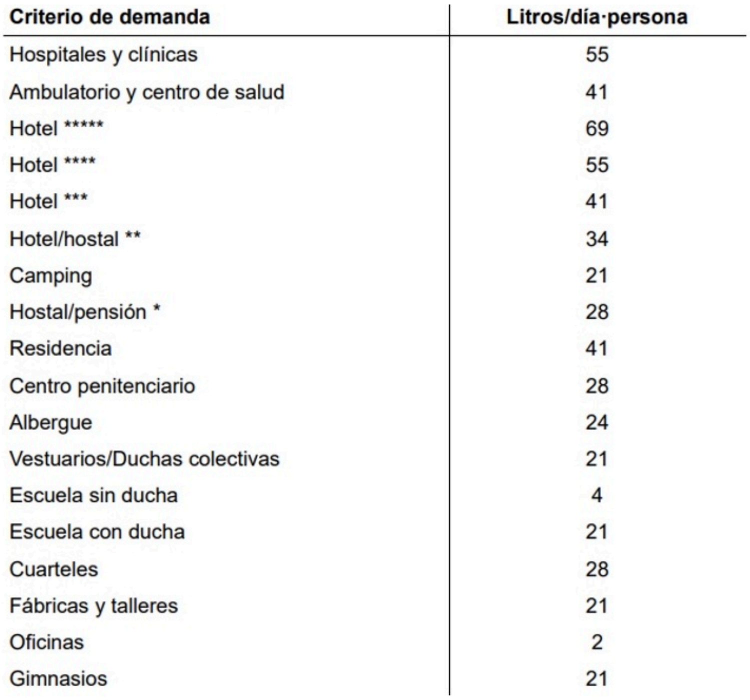
Month	Direct Normal Irradiance [kW-hr/m^2/day]	Diffuse Irradiance [kW-hr/m^2/day]	Temperature [ºC]
JAN	2.74	0.88	11.14
FEB	3.39	1.5	12.93
MAR	4.85	1.7	13.87
APR	5.06	2.43	15.52
MAY	6.92	2.07	18.62
JUN	7.53	2.1	21.19
JUL	7.71	1.95	24.18
AUG	6.44	2.16	25.17
SEP	5.3	1.64	22.79
OCT	4.35	1.4	19.58
NOV	3.24	0.91	13.8
DEC	2.4	0.85	13.11
Average	4.99	1.63	17.69

Table 1: Irradiance and average temperature per month

5.2 Housing Consumption

- ACS

According to the document "DB HE Ahorro de Energía", the reference demand for Domestic Hot Water (DHW) in single-family homes is estimated to be 41 liters per person at a reference temperature of 60ºC.



Criterio de demanda	**Litros/día·persona**
Hospitales y clínicas	55
Ambulatorio y centro de salud	41
Hotel *****	69
Hotel ****	55
Hotel ***	41
Hotel/hostal **	34
Camping	21
Hostal/pensión *	28
Residencia	41
Centro penitenciario	28
Albergue	24
Vestuarios/Duchas colectivas	21
Escuela sin ducha	4
Escuela con ducha	21
Cuarteles	28
Fábricas y talleres	21
Oficinas	2
Gimnasios	21

Water temperature (ºC)	60
Daily consumption (liters/day)	41
Number of occupants	4

Table 2: DHW consumption

$$Total\ consumption\ DHW = 4 * 41 = 164\ liters/day$$

- Electricity

Device	Amount	Power (W)	Daily usage time (h)	K_s	Daily consumption (Wh/day)	Monthly consumption (Wh/month)	Annual consumption (Wh/year)
Fridge	1	300	24	0.5	3600	108000	1296000
Washing machine	1	1700	0.6	0.66	673.2	20196	242352
Dishwasher	1	2100	0.5	0.66	693	20790	108000
TV	2	250	2	0.3	300	9000	360000
Microwave	1	900	0.3	0.66	178.2	5346	64152
Oven	1	1500	1	0.5	750	22500	270000
Lightning	20	12	4	0.75	720	21600	259200
Glass hob	1	2000	1	0.5	1000	30000	360000
Total (Wh)					7914.4	237432	2849184
Total (kWh)					7.9	237.4	2849.2

Table 3: Electricity consumption

The calculations have been made to estimate the daily, monthly, and annual consumption, assuming that a month has 30 days.

Simultaneity factor (Ks) is an estimated value that takes into consideration the fact all the devices are never switched on simultaneously at full power.

A safety factor of 1.1 is established, then the final demand can be calculated by multiplying the total value by the safety factor.

$$Demand\ E_{day} = 7.9\ kWh/day * 1.1 = 8.7\ kWh/day$$

$$Demand\ E_{month} = 237.4\ kWh/day * 1.1 = 261.14\ kWh/month$$

$$Demand\ E_{year} = 2849.2\ kWh/day * 1.1 = 3134.12\ kWh/year$$

In addition to the loads shown in the table, the energy consumption derived from heating needs to be considered. The house is equipped with a pellet boiler, which operates during the winter months of November, December, January, and February. Additionally, to cope with heat during the summer months, there are 3 fans in the house that are used in June, July, and August.The boiler operates for an average of 6 hours per day with a power consumption of 100 W/h. Therefore, during the operating months, it consumes 600 Wh/day. The 3 fans have a power consumption of 35 W/h and are used for 4 hours per day during the summer months. This results in an additional consumption of 420 Wh/day.

The selection of the distribution system for the installation is a crucial aspect to consider. In this project, a forced circulation system has been chosen, utilizing pumps and a controller to ensure the movement of the heat transfer fluid within the primary circuit. The collector surface will be positioned on the roof of the dwelling, while the storage tanks will be strategically placed in the basement area. Once the fluid within the primary circuit has been adequately heated, it passes through a heat exchanger, which in turn warms the water for consumption via a coiled mechanism situated within the storage tank.

The installation of a recirculating pump is required, which entails an additional electricity consumption of 5Wh. The pump operates for 4 hours daily, resulting in a monthly consumption of 600 Wh.

To design the hybrid system, the first step is to dimension it to meet the domestic hot water (DHW) demand. The number of panels required for the thermal part will then be used to calculate the amount of electricity they will generate, contributing to a reduction in grid electricity consumption. This approach aims to provide the necessary thermal energy while simultaneously decreasing the electricity bill by a certain percentage and reducing the emission of greenhouse gases.

5.3 Hybrid Panel Selection

This design has chosen to use the aH72 SK hybrid panel model from the Spanish company Abora Solar. The aH72SK modules combine solar panels with power conversion efficiencies of 17% and thermal efficiency of 70%.

Figure 34: aH72SK Hybrid Panel

Below are the features obtained from the technical datasheet of this hybrid panel.

