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ENERGETIC AND ECONOMIC ANALYSIS OF AN INDUSTRIAL PHOTOVOLTAIC SYSTEM INTEGRATED WITH A TRIGENERATION DISTRICT HEATING PLANT

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ABSTRACT

In this work, technical and economic criteria were used to select the best available solution for the realisation of a photovoltaic system, with possibly addition of a storage system, integrated to a trigenerative district heating and cooling power plant.

The analysis starts with a preliminary dimensioning of various simulations of PV system sizes, then it looks for the correct array-inverter combination through the choice of the types of module, inverter and batteries.

Subsequently, the Solar Edge Designer and ZCS configurator software were used to perform the energetic analysis in order to be able to compare the PV systems considered and their energy performances on the basis of the annual electricity consumption of the district heating and cooling plant. A further analysis of the energy performance of PV systems with an accumulation system is carried out to verify their possible cost-effectiveness.

Lastly, an economic analysis is performed comparing all the simulations and using several economic indicators, such as PayBack, Net Present Value, Internal Rate of Return and, in the end, Levelized Cost of Electricity.

ABSTRACT

In questo lavoro, sono stati utilizzati criteri tecnici ed economici per selezionare la migliore soluzione disponibile per la realizzazione di un sistema fotovoltaico, con eventualmente l'aggiunta di un sistema di accumulo, integrato ad una centrale di trigenerazione per il teleriscaldamento e il teleraffreddamento.

L'analisi ha avuto inizio con un dimensionamento preliminare considerando varie taglie di potenza del sistema fotovoltaico, per poi ricercare la combinazione corretta di stringatura attraverso la scelta dei tipi di moduli, inverter e batterie, in modo da evitare perdite dovute a mancate uguaglianze di stringhe messe in parallelo o a un eventuale ombreggiamento.

Successivamente, sono stati utilizzati i software Solar Edge Designer e ZCS Configurator per effettuare l'analisi energetica al fine di confrontare gli impianti fotovoltaici considerati e le loro prestazioni energetiche sulla base del consumo elettrico annuo della centrale di teleriscaldamento. È stata condotta un'ulteriore analisi delle prestazioni energetiche degli impianti fotovoltaici che sono risultati essere meglio adattabili con un sistema di accumulo, per verificare la loro eventuale convenienza economica.

Infine, è stata eseguita un'analisi economica confrontando tutte le simulazioni prese in esame e utilizzando diversi indicatori economici, come il PayBack (PB), il Valore Attuale Netto (VAN), il Tasso Interno di Rendimento (TIR) e, infine, il Costo Livellato dell'Elettricità (LCOE).

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INTRODUCTION

Energy has always been a fundamental part of human daily life for carrying out his activities.

Historically, in fact, several primary sources, such as fossil fuels, have been used to obtain this final important outcome, but the world has started to think about the process behind it only recently.

The increase of awareness of the World for climate change issues, caused by manmade environmental pollution, has accelerated the path of energy transition, highlighting the importance of renewable sources as energy vector and the problems caused by fossil fuels in the energy sector.

In addition to that, Europe, and Italy in particular, are facing an unprecedented energy crisis, which is putting many domestic and industrial users in difficulty. From these mentioned causes, consumers have decided to protect themselves by using solar energy produced from photovoltaic systems.

Therefore, as a consequence of the dramatic situation we live in and the need to find other ways to supply electric energy to become independent from other countries, the study carried out in this work comes in.

In fact, the objective of this elaborate comes directly from the need to find an available solution to limit the damage for an energy-intensive company: Telezip Srl.

Indeed, the company represents a trigenerative district heating and cooling power plant, that supplies hot water to an area of 78000 m^2, exploiting the work of two cogenerators or, in alternative, two condensing boilers, and that supplies cold water to an area of 66000 m^2, exploiting the work of a chiller or, in the case of thermal energy excess, a Li-Br absorption cycle. It is, therefore, understandable that its consumption of natural gas and electricity is not negligible over the course of the year.

For that reason, the key solution is recognised in the use of an industrial roof, located close to the Telezip plant, to develop a photovoltaic system, in order to reduce the amount and the costs of electric energy required from the grid by the company. Thus, the aim of this thesis is to find the characteristics of the PV system that best suit the energy demands of a district heating power plant.

To better understand the path followed, the first half of the thesis focuses on providing a general overview of the technologies employed by the Telezip plant, the theory behind solar energy and, furthermore, how the Italian electricity market works; the second half, instead, relates to the energetic and economic analysis carried out to evaluate the available solutions.

To achieve the latter, a preliminary study has been carried out on the roof area to verify the effective exploitable surface by the PV system and to choose its components, referring to the technical specifications. After that, an energy analysis was performed taking into account the annual load consumption of the district heating plant and several PV system sizes. Next, the cost-effectiveness of integrating a storage system was evaluated, comparing the most convincing solutions with or without a battery.

Eventually, a detailed economic analysis was conducted to verify which is the most profitable PV system among the ones previously considered. For this purpose, several economic indices were evaluated in order not to rely on only one criterion.

The project was commissioned by ForGreen Spa SB, which is partner of Telezip Srl and company where my thesis took place, to establish the energetic and economic feasibility of a similar improvement for the plant.

Introduction of FORGREEN Spa SB

Forgreen Spa is a Benefit Society (SB) that was established in 2009, in Verona, with the purpose of sharing renewable energy and new sustainable models through the development of Energy Communities.

In fact, Forgreen is both a supplier, within the Electricity Market, and a producer of renewable electric energy, as its Technical Department is in charge of projecting and developing new PV power plants. Consequently, all the electric energy sold by Forgreen to its consumer is a renewable one.

Actually Forgreen produces its energy from eight PV plants, of about 1 MWp each one, and from several PV plants on industrial roofs.

In addition, although Renewable Energy Communities, CER, do not exist yet, bureaucratically speaking, and even if they will be a supporting column of the future energetic transition, Forgreen has already developed an Energy Communities, in 2011, called Energyland and placed in Grezzana (VR). Energyland is a photovoltaic plant of 1 MWp, which shares its production of energy with the neighbouring countries.

Even though Forgreen deals with photovoltaic energy, it is half partner of a company, Telezip Srl, which manages a trigenerative district heating and cooling power plant, placed in Padua. For this reason, Forgreen Technical Department has also the duty of resolution of problems and improvement relating to this plant.

1. LITERATURE REVIEW

The aim, of this initial introductive chapter, is to give the useful general information about the technologies that will be presented and treated along the course of this thesis, in order to have a basis from which start to analyse in deeper way the concepts.

1.1. Cogeneration

The cogeneration, as suggests the word itself, is the simultaneous generation of more than one form of useful energy from a single primary energy source.

Typically the outputs obtained are mechanical and thermal energy, which can be used in different ways. Mechanical energy can be used to drive an alternator in order to produce electricity, or to drive other useful devices; while thermal energy can be used both for direct process applications or for indirect process ones, as for example through the exploitation of the district heating [1].

The cogeneration plant is also called Combined Heat and Power plant (CHP) and could be based on a single thermodynamic cycle, as in this case, or on a combination of two thermodynamic cycles in cascade mode and, in particular, is subdivided in two main sections:

- topping section: the input energy, usually fuel, is used only for electricity production and some waste heat is released still at relatively high temperature;
- bottoming section: the input energy is the heat released by the topping section and it is used for electricity production, again, but is exploited also the thermal energy for other purposes.

In both cases we can understand that a cogeneration plant is a very smart solution that allows an improvement of the total efficiency of the plant and uses energy flows that otherwise would be lost. Below we can see a clear example of convenience of a cogeneration system respect to a separated production of electricity and heat.

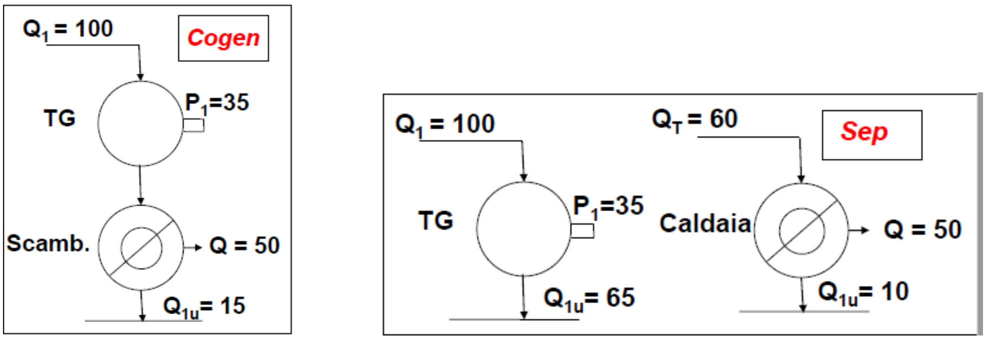


Figure 1: Comparison between cogeneration system and separated one

The cogeneration plants are subdivided depending on the type of the primary engine used for the electricity production. The main typologies are:

- vapor turbine cogeneration plants;
- gas turbine cogeneration plants;
- combined gas-vapor cogeneration plants;
- internal combustion engine cogeneration plants.

In the *Figure 1* is shown the same situation, in both cases we obtain the same mechanical and thermal power as outcomes, but the way from which are produced changes. The first thing that is possible to notice is that, in the second separated solution, it is necessary to introduce more input sources to obtain the same result and it is possible to quantify the saved input through the use of the saving index:

$$i_R = \frac{(Q_T + Q_1)_{sep} - Q_{1_{cogen}}}{(Q_T + Q_1)_{sep}} = \frac{(160 - 100)}{160} = 0.375$$

where:

- Q_1: incoming power topping section;
- P_1: mechanical power generated from topping section;
- Q: thermal power generated from bottoming section;
- Q_T: additional incoming power in separated system.

So what the saving index tells us is that using the cogeneration system is possible to save a percentage of 37.5% of primary energy, referring to the nominal conditions, in which all the electric and thermal energy are used from the customers.

Although the electric energy is always produced, the heating demand is variable over time, and could be also zero, reducing in this way the primary energy saving respect the separated solution.

Therefore, the economic advantage of the cogeneration strongly depends on the heating and electric demands and on their prices. This point will be more clear and very important when we will start to talk about Telezip.

In any case, cogeneration offers several advantages over conventional energy production methods, as the separated one:

- high efficiency: cogeneration systems can achieve overall energy efficiencies of 70%, compared to around 35% to 50% for conventional power plants. This is because waste heat, which is typically rejected in the ambient even at relatively high temperature, is exploited;
- energy and costs savings: by simultaneously producing electricity and useful heat, cogeneration systems reduce the need for separate sources of energy for heating and electricity, leading to a significant energy saving, as shown previously, and cost reductions;
- environmental benefits: cogeneration reduces greenhouse gas emissions and contributes to environmental sustainability. The high efficiency of the process results in lower fuel consumption and reduced carbon dioxide emissions;
- increased reliability: cogeneration systems can operate independently of the grid, providing a reliable source of power even during grid outages. This is especially advantageous for critical facilities that require continuous power supply, such as hospitals or data centre;
- waste heat utilization: by utilizing waste heat, cogeneration systems can meet various heating needs, including spaces heating, domestic hot water, or industrial processes. This reduces the reliance on separate heating systems and increases the overall energy efficiency of the facility [2].

On the other hands, there are some important aspects to take into account that could limit the advantages of the cogeneration:

- the mismatch between the production of energy, electric and thermal, and the demand curves could be a problem, since comports a lower efficiency of the system and a lower difference respect the separated system;
- the cogeneration system is more suitable when there is the simultaneous request of electric and heating energy;
- the utilities have to be near the plant in order to have lower leakages;

- the initial high investment cost could be a big obstacle for the development of this system.

1.1.1. Trigeneration

The cogeneration system, in the way it is talked before, is not suitable to work all the year if its utilization field is not the industrial one. In fact, if we consider the other fields in which a cogeneration system can be applied, as for example hospitals, shopping centers and so on, it would not be totally exploited since during the summer period, when the thermal energy is not useful, we have that the plant is switched off or works only for the electricity production, reducing in this way the advantages over the separated system.

Due to this limiting aspect, it is possible to implement the cogeneration system and start to talk about trigeneration one in which, now, the useful products are three instead of two, electric, heating and cooling energy, still using only one primary input source.

The strength of a trigeneration system is the possibility to use the absorption cycle, a powerful solution that uses waste heat to provide cooling, or refrigeration, through the exchange of heat instead of using mechanical energy. It utilizes a refrigerant-absorber pair as working fluid, usually the most common are ammonia/water and water/lithium bromide (LiBr).

In the latter there are some additional problems:

- since in this case the refrigerant is water, the evaporating temperature cannot go below 0°C;
- water at low temperature and pressure occupies a big volume, so a compressed layout has to be used;
- at a certain concentration of absorber, when the temperature is lower than a certain value, the lithium bromide solution will cause crystallization, blocking the cycle.

The working principle of an absorption cycle is similar to a vapor compression one, as for example a chiller, so the gaseous refrigerant is sent to the condenser, where it rejects heat to the ambient and becomes saturated water. Then, it expands through a throttling valve and eventually evaporates in the evaporator by receiving heat from a low temperature heat source, that is the room that has to be cooled, resulting in useful cooling/refrigeration.

However, here, we have an additional part, that is composed by two devices: the generator and the absorber. The function of the generator is to receive the heat, that is the waste one from the cogeneration cycle, separating the gaseous refrigerant, which is sent to the condenser, and the liquid solution. The liquid solution expands through another throttling valve and is subsequently recombined with evaporator steam in the absorber, producing a rich solution at high concentration of refrigerant, which is sent to the generator.

1.1.2. <u>District heating</u>

Since the plant treated in this thesis is a district heating plant, it is better to explain with some additional details the working principle of it, in order to understand in a clearer way its functioning.

The district energy is a proven technology used since 1900. A district heating plant is an underground infrastructure, made of several pipes, where the thermal energy is provided to multiple utilities and it can be used both to give heating and cooling conditioning .

As heat networks have evolved with the development of new energy sources and technologies, there are currently different generations of district heating with several distinctive characteristics:

- 1st generation:
    - coal and waste fuelled;
    - high temperature steam as heat carrier;
    - transport and distribution were usually concrete ducts;
- 2nd generation:
    - coal, waste and oil fuelled;
    - used pressurized water with temperatures above 100°C;
    - used CHP plant to save primary energy;
- 3rd generation:
    - prefabricated and pre-insulated pipes;
    - operation temperatures below 100°C;
    - used coal, biomass and waste, but also geothermal and solar energy;
- 4th generation:
    - integrate high shares of variable RES;
    - low temperature district heating for space heating and DHW (below 70°C);

- low grid losses;
- 5th generation:
  - distributes of heat at near ambient ground temperatures;
  - bi-directional exchange of thermal energy (heat and cold);
  - thermal storage;
  - demand driven algorithm-based control that optimizes the exergy flows [3].