General characteristics	
Length*width*thickness	1.970 x 995 × (85 + 22) mm
Total area	1,96m2
Cells amount	72
Weight	50 kg
Thermal efficiency	70%
Photovoltaic efficiency	17%
Hybrid efficiency	87%
Electric characteristics	
Cell type	monocrystalline
Nominal power (Pmax)	350 W
Maximum Power Voltage (Vmpp)	39.86 V
Maximum Power Current (Impp)	8.76 A
Open Circuit Voltage (Voc)	48.61 V
Short Circuit Current (Isc)	9.16 A

Thermal characteristics	
Optical performance	0.7
Thermal Loss Coefficient, a1	5.98 W/m^2 K
Thermal Loss Coefficient, a2	0 W/m^2 K
Interior liquid volume	1.78 L

Table 4: Hybrid Panel Characteristics

5.4 Panels orientation and inclination

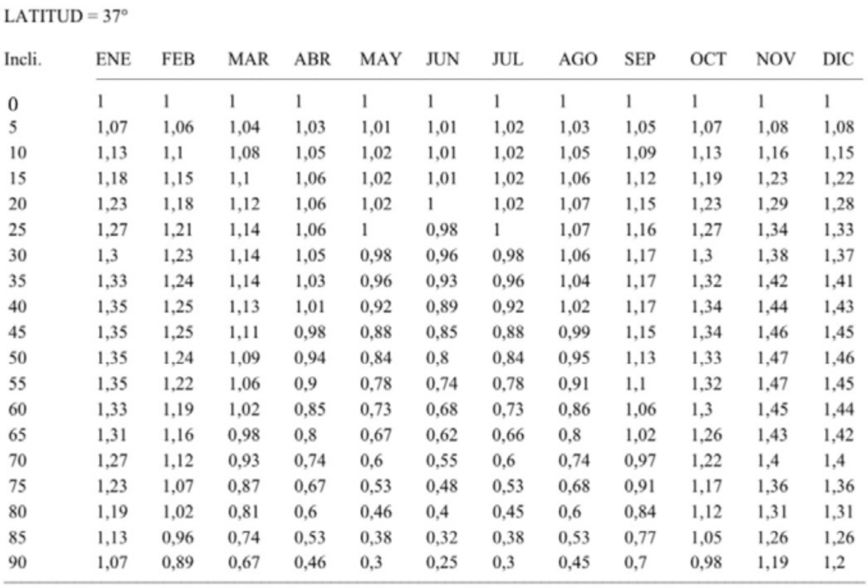
To calculate the radiation on the surface of the collectors, their placement in the house should be taken into account to avoid possible shadows, as well as their inclination.

In countries in the northern hemisphere, the panels should be oriented towards the south to capture the maximum amount of radiation possible. In this case study, this orientation will be assumed.

Additionally, the radiation will be estimated with the correction factor associated with the angle of inclination between the panel and the horizontal. In the system installation in the house, the panels form an angle of 30 degrees since it coincides with the pitch of the roof, this way, additional expenses for the support structure will be avoided, as well as potential detrimental effects on the system caused by the wind.

From the following table obtained from the "Technical Specifications for Low-Temperature Installations," the value of the correction factor can be observed, which will later be multiplied by the average irradiation value.

For a latitude of 37 degrees, the following values of the correction factor are extracted:



LATITUD = 37°

Incli.	ENE	FEB	MAR	ABR	MAY	JUN	JUL	AGO	SEP	OCT	NOV	DIC
0	1	1	1	1	1	1	1	1	1	1	1	1
5	1,07	1,06	1,04	1,03	1,01	1,01	1,02	1,03	1,05	1,07	1,08	1,08
10	1,13	1,1	1,08	1,05	1,02	1,01	1,02	1,05	1,09	1,13	1,16	1,15
15	1,18	1,15	1,1	1,06	1,02	1,01	1,02	1,06	1,12	1,19	1,23	1,22
20	1,23	1,18	1,12	1,06	1,02	1	1,02	1,07	1,15	1,23	1,29	1,28
25	1,27	1,21	1,14	1,06	1	0,98	1	1,07	1,16	1,27	1,34	1,33
30	1,3	1,23	1,14	1,05	0,98	0,96	0,98	1,06	1,17	1,3	1,38	1,37
35	1,33	1,24	1,14	1,03	0,96	0,93	0,96	1,04	1,17	1,32	1,42	1,41
40	1,35	1,25	1,13	1,01	0,92	0,89	0,92	1,02	1,17	1,34	1,44	1,43
45	1,35	1,25	1,11	0,98	0,88	0,85	0,88	0,99	1,15	1,34	1,46	1,45
50	1,35	1,24	1,09	0,94	0,84	0,8	0,84	0,95	1,13	1,33	1,47	1,46
55	1,35	1,22	1,06	0,9	0,78	0,74	0,78	0,91	1,1	1,32	1,47	1,45
60	1,33	1,19	1,02	0,85	0,73	0,68	0,73	0,86	1,06	1,3	1,45	1,44
65	1,31	1,16	0,98	0,8	0,67	0,62	0,66	0,8	1,02	1,26	1,43	1,42
70	1,27	1,12	0,93	0,74	0,6	0,55	0,6	0,74	0,97	1,22	1,4	1,4
75	1,23	1,07	0,87	0,67	0,53	0,48	0,53	0,68	0,91	1,17	1,36	1,36
80	1,19	1,02	0,81	0,6	0,46	0,4	0,45	0,6	0,84	1,12	1,31	1,31
85	1,13	0,96	0,74	0,53	0,38	0,32	0,38	0,53	0,77	1,05	1,26	1,26
90	1,07	0,89	0,67	0,46	0,3	0,25	0,3	0,45	0,7	0,98	1,19	1,2

Table 5: Correction factor

For the inclination value of 30º:

Incl.	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
30	1.3	1.23	1.14	1.05	0.98	0.96	0.98	1.06	1.17	1.3	1.38	1.37

The corrected irradiation data is shown in the following table.

Month	Direct Irradiance [kWh/m^{2}day]	Direct Irradiance [kJ/m^{2}day]	Factor	Corrected Direct Irradiance [kWh/m^{2}day]	Corrected Direct Irradiance [kJ/m^{2}day]	Equivalent sun hours (ESH)
JAN	2.74	9864	1.30	3.56	12823.20	3.56
FEB	3.39	12204	1.23	4.17	15010.92	4.17
MAR	4.85	17460	1.14	5.53	19904.40	5.53
APR	5.06	18216	1.05	5.31	19126.80	5.31
MAY	6.92	24912	0.98	6.78	24413.76	6.78
JUN	7.53	27108	0.96	7.23	26023.68	7.23
JUL	7.71	27756	0.98	7.56	27200.88	7.56
AUG	6.44	23184	1.06	6.83	24575.04	6.83
SEP	5.30	19080	1.17	6.20	22323.60	6.20
OCT	4.35	15660	1.30	5.66	20358.00	5.66
NOV	3.24	11664	1.38	4.47	16096.32	4.47
DEC	2.40	8640	1.37	3.29	11836.80	3.29

Monthly average	4.99416667	17979	—	5.55	19974.45	5.55

Table 6: Corrected irradiance and ESH

The house where the system is intended to be installed is located in the province of Malaga, and as can be seen on the map, it corresponds to climatic zone IV.