Below, the progresses of these generation of district heating systems are shown:

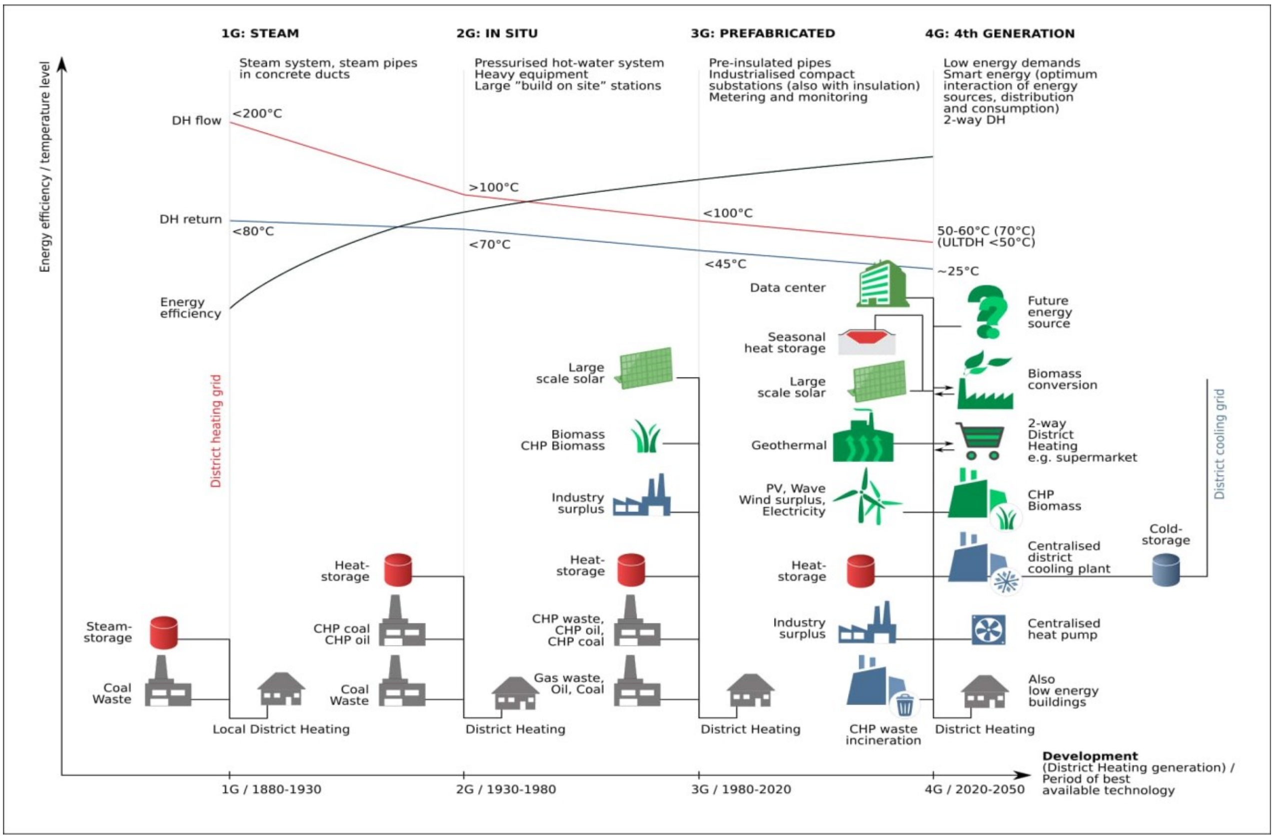


Figure 2: Evolution of district heating and cooling generations

This system can help to improve energy efficiency, reduce emissions and simplify building operations and maintenance. In addition to that, there is an important advantage of use district heating system: connecting multiple buildings creates economies of scale that enable the deployment of more efficient and cleaner energy sources, like CHP, waste to energy, solar thermal and so on. The advantages of use district heating system are also supported from IEA (International Energy Agency), which says: " District heating networks offer great potential for efficient, cost-effective and flexible large-scale integration of low-carbon energy sources into the heating energy mix" [4].

However, a negative aspect, that is necessary to mention, is that the decarbonisation potential of this system is largely untapped by the wide use of fossil fuels as primary energy to obtain the useful outcomes.

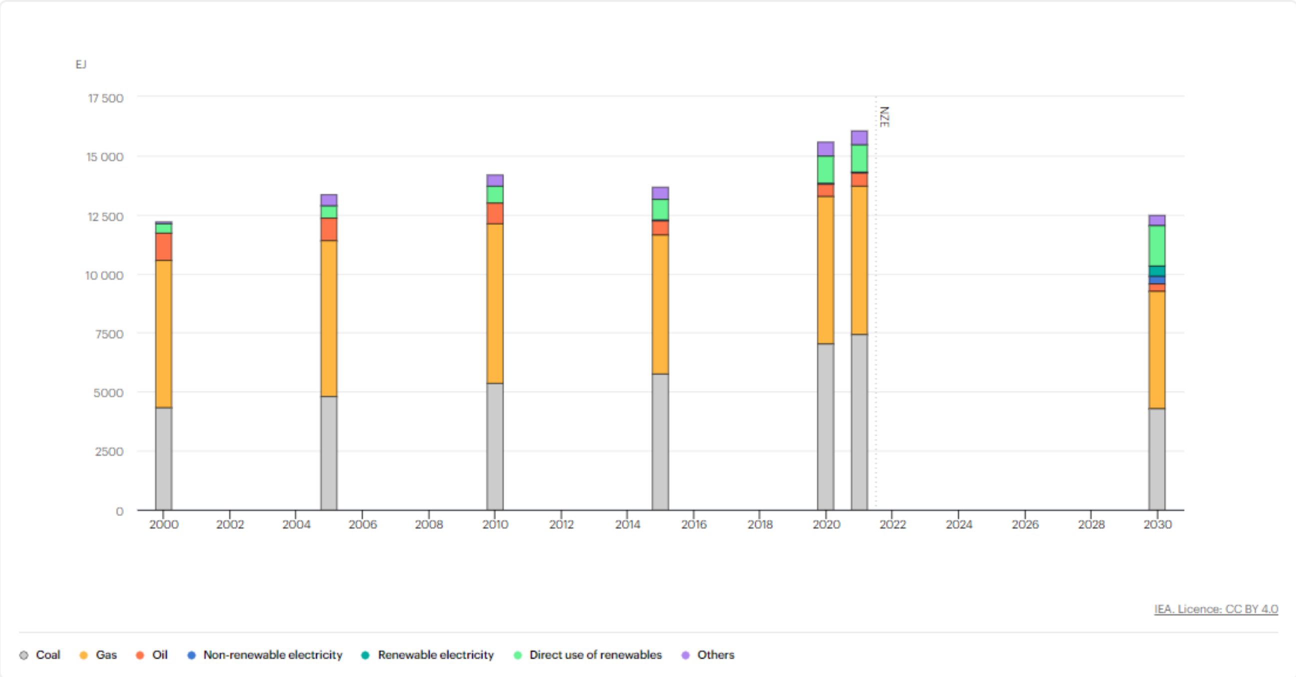


Figure 3: Annual energy supplies to district heating networks in the Net Zero Scenario, World, 2010-2030

As can be seen from *Figure 3*, in fact, in 2021 the production of heating is mainly made by coal, gas and oil. A trend that the world has to reverse if it wants to follow the Net Zero Scenario.

1.1.3. Normative and incentives for cogeneration

Along the years, due to the fact that the cogeneration system improves the energy efficiency and allows a primary energy saving, if fully exploited, several regulations and incentives have been created and approved, in order to determine the working conditions for which the combined production of electric and thermal energy could be classified as cogeneration and, as consequence, receives these incentives.

Taking the information directly from IEA source, we can have an helpful summary of how the legislation works in Italy about the promotion of High Efficiency Cogeneration (CAR), in which it says:

The ministerial decree of 4th August, 2011 contains the new Annexes which partly replace and supplement the Annexes of the Decree no. 20/2007 that implements Directive 2004/8/EC on the promotion of cogeneration (CHP). This measure defines the new calculation method for the recognition of high efficiency cogeneration. The ministerial decree of 5th September, 2011 defines the incentive mechanisms for high efficiency cogeneration. It introduced an incentive system based on White Certificates Scheme, which is recognized for a period of 10 years for generation plant and of 15 years for combined district heating plants. A coefficient (K) is applied to the White Certificates base value, for five different capacity echelons, taking into account the different average yields of the plants and the development potential of small and medium CHP. The qualification as a high efficiency cogeneration is issued by GSE (Energy Services Operator), which annually recognizes a corresponding incentive to the actual primary energy savings achieved and measured by the plant. Incentives for renovations of existing plants and those which came into operation after 1 April 1999 and before the Decree no. 20/2007 are reduced by 30% compared to those granted for new plants for a period of five years. [5]

The authority establishes that a plant produces with cogeneration characteristics when defined indicators, which are the Primary Energy Saving index (PES) and its relative Thermal Limit (LT), are respectively above threshold limits fixed by the normative.

As reported in above citation, be defined as CAR gives a series of advantages:

- priority of dispatching on the produced electric energy;
- tax breaks on excises of natural gas used for the cogeneration;
- possibility of accessing the mechanism of energy efficiency titles (TEE), also called White Certificates;
- release of the guarantee of origin (GO);
- possibility for a thermoelectric plant powered by non-renewable sources, present inside a simple system of consume and production, to be considered as CAR for the year "n" if the energy from the cogeneration is, for the year "n-1", greater than 50% of the gross total production of the electric energy of the plant [6].

Before defining the equation to calculate the White Certificates, it is necessary to say that these are negotiable securities that certify the achievement of energy savings in energy end uses through interventions and projects to increase the efficiency. The system of white certificates requires that electricity and natural gas distributors annually achieve primary energy saving targets, expressed in tons of Oil Equivalent saved (toe).

In order to obtain the exact number of White Certificates that a High Efficient Cogeneration system can have access, there is a practical procedure that is used.

The procedure imposed firstly to calculate the primary energy saving:

$$RISP = \frac{E_{CHP}}{\eta_{E^*}} + \frac{H_{CHP}}{\eta_{T^*}} - F_{CHP}$$

where:

- RISP is the primary energy saving based on a year of production;
- E_{CHP} is the electric energy produced from the cogeneration;
- H_{CHP} is the thermal energy produced from the cogeneration;
- F_{CHP} is the fuel energy used for the cogeneration;
- η_E^* is the reference electric efficiency;
- η_T^* is the reference thermal efficiency.

After that, it is possible to calculate the White Certificates:

$$CB = RISP * 0.086 * K$$

where K is a constant that depends on the electrical power size of the plant.

1.2. Components of a photovoltaic plant

This paragraph is fundamental to get a general knowhow about the working principle of a photovoltaic plant, which it will be used in the second part of the thesis to achieve the main goal of this paper.

1.2.1. <u>Photovoltaic generator</u>

The usual meaning of photovoltaic generator is the module that it is typically seen on the roof, but this component is composed, in turn, of a series of cell connected in series or parallel.

The explanation will start from the solar cell since the conversion of the solar radiation into electric energy happens inside it. There are several technologies behind the solar cells but the most commons are monocrystalline silicon, polycrystalline silicon, thin film and amorphous silicon.

The solar cell working principle is based on the ability of semiconductors to convert sunlight into electricity by exploiting the photovoltaic effect and, to do this, the formation of a junction, as for example the p-n junction, is necessary.

If a semiconductor material, for example silicon, incorporates some dopant atoms of the "p" type (boron) on one side, in which the current is carried by positively charged holes, and "n" type atoms (phosphorus) on the other side, in which the current is carried by negatively charged electrons, a junction is obtained: the two layers of material, originally electrically neutral, through the contact they give rise to an electric field. Due to the charge concentration gradient near the junction, there is a simultaneous diffusion of electrons in “p” and holes in “n”. The diffusion current creates a potential barrier between the two regions, by charging “p” negatively and “n” positively.

The potential barrier tends to oppose the motion of the charges until a condition of electrostatic equilibrium is reached. As a result of the opposite flows of the charges, a distortion of the energy bands along the junction is obtained. The internal electric field produces the diode effect. Therefore, the junction acts as a diode.

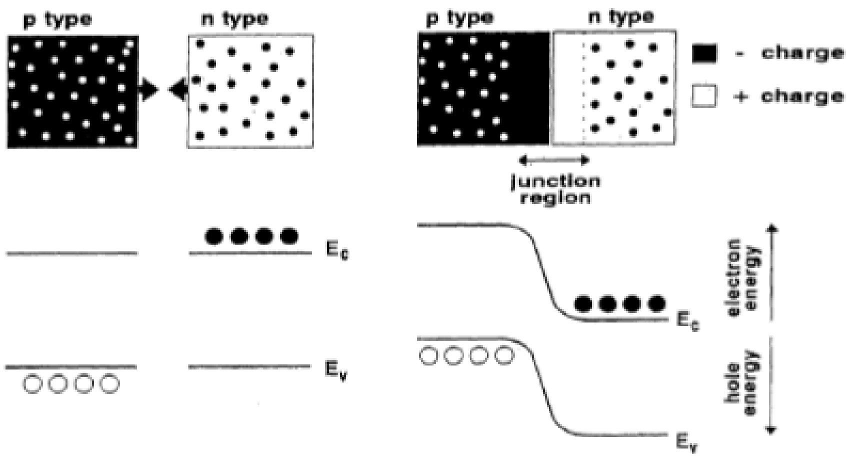


Figure 4: Diffusion of electrons due to the gradient of electrons and holes in the p-n regions

The electrical behaviour at the external clamps can be represented, as first approximation, from an ideal current generator and a real diode connected in parallel.

The first one produces the generation current:

$$I_l = qNA \ \ [A]$$

where:

- q: electron charge;
- N: photons number;
- A: area of the semiconductor exposed to the light.

The second one produces the current:

$$I_D = I_0 \left[e^{\left(\frac{qU_j}{mkT}\right)} - 1 \right] \ [A]$$

where:

- I_0: inverse saturation current of the diode;
- U_j: voltage at the external clamps;
- m: quality factor of the junction;
- k: Boltzmann constant;
- T: superficial temperature of the junction.

The output current is subsequently equal to the difference between the light-generated current, I_l, and the diode current, I_D.

$$I = I_l - I_0 \left[e^{\left(\frac{qU_j}{mkT}\right)} - 1 \right] \ [A]$$

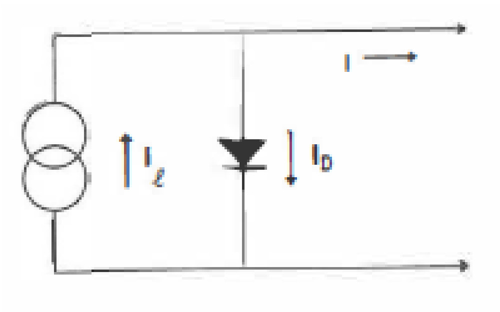


Figure 5: Equivalent circuit of a photovoltaic cell

Note that, under open circuit, when I=0, all the light-generated current passes through the diode. Under short circuit, when V=0, on the other hand, all this current passes through the external load. The I-V characteristic contains two important points: one is the short-circuit current, I_{sc}, which is simply the light-generated current, as said above. The second is the open-circuit voltage V_{oc} obtained by setting I=0:

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_l}{I_0} + 1\right) \ [V]$$

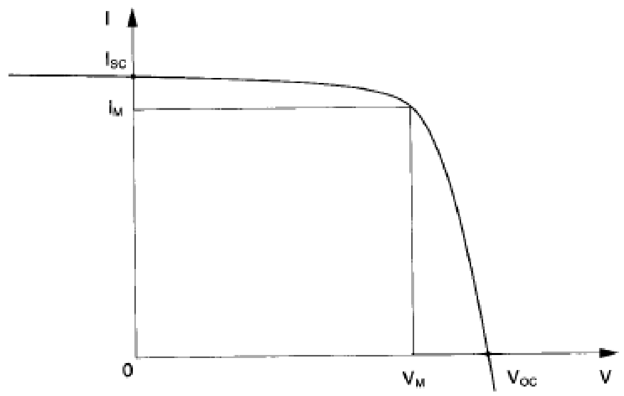


Figure 6: The I-V characteristic of a solar cell with the maximum power point

In practical applications, solar cells do not operate under standard conditions. The two most important effects, which have to be taken into account, are the variable temperature and irradiance.