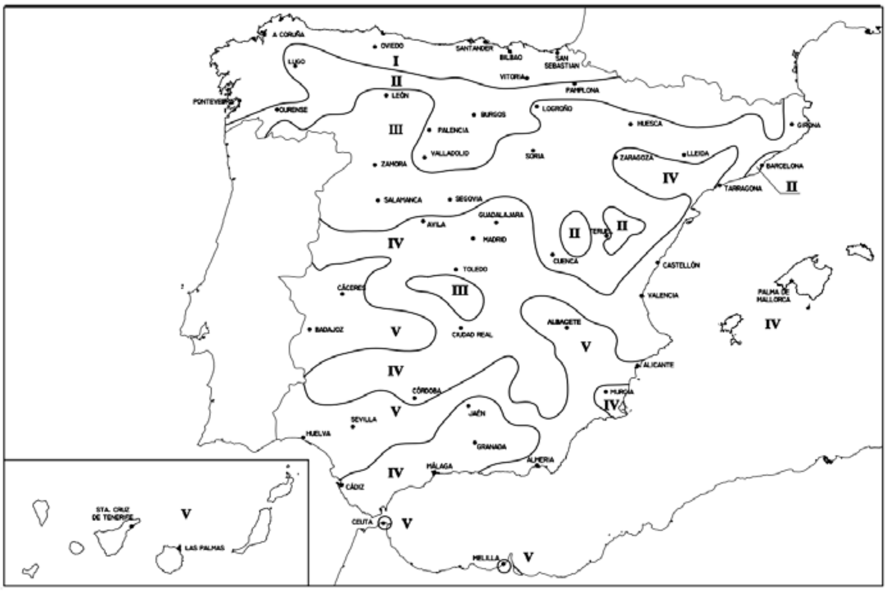
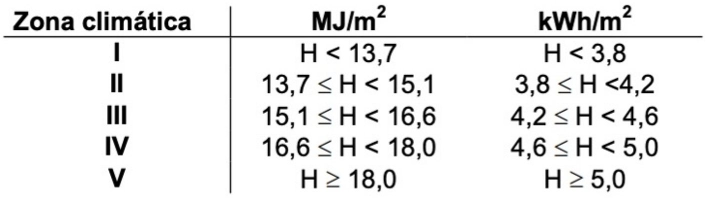


Figure 35: Climatic Zones (Source: Documento Básico HE Ahorro de Energía)

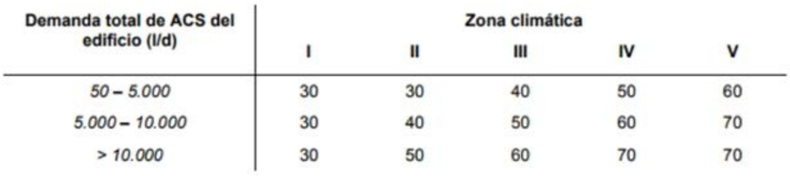
These zones are defined based on the annual average daily global solar radiation on a horizontal surface. The intervals corresponding to each zone are shown below. In the study location, the average global radiation has a value of 4.99, which corresponds to climatic zone IV.



Zona climática	MJ/m^2	kWh/m^2
I	$H < 13,7$	$H < 3,8$
II	$13,7 \leq H < 15,1$	$3,8 \leq H < 4,2$
III	$15,1 \leq H < 16,6$	$4,2 \leq H < 4,6$
IV	$16,6 \leq H < 18,0$	$4,6 \leq H < 5,0$
V	$H \geq 18,0$	$H \geq 5,0$

Table 7: Global irradiation (Source: Documento Básico HE Ahorro de Energía)

Considering that the location is in climatic zone IV and that the total daily domestic hot water (DHW) demand is 164 liters, it can be derived from the following table that a minimum solar contribution of 50% for DHW is required.



Demanda total de ACS del edificio (l/d)	Zona climática				
	I	II	III	IV	V
50 – 5.000	30	30	40	50	60
5.000 – 10.000	30	40	50	60	70
> 10.000	30	50	60	70	70

Table 8: Minimum solar contribution of for DHW (Source: Documento Básico HE Ahorro de Energía)

5.5 Thermal energy demand required for the domestic hot water (DHW) installation.

It will be calculated using the following formula:

$$D = C * \rho * C_p * (T_f - T_g)$$

C: DHW consumption [liters/day]

ρ: water density [1 kg/liter]

C_p: specific heat [4180 J/kg ºk]

T_f: final temperature [60ºC= 333K]

T_g: grid temperature [ºK]

The average monthly water temperatures from the mains have been obtained from the IDAE (Instituto para la Diversificación y Ahorro de la Energía).

Month	Days per month	Monthly consumption (liters/day)	T_{ACS} (K)	T_{grid} (ºC)	T_{grid} (K)	Daily thermal energy demand (kJ/day)	Monthly thermal energy demand (kWh/month)
JAN	31	164	333	8	281	35647.04	306.96
FEB	28	164	333	9	282	34961.52	271.92
MAR	31	164	333	11	284	33590.48	289.25
APR	30	164	333	13	286	32219.44	268.5
MAY	31	164	333	14	287	31533.92	271.54
JUN	30	164	333	15	288	30848.4	257.07
JUL	31	164	333	16	289	30162.88	259.74
AUG	31	164	333	15	288	30848.4	265.64
SEP	30	164	333	14	287	31533.92	262.78
OCT	31	164	333	13	286	32219.44	277.45
NOV	30	164	333	11	284	33590.48	279.92
DEC	31	164	333	8	281	35647.04	306.96
Average				12.25	285.25	32733.58	276.48

Table 9: Thermal energy demand

It can be concluded that 276.48 kWh/month of thermal energy will be required to meet the demand of 164 liters per day at a constant temperature of 60°C. This is equivalent to 3317.73 kWh/year of required energy.

5.6 Estimation of the number of solar panels to be installed.

To calculate the number of solar panels required to meet the calculated thermal energy demand, the thermal energy demand will be divided by the energy output of a panel.

The next step is to calculate the useful energy produced by a collector, which depends on the useful intensity of the collector, representing the power captured by the panel throughout the day.

It is defined as the ratio between the global irradiation incident on the collector and the hours of useful sunshine (PSH). Peak sun hours represent the number of hours per day with a hypothetical irradiance of 1000 W/m2. PSH values vary depending on the location and time of year. The "HM Sistemas" program was used to calculate the number of hours, and these values are shown in the following table.

Month	Global Irradiance [kWh/m^2day]	PSH [hours/day]	Useful intensity power [W/m^2]
JAN	3.56	2.54	1401.58
FEB	4.17	4.3	969.77
MAR	5.53	4.43	1248.31
APR	5.31	5.18	1025.1
MAY	6.78	6.63	1022.62
JUN	7.23	7.6	951.32
JUL	7.56	9.04	836.28
AUG	6.83	8.8	776.14
SEP	6.2	6.32	981.01
OCT	5.66	5.47	1034.73
NOV	4.47	3.72	1201.61
DEC	3.29	3.03	1085.81
Average	5.55	5.59	1044.52

Table 10: Useful Intensity Power

Next, the useful energy produced by a collector is calculated. This value is obtained based on the collector's efficiency, which depends on the thermal coefficients specified in the technical data sheet and the previously calculated useful intensity.

$$Energy = Ir * \eta_c$$

I: irradiation [kWh/m^2]

η_c: collector efficiency [%]

The following formula from the European Law EN 12975-2 is going to be used to estimate the collector efficiency:

$$\eta_c = \eta_o - \alpha_1 * x - \alpha_2 * x^2$$

η_c: collector efficiency [%]

η_o: optical efficiency [%]

α_1: thermal loss coefficient 1 [W/m^{2}K]

α_2: thermal loss coefficient 2 [W/m^{2}K]

x: relationship between the temperature difference of the fluid and the ambient temperature in relation to the useful intensity.