Temperature has an important effect on the power output from the cell. The most significant is the temperature dependence of the voltage, which decreases with the temperature increase. The temperature variation of the current is less pronounced and it is usually neglected in the PV system design.

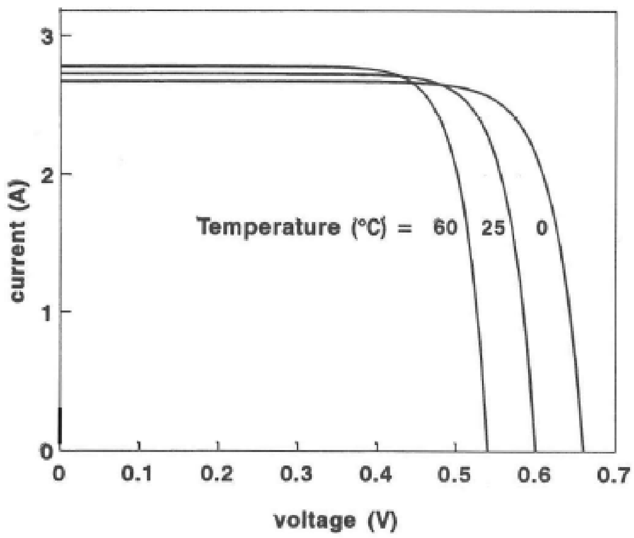


Figure 7: Temperature dependence of the I-V characteristic of a solar cell

Instead, for what concern the effects of irradiance, we have seen that the light-generated current is proportional to the flux of photons with above bandgap energy. Increasing the irradiance, the photon flux increases too, which, in turn, generates an higher current. Therefore, the short-circuit current of a solar cell is directly proportional to the irradiance.

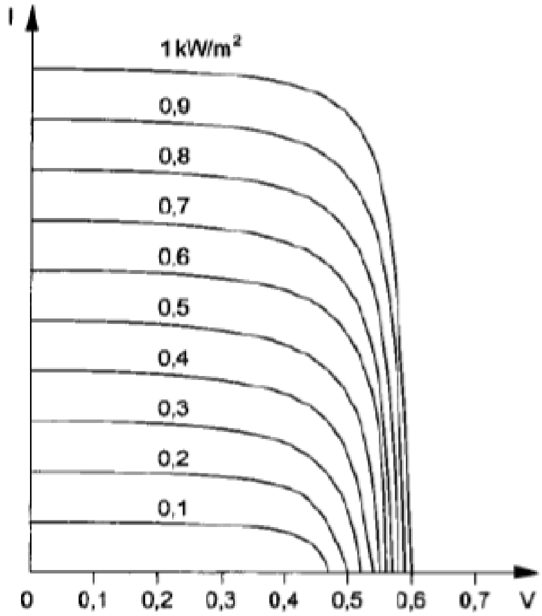


Figure 8: Irradiance dependence of the I-V characteristic of a solar cell

Several relations are present that describe the main characteristics of the cell, depending on the irradiance and temperature, but are all referred to Standard Condition (STC), which are:

- global irradiance G = 1000 Wm^{-2} ;
- air mass AM = 1,5;
- cell temperature T = 25°C.

Below, the detailed equation are reported:

$$I_{sc}(G,T) = I_{sc}(STC)\frac{G}{1000}(1+\alpha\Delta T)\ \ [A]$$

$$U_{oc}(T) = U_{oc}(STC)(1+\beta\Delta T)\ \ [V]$$

$$P_{max}(G,T) = P_{max}(STC)\frac{G}{1000}(1+\gamma\Delta T)\ \ [kW]$$

where:

- I_{sc}: short circuit current in STC;
- U_{oc}: open circuit voltage in STC;
- P_{max}: maximum power in STC;
- ΔT: temperature difference between the operating temperature of the cell and the STC one;

- α: thermal coefficient of the current, determines the dependence of the short circuit current on the temperature;
- β: thermal coefficient of the voltage, determines the dependence of the open circuit voltage on the temperature;
- ϒ: thermal coefficient of the power, determines the dependence of the maximum power on the temperature.

The coefficient α, β and ϒ are necessary for the optimal sizing of the electric wires.

In order to find the cell temperature reported above, it is important to know what is the Nominal Operating Cell Temperature, NOCT, which is given and reported by the constructor on the data sheet of the module and it represents the normal working temperature of it. To find the cell temperature, the following equation has to be used:

$$T_c = T_a + \frac{NOCT - 20}{800} G \ \ [°C]$$

where T_a represents the temperature of the air.

More precisely, the NOCT is defined as the temperature reached by the cells in a module operating in open circuit conditions and in the following standardized operating mode:

- global irradiance on the cell surface equal to 800 Wm^{-2};
- external air temperature equal to 20°C;
- wind speed equal to 1 ms^{-1};
- all sides exposed to the wind.

As said before, the module is a structure composed by interconnected cells and able to produce electric energy. The module consists of various components that seal and isolate the solar cells, protecting them from the external agents, in particular from humidity.

The module is identified by a peak power (W_p), a short circuit current, an open circuit voltage and voltage and current at the maximum power.

The PV system is normally affected from several types of losses, that could start from the temperature, as seen before, to the shading and inverter losses, affecting the overall performance and efficiency of the system. However, the main losses, that cause more problems to the PV systems, are the mismatch and the shading ones.

The mismatch losses occur when a multiple solar panels electrically wired together, that represent an array, have dissimilar characteristics as different current-voltage (I-V) characteristics, caused by manufacturing variations, partial shading or dust on the panels. Mismatch losses are, in turn, subdivided into three subcategories:

- resistive losses: are primarily caused by variations in the series resistances. When different resistances are connected in series, the current flow is limited by the module with the highest resistance, resulting in power losses.
- Shunt losses: occur when some PV modules arrays have higher shunt resistances than others. The module with higher shunt resistance allow more current to bypass the useful area of the module, resulting in power losses.
- Mismatch losses: occurs when PV modules with different I-V characteristic curves are connected in series or parallel and the module with the lowest current or voltage limit the overall generation. Due to this, is important to use the same type of panel with the same characteristics for all the PV system.

To reduce as possible the mismatch losses, maximum power point tracking (MPPT) algorithms are used, which optimize in every moment the working point according to the maximum power point. The working principle of the MPPT devices is to identify the point of maximum power on the I-V characteristic curve of the photovoltaic generator, causing small load variations at regular intervals and, as consequence, deviations in voltage and current values, evaluating if the new I-V curve is higher or lower than the previous one. If there is an increase, the load continues to vary in the same direction, otherwise the load is changed to cause a decrease.

The other important losses in the PV systems are the shading ones, which occur when a module is partly or entirely covered by obstacles, reducing the amount of solar energy received from the module. The main problematic effect, caused by these losses, is the hot-spot one, implying to a faster degradation of the modules.

When a cell or module is partially shaded, the shaded area may become a hot-spot. It refers to the situation for which the covered cells absorb less sunlight, resulting in reverse-biased conditions, so when the voltage at the cathode is higher than that at the anode. This can lead to localized heating and potential damage to the affected cells.

To mitigate the shading losses, various strategies can be employed, including system design to minimize the shading, reconfiguring the system layout to avoid shading or utilizing technologies, like bypass diodes, that allow the current to bypass the shaded cells, preventing hot-spot effects. Junction diodes act in a way that allows electrical current to flow through in one direction only.

There are two different types of diodes used in PV system: bypass and blocking diodes. Bypass diodes are commonly installed in parallel with a PV module, serving the purpose of switching the current around it. On the other hand, blocking diodes are connected in series with panels to effectively stop the flow of current back into the panels. For example, in case of presence of battery inside the PV system, they are used to prevent the batteries from draining or discharging back through the cells as they act as load in night, or in case of fully covered sky. So, blocking diodes are different from the bypass ones, even if in most cases the diode is the same, but they are installed and used for different purpose.

Below there is a possible configuration of diodes present in photovoltaic arrays.

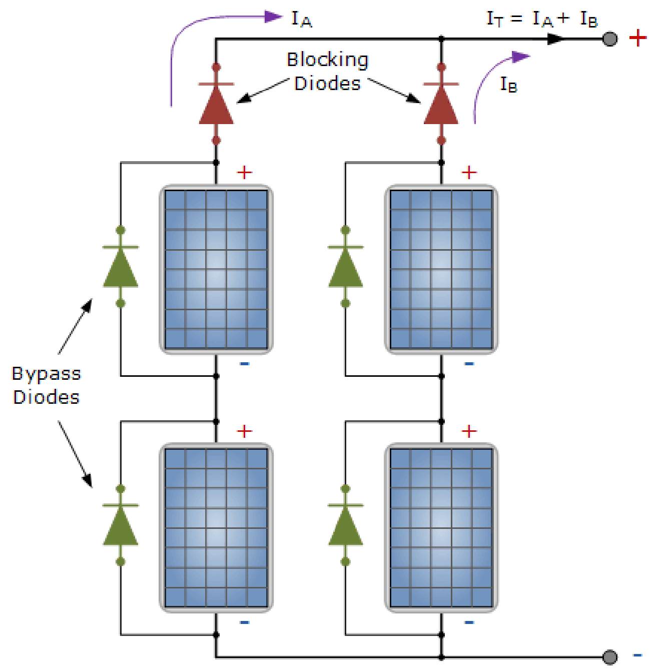


Figure 9: Schematic representation layout of PV arrays

To conclude the excursus about the photovoltaic technology, it is important to talk about the ratio between the kWh produced per kWp installed, kWh/kWp. Its physical meaning represents the equivalent number of hours that the photovoltaic system works at the peak power along an year, 8760 hours [7].

It represents the energy yield or performance of the PV system relative to its installed capacity and gives several information:

- performance evaluation: allows for a standardized comparison of the energy output of different PV systems, regardless of their size or capacity;
- system efficiency: provides insights into the efficiency of a PV system;
- system design and sizing: by analysing the expected energy yield per unit of installed capacity, it helps to optimize the size of the PV array;
- financial analysis: helps to estimate the potential revenue generated by the system and evaluate the return on investment (ROI) by comparing the energy production to the intial investment cost.

1.2.2. Inverter

An inverter is one of the most important devices in a solar energy system, since has the main purpose to convert the direct current (DC), which is the one generated by a solar panel, to alternating current (AC), the one used by the grid.

The inverter acts several steps to convert DC power into AC:

- conversion: the inverter receives the DC electricity produced by the solar panels and converts it into AC; this involves two steps: first, the DC power is converted into a high-frequency AC signal, and then this signal is transformed into standard AC power with the required voltage and frequency.
- Synchronization: ensures that the AC electricity is synchronized with the grid's voltage and frequency. Other characteristics requested to photovoltaic plant connected to the grid are:
  - high conversion efficiency;
  - power factor $cos\phi > 0.9$;
  - low harmonic distortion;
  - MPPT operations;
  - availability to limit the input power;
  - power on and shutdown with thresholds limit of irradiance.
- Monitoring: provide real-time data on the performance of the PV system. This includes information about energy production, efficiency and potential damages or faults.

Due to the required performance characteristics, the inverters, for systems connected to the distribution network and for stand-alone systems, must have different characteristics:

- in the grid-connected systems, the inverters must reproduce as reliable as possible the grid voltage and frequency, trying to optimize the yield production;
- in the stand alone systems, the inverters must be able to supply an AC voltage as constant as possible, as the generator output and load demand vary.

Inverters can have different sizes, from some kW to MW, and they can be configurated depending on the necessities of the plant, as for example optimization problems, components costs, distance between inverter and the farthest panels, that has not to be so high in order to reduce distribution losses.

There are two different configurations of inverter:

- central inverter: is installed in the central location of the solar energy system, are dimensioned to obtain exactly the power requested from the inverter, but has the disadvantage to cause the complete stop of the plant in case of fault;
- string inverter: is connected to the solar array that uses multiple strings for connection and supply of current. It gives higher efficiency and can follow better the maximum power point of each string respect to the central inverter.

The inverters do not consistently operate at their maximum efficiency, instead, their efficiency varies based on a power-dependent efficiency profile. This efficiency profile is called “European Efficiency” and it is an averaged operating efficiency over a yearly power distribution according to middle Europe climate.

The final efficiency is obtained by assigning a percentage of time to the inverter according to a given operating range.

1.2.3. Battery

Energy can be shared with electrical grid, being supplied when the PV system generates excess electricity and retrieved when the user required power. This process is known as “Scambio sul posto” or “exchange on the spot”, but exist also other processes of incentivization, as for example feed in tariff, feed in premium or dedicated retreat, also called RID.

In any case, one way to enhance the utilization of self-generated solar power is by implementing an energy storage system, such as a battery or electrochemical storage system. As a rule of thumb, the proportion of self-consumption from a PV system typically hovers around 30%. Nevertheless, with the incorporation of a battery system, this can increase substantially, reaching up to 80%.

The main characteristics of a battery in a PV system, that have to be considered for a better comprehension of the sizing and the quality necessaries, are:

- capacity: the capacity of a battery refers to the amount of electrical energy it can store and deliver. It is usually measured in ampere-hours (Ah). A higher capacity allows the battery to store more energy for longer durations;
- voltage: the voltage of a battery determines the electrical potential difference at external terminals. The voltage can vary depending on the battery technology and configuration. The voltage is subdivided into:
  - nominal voltage, V_{nom}: voltage in working condition;
  - maximum and minimum voltage, V_{max} and V_{min}: range of voltage out of that is dangerous for the battery life;
- efficiency: battery efficiency refers to the ability of the battery to convert stored energy back to usable electrical energy. This efficiency depends on several factors as charge and discharge rates, working temperature and on the specific battery chemistry. As you can imagine, higher efficiency means lower energy losses during charging and discharging processes;
- Depth of Discharge (DoD): the depth of discharge represents the percentage of the total capacity of the battery that can be used safely without damages, before that recharging is required. In some way, it represents also a safety level during the working conditions. Some batteries have a limited DoD to postpone their out of service, while others allow deeper discharges for increased usable capacity. From this, we can understand that the actual capacity, so the capacity effectively available, is not 100%, but a lower value that depends on the DoD;
- life cycle: it refers to the number of charge and discharge a battery can undergo before its capacity significantly degrades. It indicates the durability and lifespan of the battery;

- self-discharge rate: batteries gradually lose charge even when is used. Self-discharge rate refers to the speed at which a battery discharges itself over time. Lower self-discharge rates are preferable, since the stored energy remains available for longer time;
- energy density: energy that can be accumulated for unit of volume, it is expressed in watt-hours per liters (Wh/l).

Now, to have a clear picture, it is important to define the most diffused typologies of battery used in PV systems and explain how they work.

Here are some common types:

- lead-acid batteries: are one of the oldest and most widely used battery technologies. They are commonly used in off-grid or hybrid PV system for energy storage and backup power. Especially for lead-acid batteries, we have to avoid: excessive or too low voltage due to the possibility of corrosion problems, while deep discharge and prolonged periods without full charge due to possibility of sulfation problems. Sulfation refers to the formation of lead sulfate crystals on the battery plates, which can negatively affect the performances and overall lifespan.
- Lithium-ion batteries: have gained significant popularity in recent years due to their high energy density, relatively low maintenance, longer cycle life and offer high efficiency. They are used in PV system applications of various genres, from residential to commercial, off-grid systems and automotive. Since they are of our interest, there will be a better explanation of the working principle of this type of technology.
- Flow batteries: store energy in electrolyte solutions stored in separate tanks. During operation, the electrolyte is pumped through a cell stack, where the electrochemical reaction occurs, generating electricity. Flow batteries provide scalability and long life, making them suitable for large energy storage applications size.
- Sodium-based batteries: have shown substantial progress in recent years and are promising candidates for mitigating the supply risks associated with Li-based batteries. They offer high energy density and long life and are being explored for utility-scale energy storage [8].
- Nickel-Cadmium batteries: have been used in various applications for several decades. They offer high energy density, good temperature tolerance and long life.

1.2.3.1. Lithium – ion batteries

A brief more detailed explanation of the lithium – ion battery is necessary, since it will be the battery technology considered in this paper for the analysis and simulations that will be done.

This type of battery works based on the movement of lithium ions between two electrodes. The main components are:

- cathode: is usually made of a lithium metal oxide compound, such as lithium cobalt oxide (LiCoO2), lithium manganese oxide (LiMn2O4) or lithium iron phosphate (LiFePO4);
- anode: is typically composed of graphite, which can absorb and release lithium ions;
- electrolyte: Li – ion batteries use a non-aqueous electrolyte, which is a mixture of lithium salts dissolved in organic solvent.

In the article *"Towards Highly Efficient Lithium-Ion Batteries: Focusing on Electrolytes"* [9], the advantages of this type of battery are explained, as for example large capacity, high working voltage, long life cycle, no memory effect and so on, as well as its problems, like overcharge, charging imbalance and its strong dependence on ambient temperature. But, it explains in detail also how this battery works, in fact, the working principle is to extract and insert lithium ions from and into lithium-ions compounds, respectively serving as the positive and negative terminals of the battery.

During the charging process, lithium ions are detached from the positive compounds (in the Li-rich state) and embedded into the lattice of the negative electrode (in the Li-poor state). On the other hand, during the discharge, lithium ions separate from the negative electrode and enter to the lithium-rich positive electrode. This movement of lithium-ions, which is explained, is accompanied by the transfer of an equal number of electrons through the external circuit to maintain charge balance. Oxidation and reduction reactions occurs at the positive and negative electrodes respectively. Throughout the charging and discharging process, a specific potential is maintained to ensure efficient battery operation.

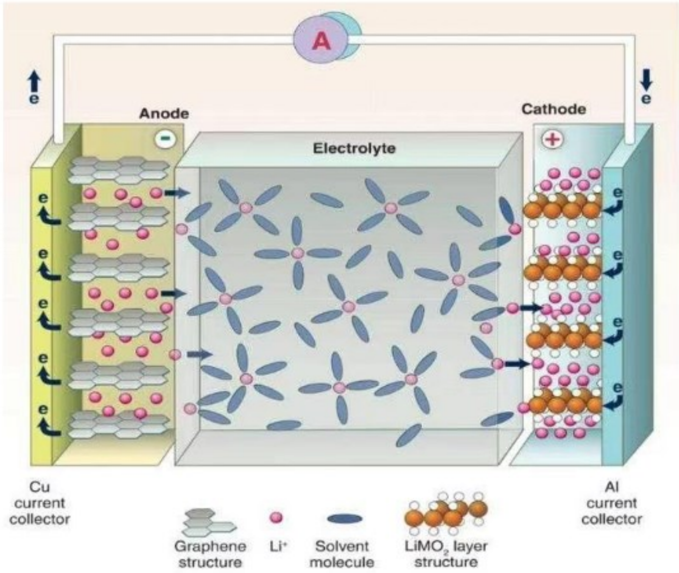


Figure 10: Lithium-ion battery charging and discharging schematic diagram

2. TELEZIP

After have had a general overview on what there is behind the principles of cogeneration and, in particular, trigeneration, it is possible to start to talk in detail of the plant of Telezip.

2.1. General overview

The trigenerative power plant of Telezip, which name derived from Teleriscaldamento Zona Industriale di Padova, is located in Corso Stati Uniti 3, inside the industrial zone.

Figure 11: Schematic map of Padua

The main purpose of this district heating power plant is to satisfy the request of heating and cooling of the industrial buildings, close to the plant, for at least 30 years, distributing the produced thermal energy through underground tubes.

The whole plant is composed by three main sub-systems:

- thermal plant: which represents all the machines and auxiliary systems for the thermal and cooling production;
- distribution line: which branches off for a total length of 3 km, in order to achieve all the users. It is totally isolated and is situated at 1.5 m of depth;

- substations: distribution substations are located near the users, here there is the heat exchange between the primary fluid, that is the heat transfer fluid coming from the plant, and the secondary fluid, that is the one present in the climatization plant of the user.

The useful area is about 87000 m^2, while the supplied area is about 78000 m^2. In particular, the supplied heating area is 78000 m^2 and the supplied cooling area is 66000 m^2, as fewer users exploit the service.

This area is composed by several shops and offices designate to the wholesale of clothes and cars, so it is understandable that the type of buildings, in terms of construction and height, could be different as their energy consumptions during the year.

2.2. Explanation of the trigenerative power plant

A trigeneration system, also known as combined cooling, heating and power system, is a smart solution that uses a single primary energy source, that could be renewable or fossil one, to generate three outcomes in a more efficient way. The advantages comes from the fact that it avoids the use of three different plants, as it is all integrated, and exploits waste energies that, otherwise, would not be used.

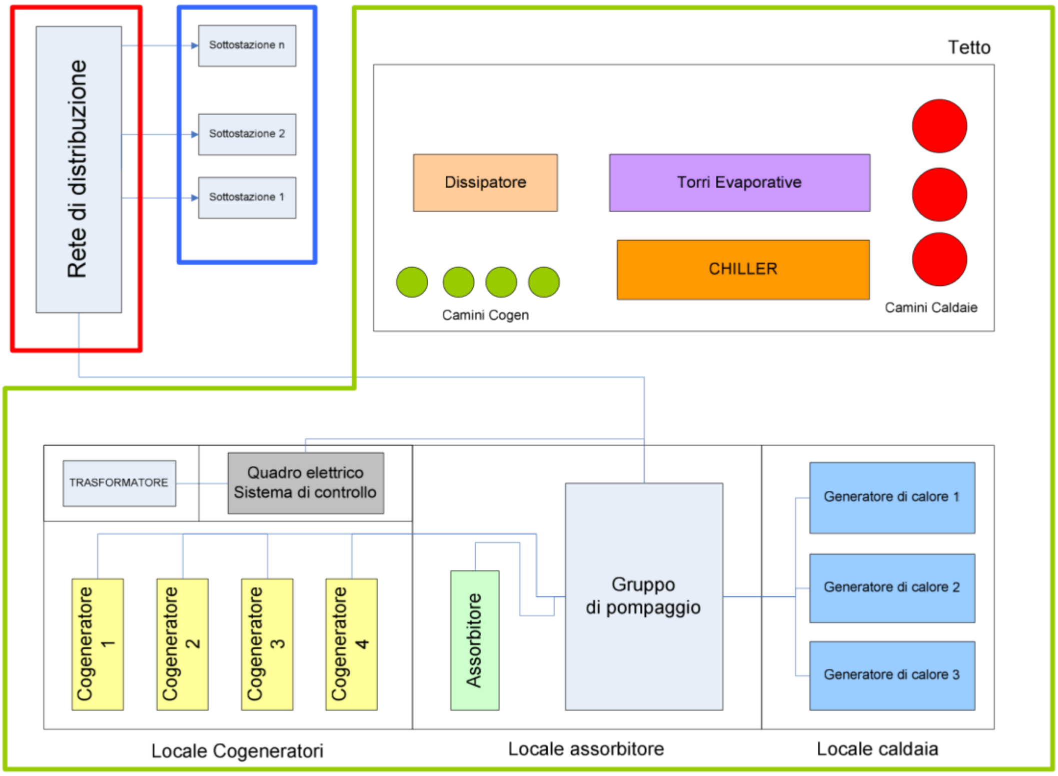


Figure 12: Schematic layout of Telezip

Above, an initial simplified schematic layout of Telezip plant is shown, in which are present the main components and how they are connected each other. In reality, some differences to the current situation are present due to the changes made to the first project and problems appeared over the years. In fact, this configuration was made considering a future increase in customers, which would consequently lead to an increase in machinery.

Following *Figure 12,* it is possible to explain a bit the functioning of the whole system.

As already said, the plant has the purpose to supply both heating, during the cold period, and cooling, during the hot period, furthermore, exploiting the cogenerators, it is possible to produce electric energy to sell completely to the net.

The system is composed by two general collectors for the secondary heat transfer fluid, which, in this case, is composed only by water without glycol, since temperature never goes below 0°C:

- one collector supplies the forward tube of the district heating;
- one collector receives the return tube of the net.

The secondary heat transfer fluid of the return tube has different working temperature depending on the season, in fact, during the winter season is at 55°C, while in summer season at 13°C.

It is possible to explain better the two distinct operations:

- winter season: the secondary fluid enters in the heat exchanger at 55°C and exchanges heat with the primary heat transfer fluid, heated by the cogenerators at 98°C, to exit at 80°C. If the primary fluid exits from the heat exchanger at an higher temperature, which means a low heating request, the heat in excess is sent to the dissipator. Instead, in case of higher heating request, the boilers are also activated.
- Summer season: the secondary fluid enters in a reservoir at 13°C and is subsequently sent to the district network at 7°C, after have exchanged heat with the primary fluid that comes from the absorption cycle. The absorption cycle will be explained in detail next, but here it is important to know that it needs of heat to work. This heat is a waste one and comes from the production of electricity of the cogenerators. In case of high cooling request, the chiller is also activated.

Now, that a general view of the plant is obtained, it is possible to explain in detail how the production of heating, the simultaneous production of heating and electricity and, subsequently, the production of cooling are done.

2.2.1. Production of heating

For what concerns the production of heating, as can be seen from the figure above, the initial project supposed to have three boilers, while currently are used only two condensing boilers, that consume methane, with a burner nominal power of 2500 kW each one, for a total power of 5000 kW. These two condensing boilers work in cascade and, even in case of out of service of one, it is still possible to satisfy the heating demand.

During the winter periods, as they have seen that most of the time one of the two burners was never used due to the low heating request, they have decided to substitute it with a lower nominal power burner of 700 kW. This replacement allows to use the lower power burner for the middle seasons and the bigger power burner during the winter seasons.

TECHNICAL DATA OF BOILER	
USEFUL NOMINAL POWER	2500 kW
THERMAL POWER	2688 kW
MAXIMUM WORKING TEMPERATURE	110°C
EFFICIENCY (referred to LHV)	107 %
ELECTRIC POWER	7,3 kW

Table 1: Technical data of boilers

2.2.2. Simultaneous production of heating and electric energy

About the simultaneous production of heating and electricity were supposed four cogenerators, but, in reality, there are only two available cogenerators with a nominal electric power of 323 kW and a nominal thermal power of 485 kW each one.

The cogeneration system can have two different modes of work:

- Electricity priority: cogenerators follow a set electricity power. The waste thermal power obtained from the electricity production, if not useful for the customers or in the absorption cycle, is dissipated from the dissipator present on the roof.
- Thermal priority: cogenerators follow a set thermal power or the heating demand curve of the customers. In this case, the waste thermal power to dissipate would not present.

In the particular case of Telezip, the cogenerators work in thermal priority mode. The thermal chase has a minimum of 60% of the nominal thermal power of the cogenerator in order to have both the cogenerator at work, while, if the heating demand from the customers is smaller, only one works and the peaks are covered from the boilers.

The plant produce electric energy at low voltage (0,4 kV) with synchronous generator and, through a transformer, is connected to the medium voltage network at 20 kV. All the electric energy produced, if not self-consumed by the plant, is totally sold.

To understand the performances of a cogeneration system, there are some indicators.

The first indicator is:

$$\eta_I = utilization\,factor = \frac{P_{el} + Q_{th}}{P_p}$$

where:

- P_{el}: useful electrical power;
- Q_{th}: useful thermal power;
- P_p: supplied power input.

In particular, for what concerns the cogenerators of Telezip, we obtain:

$$\eta_I = \frac{323 + 485}{907} = 0.89$$

this means that the cogeneration system exploits the 89% of the used fuel.

The second and more important indicator is:

$$PES = Primary\ Energy\ Saving = 1 - \frac{P_p}{\left(\frac{P_{el}}{\eta_{el}^*} + \frac{Q_U}{\eta_{th}^*}\right)} = 1 - \frac{1}{\left(\frac{\eta_{el}}{\eta_{el}^*} + \frac{\eta_{th}}{\eta_{th}^*}\right)}$$

where:

- η_{el}: combined heat and power electrical efficiency;
- η_{th}: combined heat and power thermal efficiency;
- η_{el}^*: reference electric efficiency;
- η_{th}^*: reference thermal efficiency.

Regarding the reference electric efficiency is a fixed value decided by each country and, in Italy, the mean value is equal to 0.374.

While the reference thermal efficiency depends on a series of variables as operating conditions, fuel used, power size of the plant and so on. For a supplied power of 907 kW and natural gas as fuel, is obtained a η_{th}^* equal to 0.81.

Knowing the electric and thermal efficiency of the cogenerators used in Telezip, we obtain a PES value equal to:

$$PES = 1 - \frac{1}{\left(\frac{0.356}{0.374} + \frac{0.53}{0.81}\right)} = 0.38 = 38\%$$

This index shows us what is the percentage of energy that is possible to save with the cogenerator plant compared to the two independent electric and thermal plant, in order to obtain the same amount of energy.
In this case we can save about 38% of energy.

There are some minimum percentage values of these two indicators that the cogeneration power plant has to be satisfied in order to be defined as CAR, High Efficiency Cogeneration; in particular, the minimum value for the PES index is 10%, while the threshold efficiency value for the utilization factor is 0.8 for a combined cycle gas turbines and steam condensing extraction turbines.

During the summer period, when the thermal energy is not required, the cogenerators work in electricity priority mode, following the set electricity power. The waste thermal energy, since the vapor is about 100°C, is used to satisfy the heat requested from the absorption cycle in order to produce cooling.