$$x = \frac{T_{ACS} - T_{amb}}{I}$$

Month	T_{ACS} [K]	T_{AMB} [K]	Useful intensity power [W/m^2]	x	Collector efficiency [%]	Direct Irradiance [kWh/m^{2}day]	Useful Energy [kWh/day]
JAN	333	284.14	1401.58	0.035	49.15	3.56	1.75
FEB	333	285.93	969.77	0.049	40.97	4.17	1.71
MAR	333	286.87	1248.31	0.037	47.9	5.53	2.65
APR	333	288.52	1025.1	0.043	44.05	5.31	2.34
MAY	333	291.62	1022.62	0.04	45.8	6.78	3.11
JUN	333	294.19	951.32	0.041	45.6	7.23	3.30
JUL	333	297.18	836.28	0.043	44.39	7.56	3.35
AUG	333	298.17	776.14	0.045	43.16	6.83	2.95
SEP	333	295.79	981.01	0.038	47.32	6.2	2.93
OCT	333	292.58	1034.73	0.039	46.64	5.66	2.64
NOV	333	286.8	1201.61	0.038	47.01	4.47	2.10
DEC	333	286.11	1085.81	0.043	44.18	3.29	1.45
Average	—	290.69	1044.52	—	49.15	5.55	2.52

Table 11: Useful Energy per month

Additionally, the losses generated due to the collector, pipes, and storage tank must be taken into account. In the following table, the final energy data for domestic hot water (DHW) is shown, assuming losses of 18%.

Month	Useful Energy [kWh/day]	Days per month	Useful Energy [kWh/month]	Useful Energy (18% losses9 [kWh/month]
JAN	1.75	31	54.28	44.51
FEB	1.71	28	47.84	39.23
MAR	2.65	31	82.10	67.32
APR	2.34	30	70.22	57.58
MAY	3.11	31	96.29	78.96
JUN	3.30	30	98.90	81.10
JUL	3.35	31	103.97	85.25
AUG	2.95	31	91.34	74.90
SEP	2.93	30	88.03	72.18
OCT	2.64	31	81.76	67.05
NOV	2.10	30	63.05	51.70
DEC	1.45	31	45.03	36.92
Average	2.52	—	76.90	63.06
Annual	30.30	—	922.80	756.70

Table 12: Final Useful energy

With the energy provided by each panel for DHW generation, the number of panels required to achieve the total DHW demand can be calculated.

$$N_{panels} = \frac{Thermal\ Energy\ Demand}{Energy\ generated\ per\ panel} = \frac{3317.73\ kWh/year}{756.70\ kWh/year} = 4.38$$

$$N_{panels} \approx 5$$

As expected, the number of panels required varies depending on the month. In summer, more thermal energy will be generated than necessary, while in winter, more collectors would be needed.

By performing the aforementioned calculation, the following table displays the number of panels that would be required per month.

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Panels amount	7	7	5	5	4	4	4	4	4	5	6	9

Table 13: Number of panels required per month

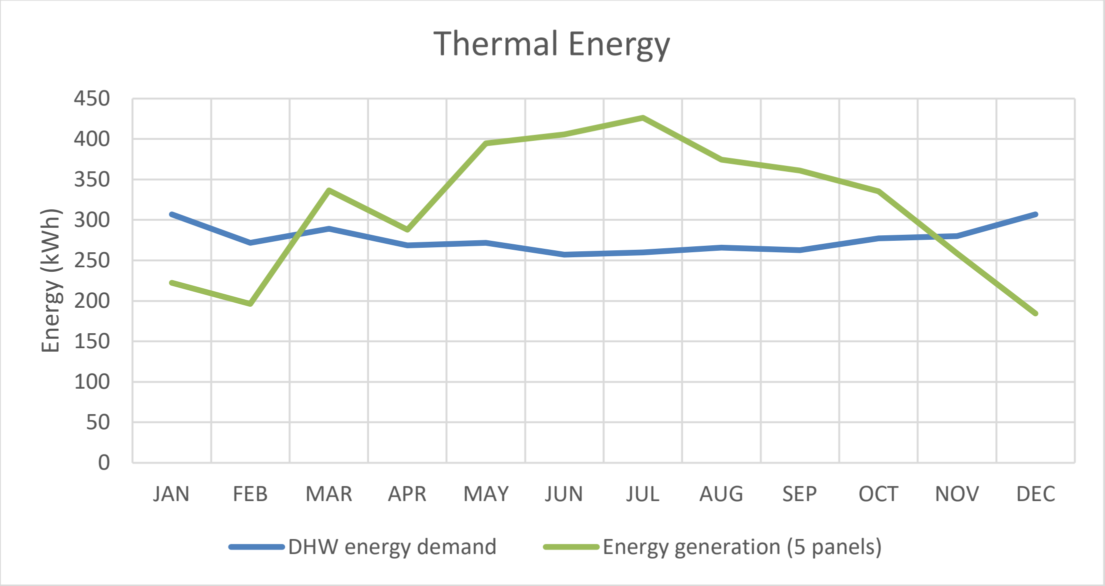


Figure 36: Thermal energy demand and generation

The graph above shows a comparison between the thermal energy required for the domestic hot water demand and the thermal energy provided by the established number of panels, which is 5, for each month of the year.

As can be seen, during the months of November, December, January, and February, the demand exceeds the generation. For this reason, an electric resistance will be installed in the storage tank, which will be responsible for generating the lacking thermal energy and will be powered by electricity.

To determine the consumption of the resistance, it is necessary to calculate the monthly production it should achieve. This value is obtained by subtracting the total demand from the generation of the 5 panels. The table below displays the energy generation values for the months in which the support system is required.

Month	January	February	November	December	Total
Resistance generation [kWh]	84.43	75.79	21.40	122.35	303.96

Table 14: Resistance generation

The electric resistances for storage tanks have a power range that can vary from 1.5 to 18 kW. The energy output of a 1.5 kW resistor can be calculated using the following equation:

$$E_r = P_r * t$$

E_r: energy generated by the resistance in a day [kWh/day]

P_r: resistance power [kW]

t: usage time [h]

With this relation the usage time per month can be estimated:

- January

$$t = \frac{84.43}{1.5 * 31} = 1.82\ hours/day$$

- February

$$t = \frac{75.79}{1.5 * 28} = 1.81\ hours/day$$

- November

$$t = \frac{21.4}{1.5 * 30} = 0.5\ hours/day$$

- December

$$t = \frac{122.35}{1.5 * 31} = 2.65\ hours/day$$

5.7 Photovoltaic generation

Once the desired number of panels has been selected to meet the thermal energy demand, the electrical energy that hybrid panels are capable of generating simultaneously can be calculated. The energy provided by each panel is obtained by multiplying the panel power (350W) by the equivalent sun hours.

As the system is composed by 5 panels, the total energy produced to be consumed by the electric loads is:

Month	ESH	Energy per panel [kWh/day]	Total energy [kWh/day]	Total energy [kWh/month]
JAN	3.56	1.25	6.23	193.24
FEB	4.17	1.46	7.30	204.32
MAR	5.53	1.94	9.68	299.95
APR	5.31	1.86	9.30	278.93
MAY	6.78	2.37	11.87	367.90
JUN	7.23	2.53	12.65	379.51
JUL	7.56	2.64	13.22	409.90
AUG	6.83	2.39	11.95	370.33
SEP	6.20	2.17	10.85	325.55
OCT	5.66	1.98	9.90	306.78
NOV	4.47	1.56	7.83	234.74
DEC	3.29	1.15	5.75	178.37

Table 15: Total electric energy produced

Peak power of the photovoltaic system will be equal to the number of panels multiplied by the peak power of each panel (350Wp), resulting in a value of 1.75 kWp.