2.2.3. Production of cooling

Instead, for the production of cooling, there are two types of systems to satisfy the request, which are a lithium bromide-water absorption cycle and a chiller.

Starting from the absorption cycle, the main advantage of use it is that, here, it is not used mechanical work to compress the refrigerant fluid, using a vapor compressor, but it is used a thermal one giving a lower consumption of electricity. Since thermal power is required inside this cycle, it is possible to exploit the waste heat that comes from the production of electricity during the summer period. In this way, the plant can be considered as a trigenerative one producing all in one the three types on energy: heating, cooling and electricity.

The cycle of Telezip, in particular, is a lithium bromide-water type, where the lithium bromide is the absorbent, so the component that absorbs and transports the refrigerant, from the low pressure side to the high pressure side of the cycle through the use of a pump, while the water is the refrigerant, so the component that condenses, rejecting the heat to the ambient, and evaporates, absorbing the heat from the room to cool it.

Below, a schematic layout of the absorption cycle is shown, where the four main components of it are represented: condenser with generator that work at the same high pressure and evaporator with absorber that work at the same low pressure. In *Figure 13*, it is possible to see the heat flows required with a greater focus on the generator, in which the heat flow, indicated as Q_n, is incoming.

This heat is exactly the waste thermal energy rejected from the cogenerators and it is still at a temperature of about 100°C, a temperature value that gives the possibility to the rich solution of LiBr-water to evaporate and obtain the separation of the two components. The water then goes to the condenser, while the poor solution returns to the absorber, where will be enriched again.

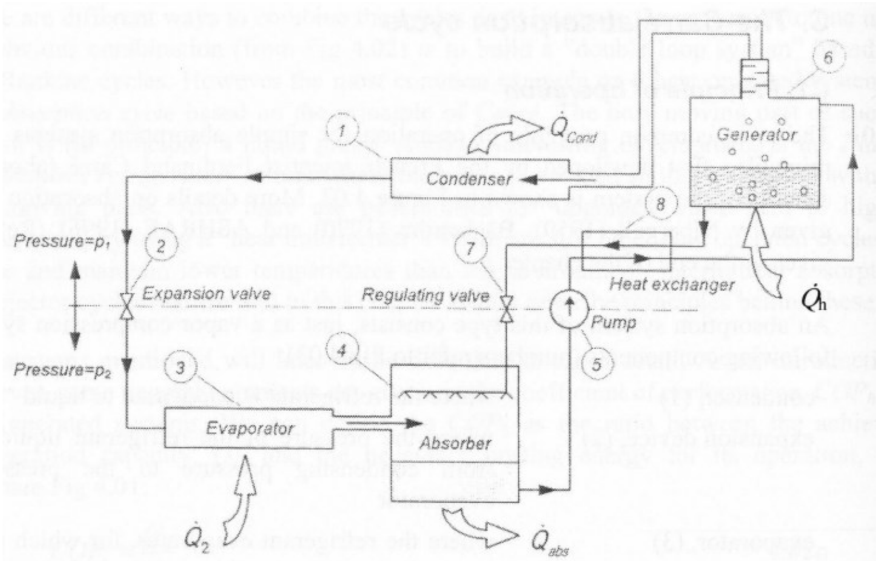


Figure 13: Schematic layout of lithium bromide-water absorption cycle

The functioning of the absorption cycle allows the cooling of the water from 13°C to 7°C.

Here, some technical data of the absorption cycle are shown:

TECHNICAL DATA OF ABSORPTION CYCLE	
REFRIGERATING EFFECT	1300 kW
NOMINAL SERVICE TEMPERATURE (IN/OUT)	13°C / 7°C
COOLING WATER TEMPERATURE (IN/OUT)	29°C / 34°C
GENERATOR WATER TEMPERATURE (IN/OUT)	98°C / 79°C
ELECTRIC POWER	7,3 kW

Table 2: Technical data of absorption cycle

The other cooling auxiliary system used in Telezip, when the cooling demand is high, is an electric chiller. Here, the cycle is a vapor compression one and the main components are the condenser and the evaporator, so there aren't the generator and the absorber as before.

Also in the chiller, the evaporating conditions are to cool the water from 13°C down to 7°C, while the condensing conditions depend on the external conditions of the air since it is where we reject the heat.

Being a vapor compression cycle, mechanical work is used and it is determined by the functioning of two screw compressors with four steps control. This control system is managed by the movement of a sliding valve used to adjust the flow rate of fixed frequency drive compressor. The inlet gas, in fact, is bypassed by moving the slide valve to discharge side of the screw compressor. The four steps control system allows to follow in a better way the demand curve in big plant, since gives more options to modulate the power without reduce the total efficiency of the compressor.

In order to improve the EER, Efficiency Energy Ratio, of the cycle, that is the ratio between the refrigeration capacity, so how is possible to cool with a given mass flow rate, and the compressor power, so how much work is spent to compress the given mass flow rate, there is an evaporative tower on the roof that has the function of dissipating heat.

The operation principle of this component is to spray the hot water, that comes from the condenser, above the heat exchange pack where comes in contact with the cold air flow sucked from the bottom, releasing the heat. The hot saturated air is rejected outside the plant from the top of the tower.

The advantage of use an evaporative tower is the possibility to reduce the outlet water temperature, of the secondary fluid used as cold sink in the condenser, down to the wet bulb temperature instead of the dry bulb temperature as with usual condition; in this way the condensing temperature, and as consequence the condensing pressure, are lower and the compressor spends lower energy.

In addition, we have to say that the refrigerant used in this cycle is R-134a.

Below, the principal characteristics of the chiller are shown:

TECHNICAL DATA OF CHILLER	
REFRIGERATING EFFECT	837,7 kW
TOTAL COMPRESSION POWER	256,8 kW
NOMINAL SERVICE TEMPERATURE (IN/OUT)	13°C / 7°C
COP	3,48
EER	3,26

Table 3: Technical data of chiller

2.3. Initial economic business plan of Telezip

An important step, that has to be done, is a roughly investigation on the return on investment plan made before the construction of Telezip, since from here, it is possible to understand the motivations behind this important project and the revenue items on which the company depended for the following years.

REVENUE ITEMS						
YEARS	CONNECTIONS TO DISTRICT HEATING	FIXED QUOTES	DISTRICT HEATING AND COOLING	ELECTRIC ENERGY SOLD	GREEN CERTIFICATES	TOT
2012	180.000,00 €	103.000,00 €	596.000,00 €	50.000,00 €	350.000,00 €	1.279.000,00 €
2013	30.000,00 €	110.500,00 €	611.000,00 €	80.000,00 €	385.000,00 €	1.216.500,00 €
2014	30.000,00 €	118.000,00 €	626.000,00 €	85.000,00 €	390.000,00 €	1.249.000,00 €
2015	30.000,00 €	125.500,00 €	641.000,00 €	90.000,00 €	395.000,00 €	1.281.500,00 €
2016	0,00 €	125.500,00 €	663.435,00 €	90.000,00 €	395.000,00 €	1.273.935,00 €
2017	0,00 €	125.500,00 €	686.655,00 €	90.000,00 €	395.000,00 €	1.297.155,00 €
2018	0,00 €	125.500,00 €	710.687,00 €	90.000,00 €	395.000,00 €	1.321.187,00 €
2019	0,00 €	125.500,00 €	735.561,00 €	90.000,00 €	395.000,00 €	1.346.061,00 €

Table 4: Revenue items of Telezip 2012-2019

From *Table 4,* it is possible to catch several important information and aspects:

- the revenues from the connections to district heating were considered only until 2015, since from the following year was supposed to not have entrances of new users;
- due to the fact that from 2016 new users were not supposed, the fixed quotas become fully operational;
- the main revenue comes from the sale of heating and cooling. The reason why there is an increase of the district heating and cooling revenue, even if the users were not increased, it is because was supposed a revaluation of the annual natural gas cost of 3,5%. About this fact, is important to note from *Table 5* that also the value of production, that are the fixed cost of the plant, increases due to this revaluation;
- others important revenues, included in the investment return of the plant, were:
    - electricity energy sale due to the functioning of the cogenerators, since, as already said in the previous subchapter, during the summer period, when the thermal request is absent, these operate to produce electricity, while the waste thermal heat is used in the absorption cycle;
    - green certificates, from which were supposed great revenues.

The Green Certificates were another important incentive present since 1999, introduced from the famous Decreto Bersani [10], currently expired and therefore not more available, which were substantially an incentive to the electricity production from RES, Renewable Energy Sources, represented by TEE, as the White Certificates explained in the first chapter.

The difference from these last ones is that the Green Certificates take into account the energy produced from RES and not only the primary energy saving; furthermore the energy produced considered is the net one and not the gross, so from the total were subtracted:

- electric energy absorbed from auxiliary systems;
- trasformer losses;
- distribution losses.

FORECAST BUDGET - INCOME ACCOUNT								
BUDGET VOICES	2012	2013	2014	2015	2016	2017	2018	2019
Net Revenue Items	€1.279.000,00	€1.216.500,00	€1.249.000,00	€1.281.500,00	€1.273.935,00	€1.297.155,00	€1.321.187,00	€1.346.061,00
Value of production	€770.500,00	€789.905,00	€810.129,00	€829.201,00	€845.150,00	€861.658,00	€878.744,00	€896.427,00
Added value	€508.500,00	€426.595,00	€438.871,00	€452.299,00	€428.785,00	€435.497,00	€442.443,00	€449.634,00
Gross operating margin	€508.500,00	€426.595,00	€438.871,00	€452.299,00	€428.785,00	€435.497,00	€442.443,00	€449.634,00
Material depreciation	€ 82.720	€ 91.120	€ 91.120	€ 91.120	€ 91.120	€ 91.120	€ 91.120	€ 91.120
Operating income	€425.780,00	€335.475,00	€347.751,00	€361.179,00	€337.665,00	€344.377,00	€351.323,00	€358.514,00
Financial charges	€ 4.991	€ 5.724	€ 5.724	€ 5.724	€ 5.724	€ 5.724	€ 5.724	€ 5.724
Financial income	€ 102	€ 572	€ 572	€ 572	€ 572	€ 572	€ 572	€ 572
Taxes	€ 22.892	€ 70.390	€ 70.390	€ 70.390	€ 70.390	€ 70.390	€ 70.390	€ 70.390
Net result	**€397.795,00**	**€258.789,00**	**€271.065,00**	**€284.493,00**	**€260.979,00**	**€267.691,00**	**€274.637,00**	**€281.828,00**

Table 5: Forecast budget - Income account 2012-2019

After have seen the total revenues, it is important also to consider the costs, as reported in *Table 5*.

At the end, it is possible to see that about each year was supposed to have a net operating margin of 300 000€.

Unfortunately, this budget has remained only a forecast and does not match with the real one due to several problems happened in these years.

In fact, the main problem comes from the users that, along these years, have reached an irregular economic position vis-à-vis Telezip, have not use the district heating and cooling, even if a contract was subscripted, or have substituted the secondary plant of the district network with an abusive one.

It is possible to clearly understand that this situation has comported a strong variation on the return on the investment plan of the plant, in fact, net of unpaid invoices, the incorrect behavior of the users has comported a reduction in the heating and cooling demand. The logical consequence was a decline in the working hours of the trigenerative plant, with the following modification of the production layout:

- during the winter period, since the demand was too low, it was worthless use the cogenerators and, therefore, only the boilers are used, involving a lower efficiency of the whole system;
- for the same reason, but during the summer period, since cogenerators are not available, it is not possible to produce electric energy to sold to the grid and there is not present waste heat to exploit through the absorption cycle, resulting in a loss of income from the sale and obtaining rather, on the contrary, an increase of the fixed cost, due to the electricity used from the chiller.

But the worst aspect of not use the cogenerators is that the plant cannot be considered as CAR, High Efficiency Combined cycle, with the direct consequence of not have the possibilities to receive the incentives, Green Certificates included.

After have exposed this bad situation, and considering *Table 4*, *t*he final conclusions about the return on the investment plan of this plant are left to the reader.

Along these last years, others external problems, as Covid-19 and Ukraine War, have aggravated the context, due to the illogical increase and speculation behind the natural gas and electric energy prices.

2.3.1. Overview about the electricity and natural gas prices trends

This description is necessary in order to understand the reasons behind the solution found to the problems described before and that coincides with the main argument of the thesis, an implementation of a photovoltaic plant.

As said just now, these last three years have shown two very important things:

- how the market, and so the world, is vulnerable and dependent on fossil fuels;
- how the renewable energy sources are important.

In fact, never as in these few years, the world has understood the importance of the electricity in the life of all days and how the situation changes depending on what is the primary energy source used to produce it.

As described from the European Central Bank, citing another source, the purchasing power of consumers has seen a net decrease due to the record-high energy price at the end of 2021 and beginning of 2022, but also at the end of august 2022.

The energy price increases that occurred were a direct response to the significant decrease in energy prices at the start of the Covid-19 pandemic. The initial rise in prices was primarily due to the recovery in energy demand following the relaxation of lockdown measures after the first wave of the pandemic. However, the subsequent price surge throughout 2021 was also heavily influenced by issues related to the supply side of the energy market. The situation worsened in early 2022 due to the Russia invasion to the Ukraine. European gas prices experienced particularly sharp increase since the summer of 2021. This was caused by the combination of factors, including both supply and demand issues. European gas storages were historically low levels before the winter season, leaving the gas market susceptible to uncertainty regarding supply and demand, especially in light of escalating geopolitical tensions. Consequently, consumer prices for gas and electricity, both linked to natural gas prices, due to the fact that in Europe and particularly in Italy the production of electricity is made mainly using natural gas, became increasingly influential in the overall energy price trends. This uncontrollable increase of the prices reaches its apex at the end of august 2022 due to the tensions for the war and the explosion happened to the Nord Stream 2 pipeline, rendering effectively it unusable, and the out of service of Nord Stream 1, from which almost all the gas used in Europe came. This situation was accompanied by an unprecedented variation in energy price development across different countries [11].

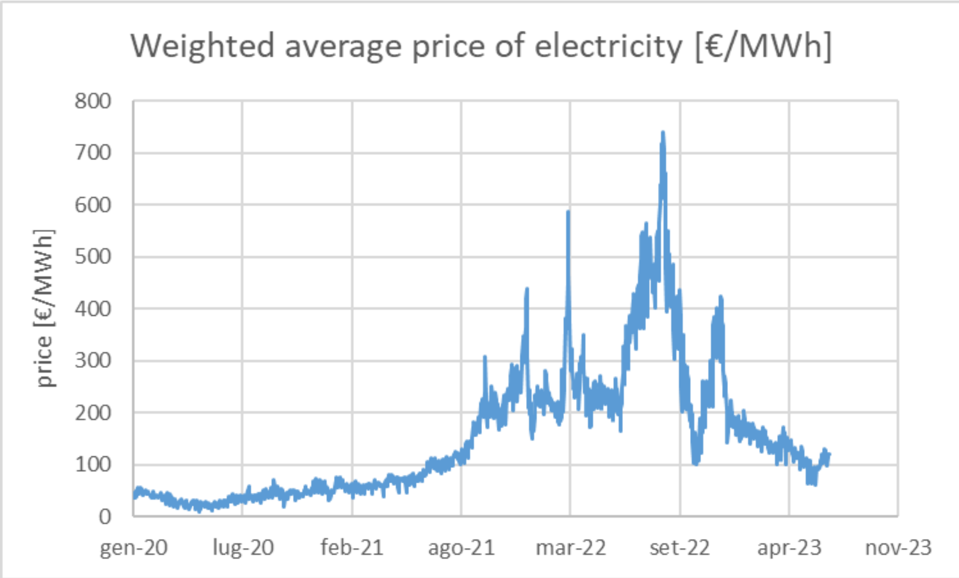


Figure 14:Weighted average price €/MWh, Source: GME, Dati Storici [12]

As it is possible to see from *Figure 14*, the trend of electricity reached the price of 70 cent / kWh.