The panels will be connected in series as it will result in a more efficient system with lower losses and cost-effectiveness due to the reduced amount of electrical wiring required. Additionally, the location allows for a shade-free installation, which is crucial because if any panel is affected by shadows, the operation of the entire system would be compromised.

In this section, an analysis will be conducted to determine to what extent this electrical generation can meet the household's consumption. As mentioned earlier, any portion of the consumption that cannot be covered by photovoltaic generation will be supplied by the electrical grid.

The following table displays the monthly values of electrical consumption, considering the electric resistance, pellet boiler, fans, and fixed loads.

Month	Fixed loads [kWh/month]	Electric Resistance [kWh/month]	Pellet boiler [kWh/month]	Fans [kWh/month]	Recirculating pump [kWh/month]	Total electric consumption
JAN	261.14	84.43	18.6	—	0.6	364.77
FEB	261.14	75.79	16.8	—	0.6	354.33
MAR	261.14	—	—	—	0.6	261.74
APR	261.14	—	—	—	0.6	261.74
MAY	261.14	—	—	—	0.6	261.74
JUN	261.14	—	—	12.6	0.6	274.34

JUL	261.14	—	—	13.02	0.6	274.76
AUG	261.14	—	—	13.02	0.6	274.76
SEP	261.14	—	—	—	0.6	261.74
OCT	261.14	—	—	—	0.6	261.74
NOV	261.14	21.40	18	—	0.6	301.14
DEC	261.14	122.35	18.6	—	0.6	402.69

Table 16: Total electric consumption

The graph depicts the consumption of loads compared to the generation of the photovoltaic system. As can be observed, there is a region in the graph where the consumption exceeds the generation. During these months (November, December, January, and February), it will be necessary to rely on the electrical grid to meet the demand.

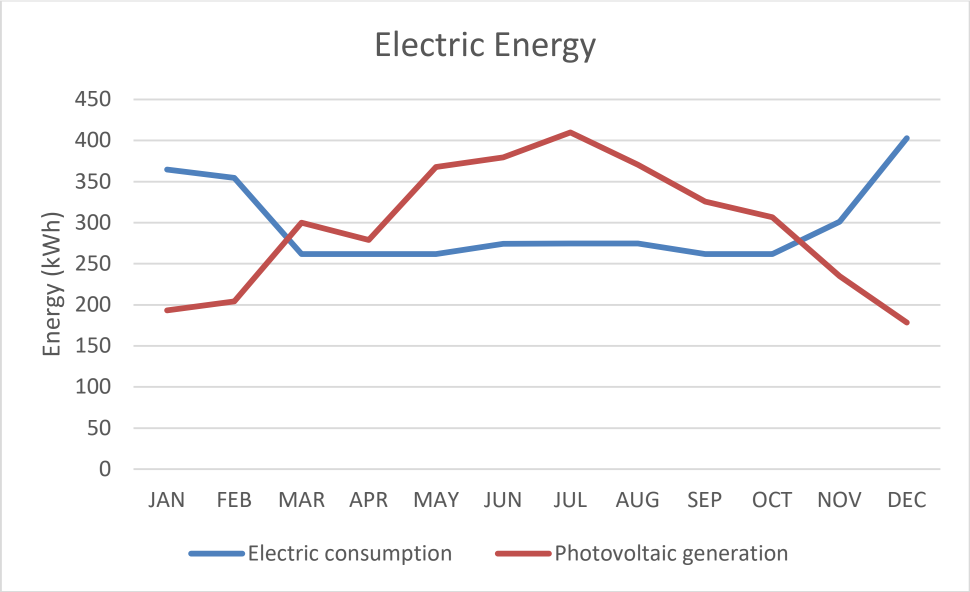


Figure 37: Electric energy demand and generation

However, the excess generated electrical energy can be injected into the grid. Regarding the excess in thermal energy generation during certain months of the year, the possibility of using this surplus for pool heating can be explored.

CHAPTER 6. ECONOMIC VIABILITY

6.1 Initial Investment

Below is the table showing the necessary components for the installation of the solar photovoltaic thermal system, along with the quantities and costs:

Concept	Amount	Cost (euros)
Hybrid Solar Panel aH72	5	3250
Inverter, 2000W	1	350
Electric wiring	15m	25
Electrical protection panel for both direct current (DC) and alternating current (AC)	1	30
Energy meter	1	20
Hot water storage tank, 300L	1	700
Copper pipes	17m	40
Instrumentation (thermostat)	1	35
Heat transfer and antifreeze liquid (Glicosol)	1	90
Recirculating pump	1	250
Support structure	1	200
Transportation and installation (10%)	1	499
Total		5489

Table 17: Initial Investment

6.2 Operation and maintenance costs

A maintenance plan will be implemented to ensure the proper functioning of the system. It will involve checking for any leaks in the pipes, inspecting the foundations and supports to prevent corrosion from affecting the metallic structures or pipes. Additionally, the panels will be cleaned using suitable products that do not impair their performance. Hence, an estimated maintenance cost of 85 euros per year has been assigned, which corresponds to 1.5% of the initial investment (Inquiry to Altersol, a solar photovoltaic maintenance company)

6.3 Costs of electricity consumption from the grid

In order to compare the economic effects of the two options, the expenses related to electricity consumption will be studied.

The household has a contracted electricity consumption rate of 3.3 kW with Repsol company, with fixed costs of 0.109 euros per kW contracted per day. In addition to this fixed cost, the amount of energy consumed needs to be added, which has a cost of 0.14 euros per kWh.

The following values show the electricity consumption amounts in a year and their corresponding costs.

Month	Electricity consumption invoice [kWh]	Cost [euros]
JAN	586.70	92.92
FEB	549.86	87.76
MAR	550.39	87.84
APR	529.64	84.93
MAY	532.68	85.36
JUN	530.81	85.09
JUL	533.90	85.53
AUG	539.80	86.35
SEP	523.92	84.13
OCT	538.59	86.18
NOV	559.06	89.05
DEC	586.70	92.92

Table 18: Consumption from the grid (traditional system)

To perform the analysis of the amount to be paid after the installation of the hybrid system, the company offers a remuneration of 0.05 euros per kWh injected into the grid. In the table, negative values represent months with excess energy generation, which will be injected into the grid.