Despite of this global energy crisis triggered by Russia's war, the world electricity demand remained resilient in 2022, since the electrification of the transport and heating sectors continued to accelerate globally [13].

Similarly in *Figure 15*, updated at July 2023, it is possible to obtain a graph also for the natural gas price, which has reached unimaginable values before august of the last years, seeing its cost increases of 3000%. From this last significant percentage value, it is possible to understand that no one could have foreseen a similar bad situation, all the more so, if compared to the ridiculous revaluation of the annual natural gas cost of 3,5%, but that, in 2011, it was considered quite protective.

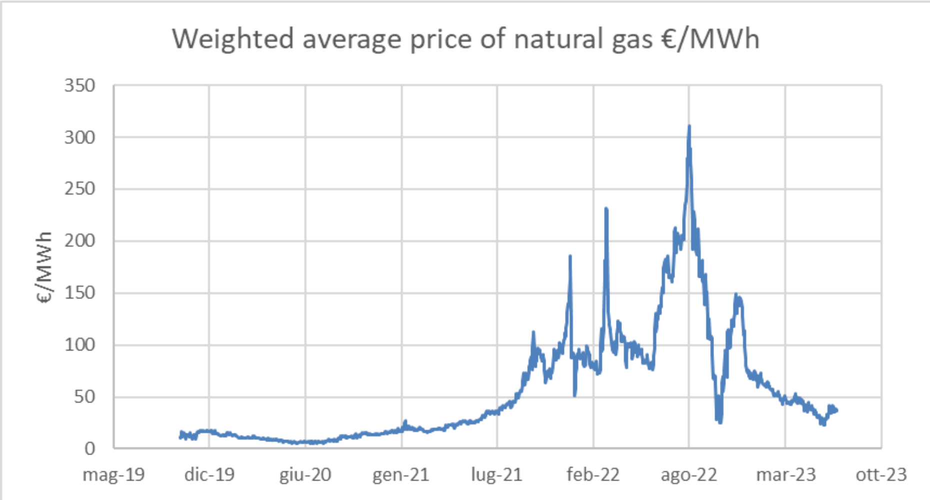


Figure 15: Weighted average price €/MWh, Source: GME, Dati Storici [12]

An interesting thing that is possible to note from *Figure 14* and *Figure 15*, is that the electricity and natural gas price trends are very similar. The explanation of that is because the price of the electric energy is determined by the mean value of sale of several producers constituted by a technology mix ordinated from the cheapest to the most expensive. All the energy traded on this market is recognized at the price of the marginal technology, the latest and most expensive, necessary to cover the demand at that specific hour. Since in Italy, in the production mix, the gas is the marginal technology used for about half of the time, the electricity price is importantly affected by the natural gas price.

From all these economic and energetic reasons, it is easy to understand why, as possible solution, ForGreen has chosen to verify if it could be worth to implement a photovoltaic power plant on a roof of an industrial building near Telezip. This solution might allow Telezip to be partially independent from the electric energy during the summer for the cooling, while during the winter and the mid seasons the electricity produced could be sold generating a revenue.

3. ELECTRIC ENERGY PRICE

This chapter will go into detail the electric energy price, in order to understand the reason behind the one that will be used for the economic analysis of the case study.

3.1. Electricity market

The inception of the Electricity Market in Italy can be traced back to the approval of Legislative Decree no. 79/99 [14], which marked the initiation of a structural reform in the electricity sector. The primary goals were twofold:

- foster competition in production and wholesale sales by establishing a dynamic "marketplace";
- ensure optimal efficiency and transparency in the dispatching process, which operates as a natural monopoly.

The Electricity Market functions as a digital platform for wholesale electricity trading. The energy price, on this platform, reflects the equilibrium achieved through the interplay between the quantities of electricity demanded and offered by participating operators.

It is a real physical market, where the schedules for the injection and withdrawal of electricity into, and from, the grid are determined based on the criterion of merit order. Relying on the ordering of the plants, according to their marginal cost of production, which is the additional cost incurred to produce one additional unit of output in the short term, the merit order of the available park can be organized. Due to the fact that the park is constituted by different types of plant, with different marginal cost, the merit order curve will be a stepped one. The interpolation of these marginal cost represents the energy supply curve. [15]

The price, at which power is sold, is the one of the last plant in operation, that is indicated by the meeting point between the demand and supply curves in *Figure 16*, which represents the value of energy that varies in any moment and that is represented by the hourly PUN, or the Zonal hourly PUN, as shown in *Figure 3*. Since RES have more or less a null marginal cost, their revenues to cover the fixed ones coincide with this meeting point, also called inframarginal rent.

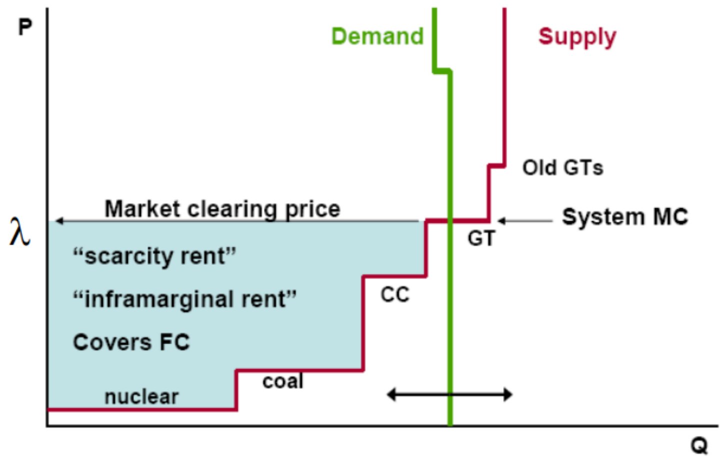


Figure 16: Merit order curve based on marginal cost. [15]

The national electrical system is a networked system organized in which, in a context of a free market, the activities that characterize it are distinct and carried out by different entities. These activities involve the production, transmission and distribution of electrical energy, which are subject to very strict technical constraints, such as:

- the requirement for instantaneous and continuous balancing between the amount of energy injected into the grid and the amount withdrawn from the grid, net of transport and distribution losses;
- the maintenance of the frequency and voltage of the energy within an extremely narrow range to ensure the safety of the installations;
- the need to ensure that energy flows on each individual power line do not exceed the maximum allowable transit limits for that power line.

Even slight deviations from any of the above parameters, for more than a few seconds, can quickly lead to a crisis of the system.

The electricity market is organized and managed by the GME, Italian Market Operator, and is aimed at scheduling the units of production and consume, also called SSPC, Simple System of Production and Consumption.

In order to have the instantaneous and continuous balancing mentioned before, the SSPC have to produce the exactly amount of energy in the exactly precise time following what was established inside the Day-Ahead Market, MGP, which is a market where producers, wholesalers and eligible end consumers can sell/purchase electrical energy for the following day through offers.

These are constituted of couples of quantities and unitary prices of electrical energy (MWh; €/MWh) and represent the availability to sell a quantity of energy not greater than the one specified in the offer and at a price not lower than the one of the offer.

3.2. Day-Ahead Market (MGP)

The Day-Ahead Market, MGP, as already said, is a wholesale electricity exchange where hourly blocks of electricity for the following day are traded, so prices, quantities and injection/withdrawal schedules for the following day are determined in this market [16].

The GME is the central counterparty, which, before the MGP session, provides operators with information regarding the forecasted energy demand for each hour and zone and the maximum transit limits allowed between neighbouring zones.

After the bidding session, GME initiates the market clearing process. If flows on the network meet the accepted schedules without violating transit limits, a unique equilibrium price is determined for all zones. If at least one limit is violated, the algorithm splits the market into two zones: an exporting and an importing zones. The process is repeated in each zone, resulting in zonal equilibrium prices, P_z, that differ between the two zones. In particular, P_z is higher in the importing zone and lower in the exporting zone.

Regarding the price of energy intended for consumption in Italy, GME has implemented an algorithm that, based on differentiated prices per zone, applies a single National Purchase Price (PUN), equal to the weighted average of zonal selling prices for zonal consumption. PUN is applied only to consumption points in the national geographic zones.

Figure 17: Subdivision of zone in Italy for the zonal prices

At the end of the MGP, there are others two markets called Intraday Market (MI) and Dispatching Service Market (MSD), in which is possible made some adjustments to the MGP after its closure. As final result, is possible to obtain for the following day a trend, as in *Figure 18*, that describes the expected electricity demand price.

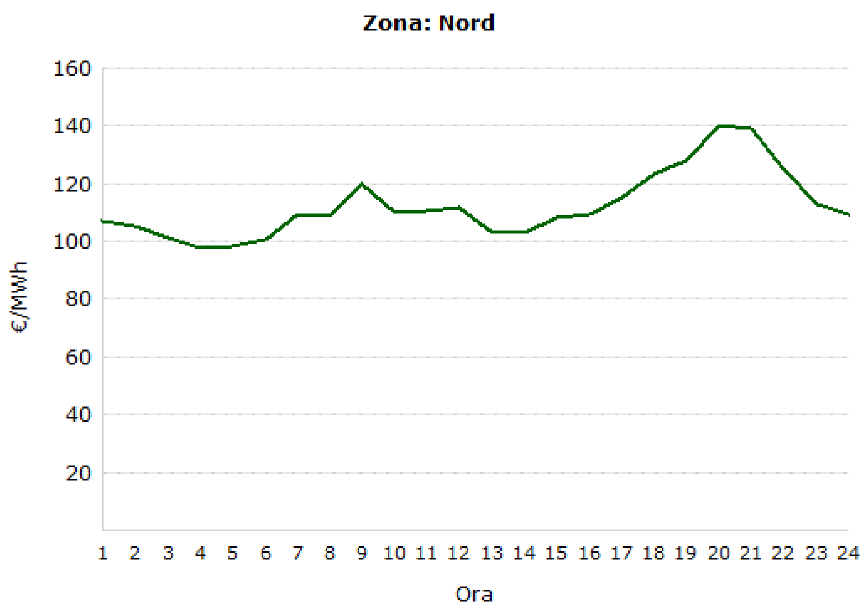


Figure 18: PUN on 21/07/2023, source: https://www.mercatoelettrico.org/it/Esiti/MGP/EsitiMGP.aspx

In particular, from the figure above is important to note that during these summer nights, when people use their air conditioning systems, increasing the energy demand, the electricity price is higher even than during peak hours during the day. This due to the fact that from the late evening, the production from renewable energy sources lacks, so only power plants with high marginal costs are in function, as gas turbine or hydroelectric plant, increasing the electricity price.

The electricity price trend for each day turns out to be important when we start to talk about economic indicator as the return on investment, since the hourly price of electricity gives us the effectively economic saving from the bought of it from the net. But, since these information about a day are available only the day before, in order to have an idea if the investment is worth and to view the general market expectations through future forecasts, it is necessary to consult market futures. These are continuous trading platforms on which sellers and buyers exchange quantities of gas and electricity with different delivery periods over time and standard profiles.

3.3. Forecast electricity price

In order to make some considerations on market expectations regarding future forecast of the electricity price, a report of Standard&Poor's [17], which is an American rating agency that publishes financial research and analysis on stocks, bonds and commodities, and one of Energy Brainpool [18], which is an independent analysis and consulting company for energy participants, will be considered.

Both in [17] and [18] are shown the currently market conditions that are affected by high electricity prices due to geopolitical tensions caused by the war, but on the other hand they agree on the fact that the future market will be less and less affected by the fossil sources and, in particular, by the trend of the natural gas price, which will be replaced in turn by the liquefied natural gas. As explained in both reports, the market and the gross electricity production will be governed by the increasingly massive presence of the solar and wind power, as we can see from *Figure 19*, leading to a large and rapid decrease in the electricity price from 2026.

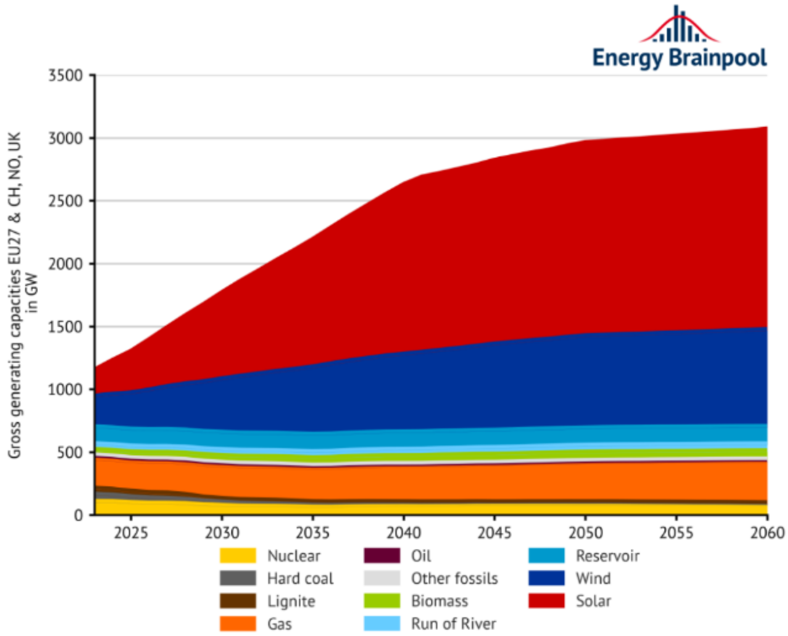


Figure 19: Installed generation capacity in EU27 & CH, NO, UK

It is important to note also that the electricity demand will increase, in particular, by 65% by 2050 and by approximately 71% by 2060 primarily due to:

- the national hydrogen strategies and expansion of hydrogen applications;
- the growing degree of electrification of various energy services for households;
- the rise of electric mobility.

These last three motivations are mentioned also in [17] and are grouped below the physical market-dynamics category, which is one of the two categories underpinning of a decline in power prices. The second category is grouped below the impacts of the energy supply mix, in which the key factor will be the so called renewables cannibalization effect, that refers to the tendency of similar assets to produce energy simultaneously, leading to output peaks that depress wholesale prices.

On the other hand the downside of cannibalization is that during periods of low solar and wind energy generation, the energy supply can decrease significantly, leading to higher electricity prices. However, power generators that have flexible output capabilities, such as pumped and reservoir hydroelectricity and gas fired plants can capitalize on these situations and play crucial role in maintaining stable energy supply. It is also important to mention that batteries could have a big influence on these aspects and it is for this reason that simulations of this thesis account also a possible project with a battery.