Month	Electricity consumption invoice [kWh]	Cost [euros]
JAN	171.53	34.80
FEB	150.01	31.78
MAR	-38.21	8.87
APR	-17.19	9.92
MAY	-106.16	5.47
JUN	-105.17	5.52
JUL	-135.14	4.02
AUG	-95.57	6.00
SEP	-63.81	7.59
OCT	-45.04	8.53
NOV	66.40	20.08
DEC	224.32	42.19

Table 19: Consumption from the grid (hybrid system)

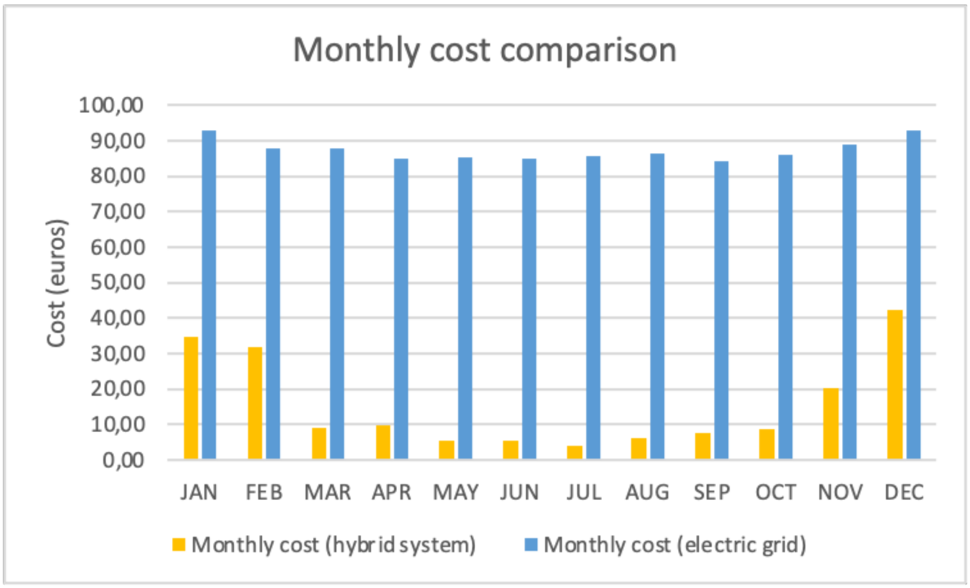


Figure 38: Monthly cost comparison

As expected, the amounts to be paid after the installation are much lower. What is important is to estimate whether the project is viable considering the initial investment and other additional costs such as maintenance.

5.4 NPV, IRR, payback period

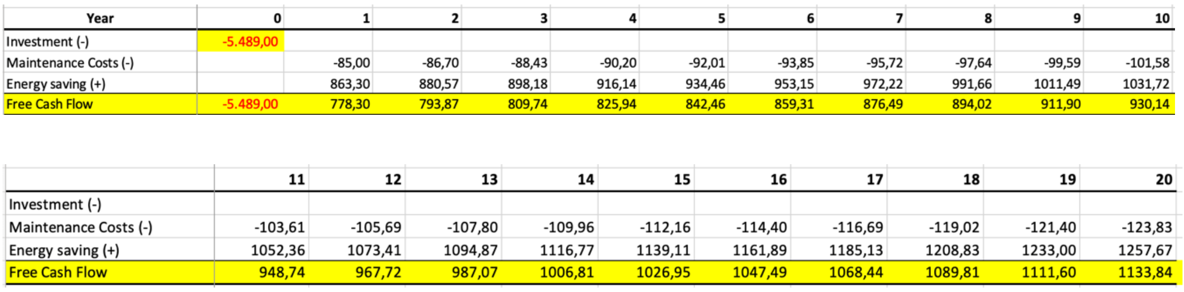
To assess the profitability of this project, two tools from financial mathematics will be used to determine its economic viability.

The first tool is Net Present Value (NPV), which measures the future inflows and outflows of cash associated with the project. The future cash flows take into account the savings resulting from the implementation of the new system, as well as the costs associated with its maintenance. If the result is positive, the project is deemed viable considering the initial investment and cash flows. If the value is negative, the initial investment is not recovered within the specified time period. The values obtained over the years are shown in the table below.

The Internal Rate of Return (IRR) allows determining the percentage of profitability generated by the investment. In this case study, the IRR has been calculated for 5, 10, 15, and 20 years. If the IRR value is higher than the discount rate, it is advisable to proceed with the investment.

Lastly, the payback period indicates the time required to recover the investment. Beyond this period, the investment becomes profitable, so it is essential for it to exceed the system's useful life. In this project, a Weighted Average Cost of Capital (WACC) of 7% has been considered, with a nominal interest rate of 2%.

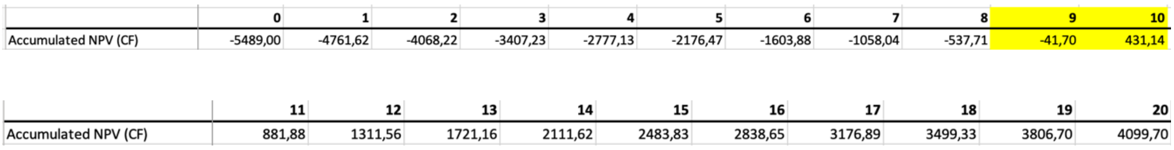
Inflation	2%
Discount Rate (WACC)	7%



Year	0	1	2	3	4	5	6	7	8	9	10
Investment (-)	-5.489,00										
Maintenance Costs (-)		-85,00	-86,70	-88,43	-90,20	-92,01	-93,85	-95,72	-97,64	-99,59	-101,58
Energy saving (+)		863,30	880,57	898,18	916,14	934,46	953,15	972,22	991,66	1011,49	1031,72
Free Cash Flow	-5.489,00	778,30	793,87	809,74	825,94	842,46	859,31	876,49	894,02	911,90	930,14

	11	12	13	14	15	16	17	18	19	20
Investment (-)										
Maintenance Costs (-)	-103,61	-105,69	-107,80	-109,96	-112,16	-114,40	-116,69	-119,02	-121,40	-123,83
Energy saving (+)	1052,36	1073,41	1094,87	1116,77	1139,11	1161,89	1185,13	1208,83	1233,00	1257,67
Free Cash Flow	948,74	967,72	987,07	1006,81	1026,95	1047,49	1068,44	1089,81	1111,60	1133,84

[1] *Table 20: Free Cash Flow*



	0	1	2	3	4	5	6	7	8	9	10
Accumulated NPV (CF)	-5489,00	-4761,62	-4068,22	-3407,23	-2777,13	-2176,47	-1603,88	-1058,04	-537,71	-41,70	431,14

	11	12	13	14	15	16	17	18	19	20
Accumulated NPV (CF)	881,88	1311,56	1721,16	2111,62	2483,83	2838,65	3176,89	3499,33	3806,70	4099,70

Table 21: Accumulated NPV

IRR (20 years)	14.86%
IRR (15 years)	13.21%
IRR (10 years)	8.62%
IRR (5 years)	-9.24%

The investment for the installation of the PVT system in the house becomes profitable starting from the ninth year. As can be seen, the NPV becomes positive in the 10th year, with a value of 432.14 euros and a return of 8.62%.

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[1] The potential loss of efficiency in solar panels due to progressive deterioration caused by exposure to environmental conditions is not taken into account in this study.

CHAPTER 7. ENVIRONMENTAL IMPACTS

Considering that environmental impact is defined as "Any alteration to the environment, in one or more of its components, caused by human action". (MORE92)

To study the environmental repercussions of these systems, it is necessary to analyze the impacts related to their operation, as well as those caused by the manufacturing and raw material extraction processes, and the impacts that will occur at the end of their life cycle.

The operation of hybrid systems throughout their life cycle does not have a negative impact on the environment. The modules are completely silent, and the generation of energy through solar resources does not emit any type of polluting gas. It is also important to mention that this technology does not generate waste or toxic discharge, unlike the use of conventional energy sources.

However, the manufacturing process of the modules and their components requires energy consumption, which may result in greenhouse gas emissions. To analyze the emissions produced during manufacturing, three stages can be distinguished:

- Extraction and processing of the raw materials that compose the solar module.
- Transportation of raw materials to the factory.
- Production processes of the panels, including energy expenses, production of auxiliary materials, and packaging.