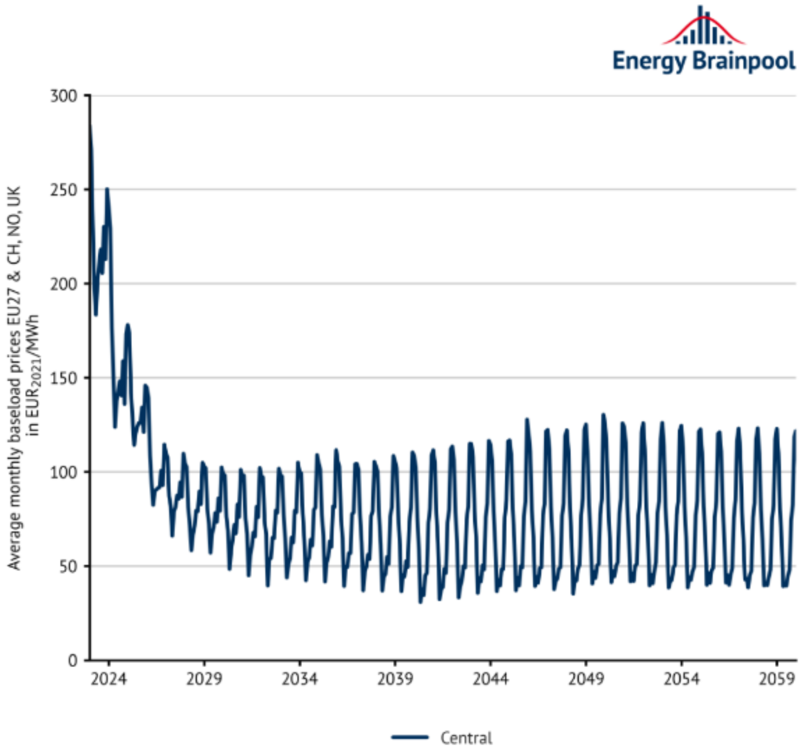


Figure 20: Monthly baseload prices on average

As it is possible to note from *Figure 20*, when examining power prices on a monthly basis, we can observe the expected seasonality and fluctuations inherent in the electricity market. During winter, prices tend to rise due to the heightened electricity demand driven by colder temperatures. Conversely, in summer, power prices typically experience a significant decrease. The growing presence of solar power generation further amplifies this trend.

Another relevant aspect that is possible to catch from *Figure 20* is that from 2026 the electricity price decreases abruptly and then remains constant at about 75/80 €/MWh; this information is confirmed also in [17] and reported in *Figure 21*, especially for Italy.

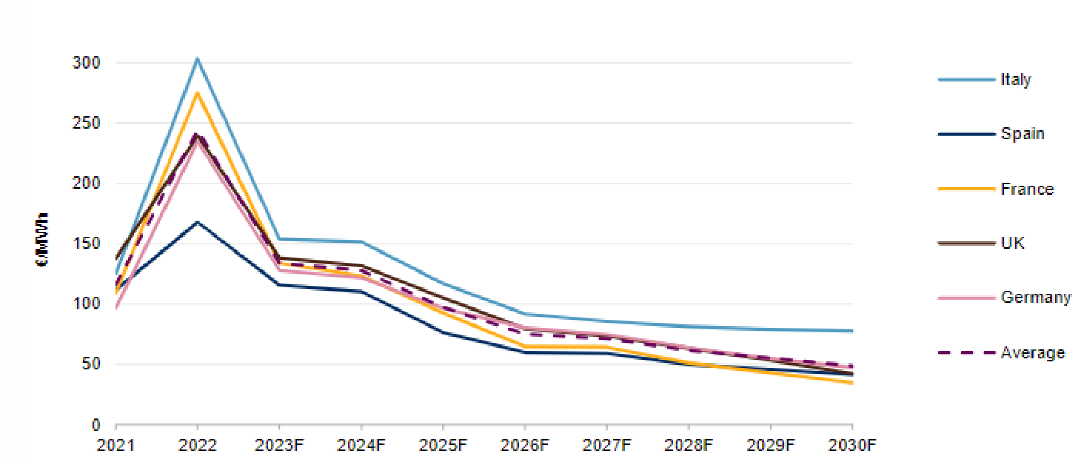


Figure 21: €/MWh forecast. Source: S&P Global Commodity Insights.

So, have information about the expected trend of the electricity is very important in order to make investments in the renewables, and what is possible to understand from the aspects shown above is that the RES will have a relevant position due to the increase of the electricity demand, but also the price trend must be taken into account to see when a project is profitable.

Due to this, Forgreen refers to EEX site to make their business plan.

3.3.1. EEX

European Energy Exchange, EEX, is a central European electric power and related commodities exchange located in Germany.

On EEX, electricity futures contracts are traded as purely financial products, without involving physical delivery of the energy. These contracts are related to different national markets, such as Italy, Germany and so on, referring to electricity market, while on the Ice Future and Pegas platforms, natural gas is traded, and physical delivery is typically the default option.

To initiate a transaction on these platforms, operators must interact with others who have expressed their intentions to buy or sell a specific product and quantity. Transactions are organized in a way that the displayed price reflects both the highest price at which someone is willing to buy and the lowest price at which someone is willing to sell. At the end of each day, the settlement price is published. This price acts as a reference for the various transactions that occurred during the day for each product. It is important to see these platforms because the future prices represents the best approximation of the weighted prices that could be verified in the future on the spot market.

Base

Future	Last Price	Last Volume	Settlement Price	Volume Exchange	Volume Trade Registration	Open Interest
Cal-24	147,00	8.784	146,99	202.032	895.968	5.248
Cal-25	-	-	127,56	0	113.880	854
Cal-26	-	-	101,62	-	-	104
Cal-27	-	-	86,15	-	-	15
Cal-28	-	-	82,63	-	-	6
Cal-29	-	-	80,88	-	-	5
Cal-30	-	-	79,63	-	-	5
Cal-31	-	-	78,70	-	-	5
Cal-32	-	-	77,94	-	-	5
Cal-33	-	-	76,95	-	-	5

Figure 22: EEX Italian Power Futures prices defined on 18/07/2023

As can be seen from *Figure 22*, on EEX it is possible to see the base power futures prices for the Italian electricity market until 2033 for the same day, in fact "Cal-33" means the called price for July 18th 2033.

An important thing to note, coherent to what said before, is that the reports [17] and [18] only describe what is shown on EEX platform. In fact the market expects a rapidly decrease of the electricity price in 2026 followed by a constant price at about 75/80 €/MWh.

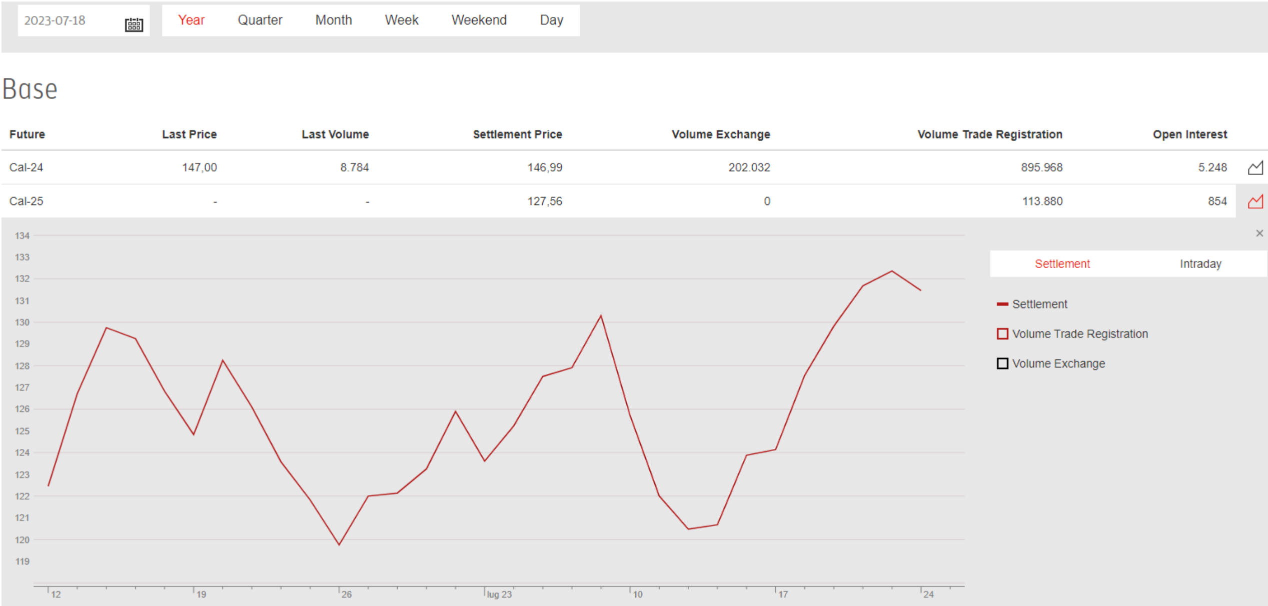


Figure 23: Base future power price trend for Call-25 on 18/07/2023 [26]

In particular, *Figure 23* represents the trend of the base electricity price expected on 18/07/2023 for 18/07/2025. Obviously is only an expectation, does not represent exactly the real price for that day and in that specific hour, but gives information of the possible trend.

3.4. Grid parity

For what concern the PV plant of this thesis, the purpose is to not receive any incentive from the sale of the electric energy not self-consumed, this due to the fact that could be a problem connect two production energy systems, one of the PV and one of Telezip, to the same point of delivery (POD), which is the geographical point of exchange of electricity.

In fact, connecting the two plants at the same POD, it could be very difficult to know from where comes the production of electric energy, if from the PV plant or the cogenerators, making difficult to quantify the energy fed into the grid to be incentivised. For this reason, it is better to project the PV plant in order to be feasible and convenient in grid parity, which means that all the energy produced by the PV is sold to the grid, or SEU, *Sistema Efficiente di Utenza,* which means that the energy produced by the PV is mainly used for self-consumption and the rest is sold to the grid. Be recognised as SEU gives the possibility to not pay the network charges of transmission and distribution on the self-consumed energy.

As explained in "*A bibliometric review of grid parity, energy transition and electricity cost research for sustainable development"* [19], the concept of grid parity lacks a single universal definition. In general, grid parity refers to the point at which the price of electricity generated from a renewable energy source, such a PV system, is equal to or lower than electricity produced by conventional grids. Another perspective of grid parity is when the cost of generating one kWh of renewable energy becomes equivalent to the cost of generating a kWh of electricity from the grid. Grid parity can also be seen as the stage where an alternative energy source can produce power at a Levelized Cost of Electricity (LCOE) that is less than or equal to the cost of obtaining power from the traditional power grid. The primary objective of achieving grid parity involves reducing the cost of the alternative energy generation source to enable it to compete effectively with conventionally supplied grid electricity.

Instead, for what concerns the SEU definition, it can be used the one given by the GSE, *Gestore Servizi Energetici,* in which it is defined as a system characterised by the presence of at least one power generation facilities, that uses renewable energy sources or operates in a highly efficient cogeneration mode, CAR, and one consumption unit managed by the same operator, which may be distinct from the end user. These facilities are directly linked to the consumption unit of a sole end user through a private connection, without the requirement to connect to external parties, and connected, directly or indirectly, via at least one connection point to the public network [20].

In conclusion, after have sized the plant in order to achieve the configurations mentioned before, it is possible to say that the energy produced by the PV will be remunerated at the Zonal PUN, in particular with the Nord Zone one.

However, inside this work and according to the business plan guidelines of ForGreen SpA SB, the simulation projects considered will have to be profitable even in case of electricity price close to 75/80 €/MWh for the entire life cycle.

4. PRELIMINARY SIZING OF THE PV PLANT

Now it is finally possible to talk of the main topic of this work: the realization of the photovoltaic plant project, useful to Telezip, for the motivations already explained.

The aim of this chapter is to analyze the site where the plant will be located, since the sizing and the dimensioning depend on the location and on the characteristics of the installation site. It is also necessary to give information about the technical data of the module, inverter, battery and the mode of use of the configurator used in the simulations.

4.1. Site analysis

The first important step when talking about a photovoltaic project is to define the characteristics of the site. The industrial establishment, where the PV plant will be placed, is located in the industrial agricultural area of Padua, next to Telezip, and it is constituted by a single structure totally covered by a flat groundwater.

The total area is about 15000 m^2, but cannot be entirely used, since there are some skylights, which divide the roof in several sectors, and also the entrance of the parking lot, due to the fact that this space is exploited as parking. In any case, even if the total area cannot be exploited, there will not be problems of space for the sizes considered for the photovoltaic plant.

Another important information is the azimuth angle of the building, that is the angle between the module horizontal orientation placed on the roof and the South, which in this case is 21°, therefore it means that the building and, consequently, the modules are oriented towards South-West.

Figure 24: South view from above

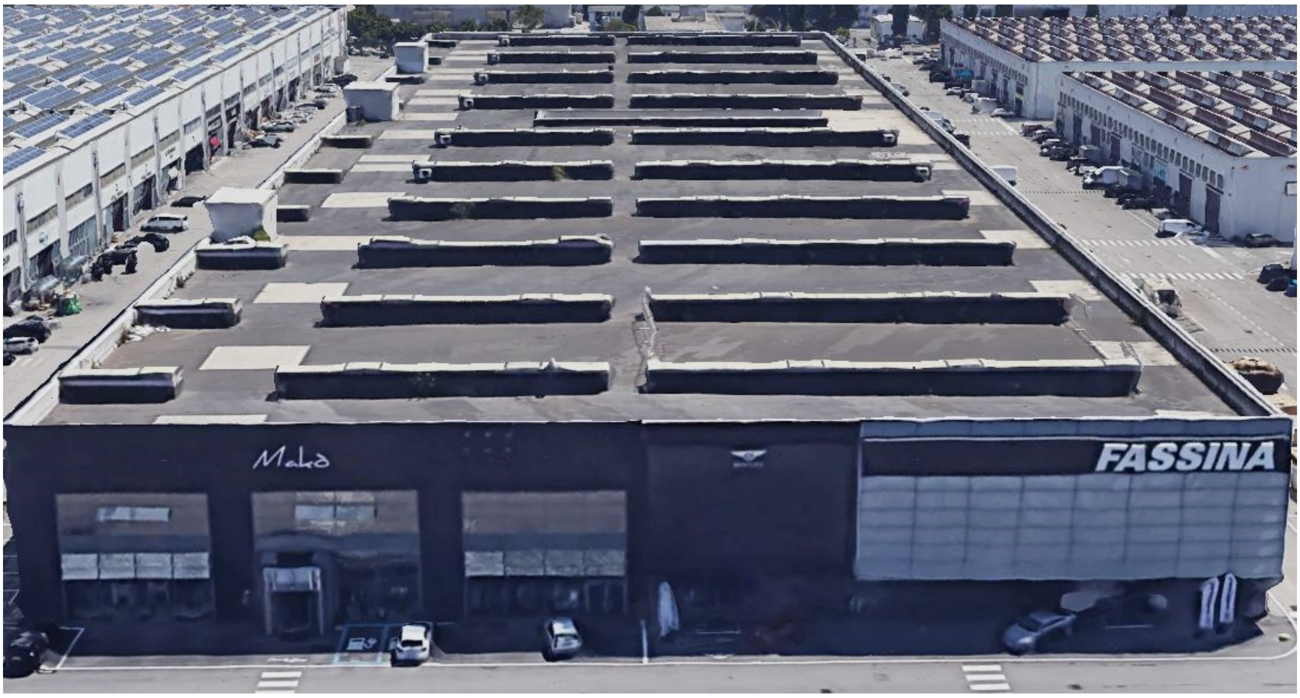


Figure 25: Lateral view of the building from West, with focus on heigth of skylights

Figure 26: View from above

The views reported above are important for the general comprehension of the sizing of the structure. For the optimization of the project, the modules will be located starting from the right side of the roof, since the space between two consecutive skylights is greater and so more area can be effectively exploited.