The manufacturing process is complex, and the production of photovoltaic cells involves the use of chemicals, heat, and electricity. These cells are composed of a material that is melted at 1414°C. Naturally, pollutants such as sulfur dioxide, nitrogen oxide, or carbon monoxide are generated during the manufacturing process.

There are two main categories of photovoltaic cells. Monocrystalline cells are made from a single piece of silicon cut into thin layers, as mentioned earlier, they are widely used due to their higher efficiency. However, there are inherent difficulties in manufacturing individual silicon crystals, resulting in a higher number of emissions during the production process. On the other hand, polycrystalline solar cells involve the fusion of multiple silicon crystals, which requires less energy and consequently leads to reduced emissions.

The analysis of these manufacturing factors leads to the conclusion that these panels must be in operation for a minimum of three years to offset their carbon footprint. Considering their much longer lifespan, these systems represent a significant contribution to improving the environmental situation.

Next, the CO2 emissions before and after the installation of the hybrid system in the house have been calculated.

The CO2 emissions associated with the consumption of the mainland electricity grid, estimated by the National Commission on Markets and Competition (CNMC) in 2022, are 0.27 kg of CO2 per generated kWh.

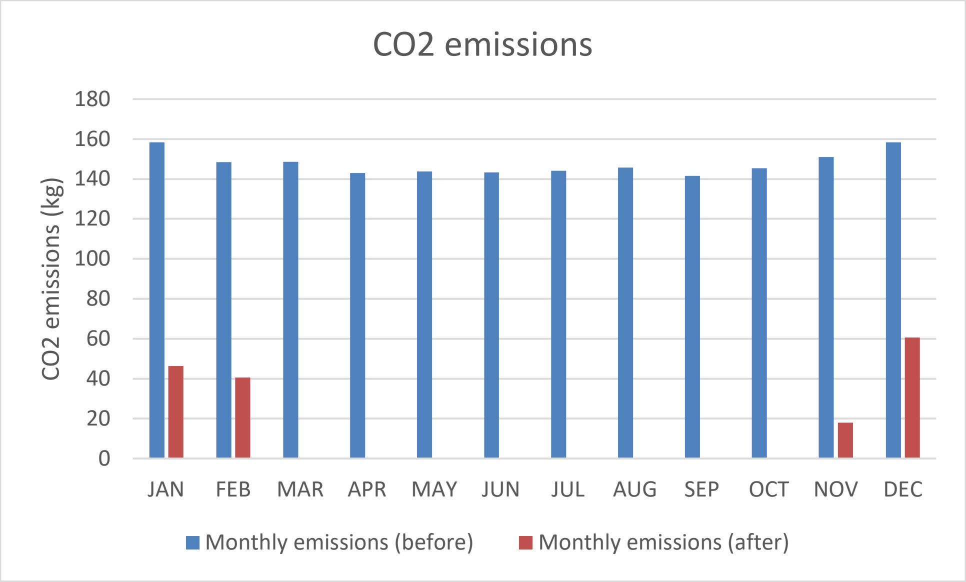

Figure 39: CO2 emissions

In this project, it has been considered of particular interest to analyze the waste generation associated with the manufacturing and use of solar panels as an energy source. It is evident that there is a significant unresolved problem regarding the generation of a large number of highly contaminating waste.

While the solution could be recycling, it should be noted that recycling is not mandatory in all countries. The development of different models and strategic plans to implement recycling is crucial at present. Unfortunately, in the Spanish context, there is no specific regulation that addresses this type of waste.

So far, the volumes of waste generated are not very high. Solar panels have a lifespan of around 25 to 30 years, and most panels currently in use still have years of operation ahead of them. Only a few panels that have been damaged or are old end up in waste containers. For this reason, it is currently not profitable to extract materials such as glass, aluminum, or copper from old panels.

However, in a few years, the volumes of waste generated will increase dramatically. Year after year, decommissioned panels will accumulate, and there will be thousands of tons of different components that need to be managed. BloombergNEF has estimated that by 2035, the global volume of waste generated will exceed 1 million metric tons, and by 2050, it will surpass 10 million.

An estimated calculation has also been made regarding the potential value of the recovered materials from these panels, as reflected in the following graph. By 2035, these waste materials will represent a value of around $1.02 trillion, and by 2050, it will reach $5.66 trillion.

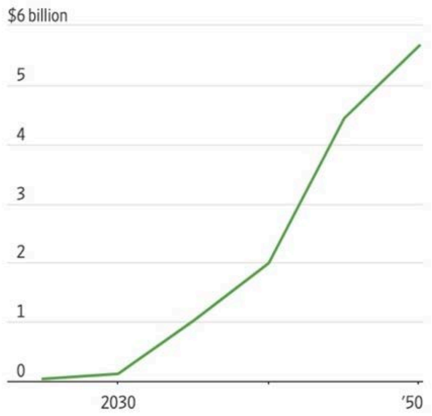

Figure 40: Estimated value of the materials from solar-panel waste (source: BloombergNEF)

The recycling of solar panels poses challenges due to the diversity of components present in their structure.

Silver is the most valuable material found in photovoltaic panels, followed by copper, silicon, aluminum, glass, and polymers. However, advancements in technology have significantly reduced the use of silver in solar panel manufacturing.

It is important to note that the different components of a solar panel are often bonded together using adhesives or sealing processes, which complicates the recycling process.

The glass component of a solar panel can be reused up to 90% for the production of new solar panels or other products. However, the low value of recycled glass reduces the incentive for recycling.

There are two main approaches to solar panel recycling:

- Thermal treatment recycling: The conventional recycling technique involves using heat to separate the components of solar panels. Plastics, adhesives, and sealants are burned to separate the solar cells from the glass. This fraction represents approximately 80% of the panel's weight and components. Various chemical processes are then applied to separate the metal contacts and eliminate the anti-reflective coating, if present. Silicon wafers can also be reused in this recycling process, with estimates suggesting they can be recycled up to four times.

- Mechanical recycling: The second recycling approach is mechanical recycling. It involves shredding the entire panel, removing the frame, cables, and junction box, and subjecting it to chemical processes. The shredded panel is processed to extract the main materials, which are then separated and sent to separate recycling streams to obtain secondary materials.

CHAPTER 8. CONCLUSIONS AND FUTURE RESEARCH

Comentar las conclusiones del proyecto, destacando lo que se ha hecho, dejando claros qué objetivos se han cubierto y cuáles son las aportaciones hechas.

Based on the economic analysis conducted, it can be concluded that a solar installation of these characteristics is economically viable. Over a 15-year period, the Net Present Value (NPV) will have a positive value of €2483.83, and the Internal Rate of Return (IRR) of 13.21% is significantly higher than the 7% discount rate considered for this installation. Therefore, it can be affirmed that the installation is financially profitable. This solar installation will be able to cover almost the entire annual electricity demand of the household.

Although the initial investment may be considered high for an average family of four in Spain, the long-term results justify carrying out the installation. Additionally, such installations have a beneficial impact on the environment, as demonstrated by the significant reduction in CO2 emissions that a single family can achieve, as shown in Figure 38.

As seen in the case study, during months of electricity overgeneration, the surplus energy can be injected back into the grid, resulting in savings. However, when thermal generation exceeds demand, it goes to waste. Therefore, there is a proposal to conduct a future analysis for utilizing this excess energy in heating the home's swimming pool. Figure 35 illustrates the months of excess generation, coinciding with the typical months of usage for such an installation.

Furthermore, harnessing the surplus thermal energy for pool heating presents a promising opportunity to maximize the system's efficiency and further offset energy costs. By integrating a heat exchanger and a smart control system, the excess thermal energy could be diverted to heat the pool water, providing an eco-friendly and cost-effective solution for maintaining a comfortable water temperature throughout the year.

Apart from the direct cost savings, utilizing the excess energy for pool heating aligns with sustainable practices and enhances the overall environmental impact of the solar photovoltaic thermal system. This integration not only promotes renewable energy adoption but also contributes to reducing the household's carbon footprint, making it a more environmentally responsible choice.

However, before implementing such a system, a detailed feasibility study should be conducted to assess the technical requirements, potential modifications to the existing setup, and the overall economic viability. Factors like the pool's size, thermal demand, seasonal variation, and equipment compatibility need to be thoroughly evaluated to ensure optimal performance and cost-effectiveness.

In conclusion, the case study has shed light on the potential benefits of reusing excess energy for pool heating during the months of surplus generation. This innovative approach represents a promising direction for enhancing the self-sustainability of the solar photovoltaic thermal system and achieving long-term energy and cost savings while contributing to a greener and more sustainable future.

Finally, the main mission of using these systems is to produce energy in a clean and sustainable manner, reducing dependence on non-renewable energy sources and lowering greenhouse gas emissions. These photovoltaic and thermal systems are essential for advancing towards a greener and more environmentally friendly future.

However, one of the significant challenges posed by the increasing manufacturing and use of solar panels is the future management of the large amount of waste that will be generated. As technology advances and the demand for solar panels grows, the number of panels reaching the end of their life cycle will also increase. Solar panels contain materials such as glass, aluminum, plastics, and in some cases, hazardous materials such as cadmium and lead.

To address this challenge, it is essential to develop effective strategies for recycling and proper disposal of solar panels once they have reached their end-of-life. Proper recycling will allow for the recovery of valuable materials and reduce the environmental impact of improper disposal of these panels.

Additionally, promoting more sustainable design and manufacturing practices that facilitate component reusability and the reduction of harmful materials is crucial. It is also important to raise awareness among consumers and businesses about the importance of recycling and adopting responsible measures regarding solar panel waste management.

In summary, while the use of photovoltaic and thermal solar systems offers significant benefits in terms of clean energy production, effectively managing the waste generated is critical to maintaining sustainability and environmental benefits over time. By implementing recycling and sustainable design practices, we can ensure that the transition to solar energy is truly sustainable and environmentally friendly.

CHAPTER 9. BIBLIOGRAPHY

[JAY_19] Jay Withgott and MatthewLaposat , "The science behind the stories", 6th edition, 2019.

[JAAF18] Jaafer Ali Kadhem Alanbary, "Design and Construction of a Tracking Device for Solar Electrical Systems", Journal of Scientific and Engineering Research, 2018.

[HABE11] I E Haber e I Farkas, "Combining CD simulations with blockoriented heatflow-network model for prediction of photovoltaic energy-production", Journal of Physics: Conference Series, vol. 268, 2011.

[DIEG15] Diego A. Pilco P., Jorge L. Jaramillo P, "Sistemas fotovoltaicos para iluminación: paneles fotovoltaicos", Loja, Ecuador, 2015.

[ROCI11] Rocío E. Rojas Hernández, "Caracterización espectral de células solares comerciales", TFM, Universidad de Salamanca, Facultad de Física, 2011.

[GUST20] Gustavo Núñez Ortiz, Carlos Robles-Algarín, Juan Tobón Pérez, Adalberto Ospino Castro, Antonio Martínez Lengua, "Performance evaluation of single-diode and two-diode models for photovoltaic modules", Revista Espacios, Vol. 41 (36) 2020, Art. 14, 2020.

[MARÍ20] María Mónica Sierra Céspedes, Carmen Luisa Vásquez Stanescu, Rodrigo Ramírez-Pisco, "Final disposal and environmental impact of photovoltaic cells", Publicaciones en Ciencias y Tecnología. Vol 14. No 2, 2020.

[RICC21] Riccardo Colombini, Luca Molinaroli, Riccardo Simonetti, Luigi Pietro Maria Colombo, Giampaolo Manzolini, "Numerical analysis of different designs of roll-bond absorber on PV/T module and performance assessment", Applied Thermal Engineering, ScienceDirect, 2021.

[MINI10] Ministerio de Energía, "Guía de diseño e instalación para grandes sistemas de agua caliente sanitaria", SISTEMAS SOLARES TÉRMICOS II, 2010

[ALVA21] Álvaro Batuecas Lacasa, "Estudio de viabilidad de colectores solares híbridos fotovoltaicos térmicos (PVT) en Chile", 2021

[MARI13] María HERRANDO, Christos N. MARKIDES and Klaus HELLGARDT, "A UK-Based Assessment of Hybrid PV/Solar-Thermal Systems for Domestic Heating and Power – Part I", Department of Chemical Engineering, Imperial College London, London SW7 2AZ, U.K., 2013

[AMAL20] Amal Herez, Hicham El Hage, Thierry Lemenand, Mohamad Ramadan, Mahmoud Khaled, "Review on photovoltaic/thermal hybrid solar collectors: Classifications, applications and new systems", vol. 207, pp.1321-1347, 2020.

[ALI_12] Ali Sayigh, "Comprehensive Renewable Energy", Eight Volume Set, Elsevier, 2012.

[FELI14] Félix Manuel Lorenzo Bernardo, Edwin Xavier Domínguez Gavilanes, "Computer Tool for assessing the power generation-mix in residential Nearly Zero-Energy Buildings", edp renewables, 2014.

[MORE92] Moreira, I. V. D. Vocabulário básico de meio ambiente. FEEMA/PETROBRÁS, Río de Janeiro, 1992.

[IDAE19] Instituto para la Diversificación y Ahorro de la Energía (IDAE), "Guía Profesional de Tramitación del Autoconsumo", 2019.

Web sites

https://energiasolarfotovoltaica.org/conexion-de-multiples-paneles-solares-serie-vs-paralelo

http://seslab.org/fotovoltaico/121_primera_generacin.html

https://coolproyect.es/website/wp-content/uploads/2017/02/Energia-solar-1.pdf

ANEXO I

Alignment with the Sustainable Development Goals (ODS)

The project that it intends to develop is related to objectives 7 and 13 contained in the 2030 Agenda for sustainable development, approved by the United Nations National Organization in 2015.

Goal 7 involves guaranteeing access to affordable, safe, sustainable, and modern energy. Especially in recent years there seems to be a commitment from many countries and international organizations to make energy sustainable and widely available. The objective of this project is to analyze, precisely, the implementation of a renewable energy system, accessible not only for large companies, but for all types of organizations and individuals.

Goal 13, “Climate Action”, involves reducing the levels of carbon dioxide and other greenhouse gases in the atmosphere. The adoption of cogeneration systems, such as the one we intend to analyze in our TFG, which uses renewable energy, will prevent air pollution, and help slow down climate change.

But, in addition, our object of study is also indirectly related to objectives 1 (End Poverty), 2 (Zero Hunger) and 3 (Health and well-being) of the 2030 Agenda. The design of a cogeneration system capable of Being used not only in developed countries, with a reduced cost, which allows families and companies to undertake its installation and, in addition, avoid emissions of polluting gases, it would effectively contribute to the achievement of these objectives.