Another aspect to take into account, is the height of the skylights, which can reduce the available area. In fact, as it can be seen from *Figure 25*, these objects are very tall, about 1,5 m. Therefore, the modules will be appropriately far from them to avoid possible shadings.

Last but not least, the inclination of the modules, which in this case is 15°, and their positioning, which will be the "landscape" mode one, so with the long side resting on the structure.

Although at these latitudes the optimal tilt is around 30°, the lower angle is dictated by the desire to occupy as much area as possible without having to space out the rows of modules too far apart. As far as the use of the landscape position is concerned, the reason is that with the horizontal module it is possible to obtain more power for each space between two successive skylights.

In fact, in the case of the vertical position, the number of possible rows in a sector is lower due to the greater spacing required, although there are more modules for each row, as can be seen in *Table 6.*

Module position	Number of rows	Modules per rows	Power of single module [Wp]	Installed power per area [kWp]
Horizontal	35	8	550	154
Vertical	18	13	550	128,7

Table 6: Calculation of the max available installed power per area

At the end of this preliminary analysis, taking into account all the assumptions mentioned above, the performance index obtained is about 1200 kWh/kWp. As explained in previous chapter, this index represents the producibility of the plant and, in particular, how much energy 1 kWp installed produces under the conditions considered.

However, this value is in line with the usual producibility achievable with a PV plant located in North Italy and oriented towards South.

4.2. Datasheets

4.2.1. Photovoltaic module

For what concern the typology of module chosen for this project, it has been opted for the model Tiger Pro of the manufacturer Jinko Solar. The choice is dictated by the fact that modules of Jinko Solar are often used by ForGreen company inside its new PV plant projects, but also inside revamping of old ones. Other important aspects, that add value to this choice, are the fact that, historically, modules of Jinko Solar have never had problems of hotspots, as, instead, it happened to modules of other manufacturers, as shown in *Figure 27*, and their real annual degradation is lower than what expected by the datasheet.

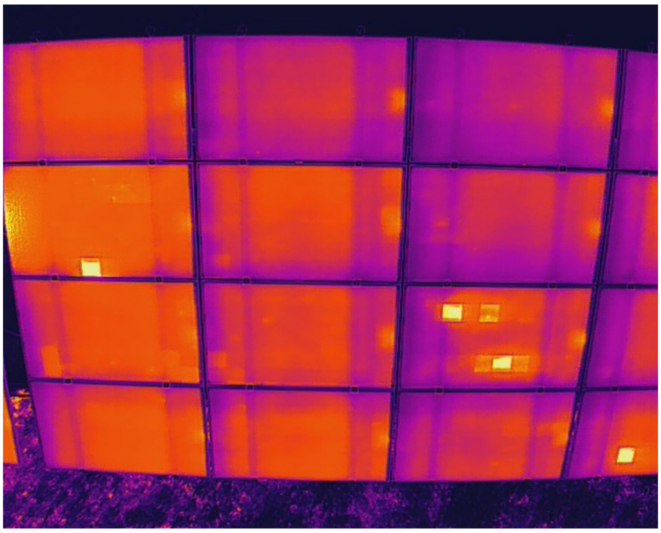


Figure 27: Archive imagine of X Group modules with hotspots found inside a PV plant in Puglia

As can be noted from *Table 7*, this type of module is divided into two parts and, for this reason, it is also called “Half-cut”. This has been chosen due to several advantages:

- reduced shading losses;
- lower resistive losses;
- improved temperature performance;
- enhanced durability;
- improved bypass diode operation;
- potential higher power ratings.

Below, the technical datasheet of the chosen PV module are reported and are referred to STC:

JINKO SOLAR TIGER PRO 72 HC 550 W_P	
Peak Power [W_p]	550
Power Tolerance [%]	0/+3%
V_{mpp} [V]	40.9
I_{mpp} [A]	13.45
V_{oc} [V]	49.62
I_{sc} [A]	14.03
Efficiency STC [%]	21.33
Cells disposition	144 (6x24)
Module dimensions [mm]	2274x1134x35
Area [m²]	2.58
Weight [kg]	28.9
Operating Temperature [°C]	-40°C/+85°C
P_m Thermal Coefficient [%/°C]	-0.35%/°C
I_{sc} Thermal Coefficient [%/°C]	-0.28%/°C
V_{oc} Thermal Coefficient [%/°C]	-0.048%/°C

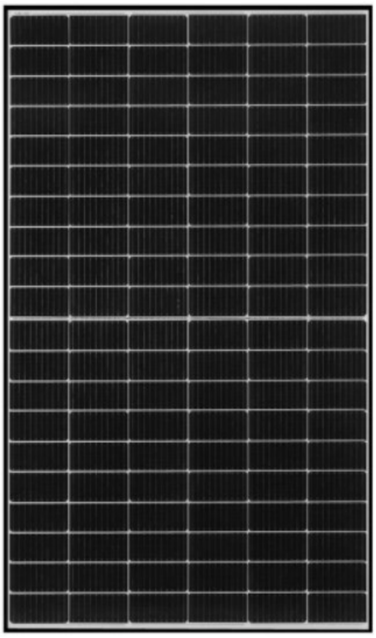


Table 7: Photovoltaic module Jinko Solar Tiger Pro [20]

4.2.2. Inverter

ZCS AZZURRO 3PH 100KTL-V4	
Input data DC	
DC Nominal Power [W]	120000
Nr. Independent MPPT/Nr. strings per MPPT	10/2
Maximum input DC voltage [V]	1100
Activation voltage [V]	200
Nominal input DC voltage [V]	625
DC voltage range at maximum load [V]	500-850
Maximum input current per MPPT [A]	40
Output data AC	
AC Nominal Power [kW]	100
Nominal Net Frequency [Hz]	50
Maximum Efficiency [%]	98.6
EURO Efficiency [%]	98.3
Temperature working range [°C]	-30/+60

Table 8: Inverter ZCS 3PH 100KTL-V4 [21]

The 100 kW inverter has been opted because facilitates to design the connections between the strings, thanks to the possibility of having 10 independent MPPT, and to always use the same type for each simulation. With 10 MPPT, the different strings can operate separately without affecting the behavior of the whole system in the presence of shadings.

4.2.3. Battery

SOLAREDGE HOME BATTERY 48V		
Usable energy [kWh]	4,6	
Continuous output power [kW]	5	
Peak roundtrip efficiency (DoD) [%]	>94,5	
Voltage range [V]	44,8 - 56,5	
Module of battery per Inverter	Up to 5 connected in parallel	
Dimensions [mm]	540 x 500 x 240	

Table 9: Data sheet of the battery of Solar Edge [22]

The accumulation system used in the simulations is the one offered by SolarEdge, which included three racks of 23 kWh each one and, in turn, it is composed by 5 batteries of 4,6 kWh of usable energy connected in parallel.

4.3. Array-inverter matching

For the purposes of the project, it is necessary to realize the matching between the array and the inverter, respecting the current and voltage limits imposed by the inverter, in order to maximize the number of modules for each string. It is also very important to design each string of modules as equal as possible, to do not have problems of superheating or mismatch losses between different strings.

The lacing chosen for this project, according to the limitations and using the photovoltaic module reported before, is the following:

- nr. 10 of strings;
- nr. 18 modules for each string;
- 9,9 kW of power for each string;
- 99 kW of total power for each inverter;

in this way, there are 180 modules for each inverter and no one is overstressed.

The optimal configuration obtained has followed these relations:

$$V_{min}(T_{\max}) > V_{\min\ \_inverter}$$

$$V_{max}(T_{\min}) < V_{\max\ \_inverter}$$

$$V_{OC\_string}(T_{\min}) < V_{\mathrm{DC}\ \_inverter}$$

$$I_{SC}(T_{\max}) < I_{\mathrm{DC}\ \_inverter}$$

As can be noted from the following table, all the limits are respected:

PHOTOVOLTAIC ARRAY OF EACH INVERTER	
Nr total of module	180
Nr of module for string	18
Nr of strings	10
Peak power [kW]	99
V_{oc} max for strings at min temperature [V]	969,44
V_{oc} min for strings at max temperature [V]	798,18
I_{sc} at max temperature [A]	14,29
I_{mp} at max temperature [A]	13,69

Table 10: Photovoltaic array of each inverter and limitations followed (Appendix A)

4.4. ZCS and Solar Edge Designer software

For what concerns the carrying out of the simulations, ZCS Software and Solar Edge Designer were used, which are software developed by the homonymous inverter and battery production company, respectively.

The software require a series of preliminary information to allow the user to dimension the photovoltaic plant. As results, they provide the annual self-consumed, sold and produced energy, hour by hour, by the PV, which they will be used for the energetic and economic analysis.

The reports issued by the software, relating to the reference case of a 500 kWp PV plant at year 0, can be found in Appendix A, for the ZCS Software, and B, for the Solar Edge Designer.

4.4.1. Layout

In order to start the dimensioning of the plant, the inputs required are:

- location of the plant: Corso Stati Uniti, 1, Padova (PD);
- weather data, imported from Meteonorm;
- hourly annual load profile of the user;
- possible obstacles present around the area of relevance;

- delimitation of the roof borders.

It is, then, possible to define the type of modules used, their inclination and orientation and how and where they should be positioned. Inside Solar Edge Designer software, it is also present a very useful tool for the correct implementation of the plant: the irradiance map.

In fact, inserting some obstacles and their relative height, the program develops a heat mapping, which graphically represents the intensity of the irradiance received by the surface respect to the irradiance arrived on that, in case of no obstacles.

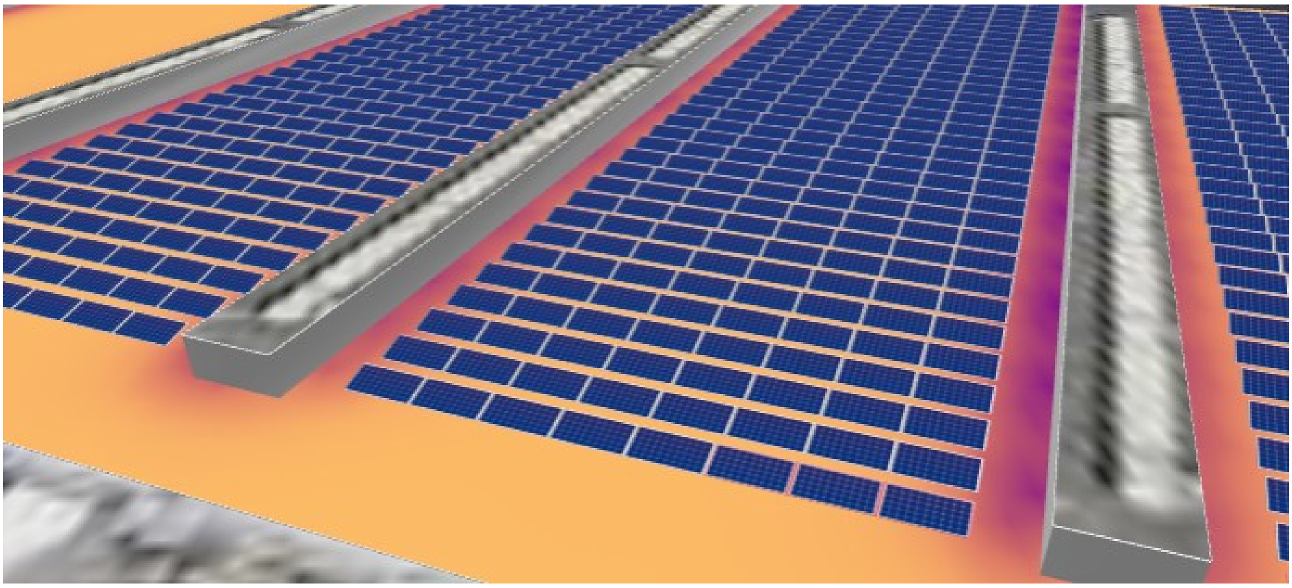


Figure 28: View of the heating map from South (Appendix B)

As can be seen from *Figure 28*, the area around the skylights is colored violet, instead of yellow, since they produce a shadow, therefore the modules were positioned far from them in order to do not penalize the production. In addition, the rows of modules do not start from the lower border of the roof, since it also produces an important shadow, due to its height of 2 meters.

To calculate the appropriate distances, it is necessary to know the height of the skylights, or border, and the angle, α_{max}, created by the sun and the horizontal surface on the worst culmination of the year, which happens on the winter solstice, 22nd of December.

Just to know, the culmination represents the instant of time of the transit of the sun across the observer's local meridian.

The culmination on winter solstice is obtain through:

$$\alpha_{max} = 90° - \varphi + \delta \ \ [°]$$

where:

- α_{max}, maximum solar height angle;
- φ, latitude of the location;
- δ, declination angle, which is the angle between the equator and a line drawn from the center of the Earth to the center of the Sun and equal to - 23,45°;

while the distance between two consecutive modules rows is calculated from:

$$d = L - h\left(\cos\beta + \frac{\sin\beta}{tg\alpha_{max}}\right) \ \ [m]$$

where:

- d, distance between the projection of the module and the consecutive row;
- L, distance between the starting point of two consecutive rows of module;
- h, length of the module;
- β, inclination of the module;
- α_{max}, maximum solar height during the winter solstice.

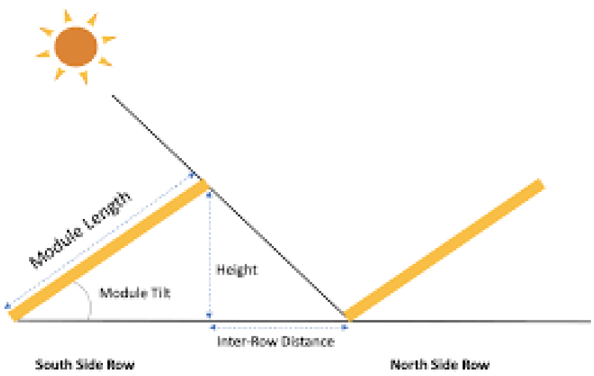


Figure 29: Representation of the calculation mode of the shadowing

From these calculations, it is obtained that two consecutive rows must to be distant 1,55 m each other, while the first row has to start 5,55 m far from the border, to do not have presence of shadow. Another important aspect to reduce the shading losses, it is to string the modules in such a way as to exclude the smallest number of strings from production. Since the shadow generated by the skylight affects only the firsts two/three modules of each row, it is better to create vertical strings that contain all these shaded modules. In this way, only the most shaded modules are excluded from the production, as shown in *Figure 30*.

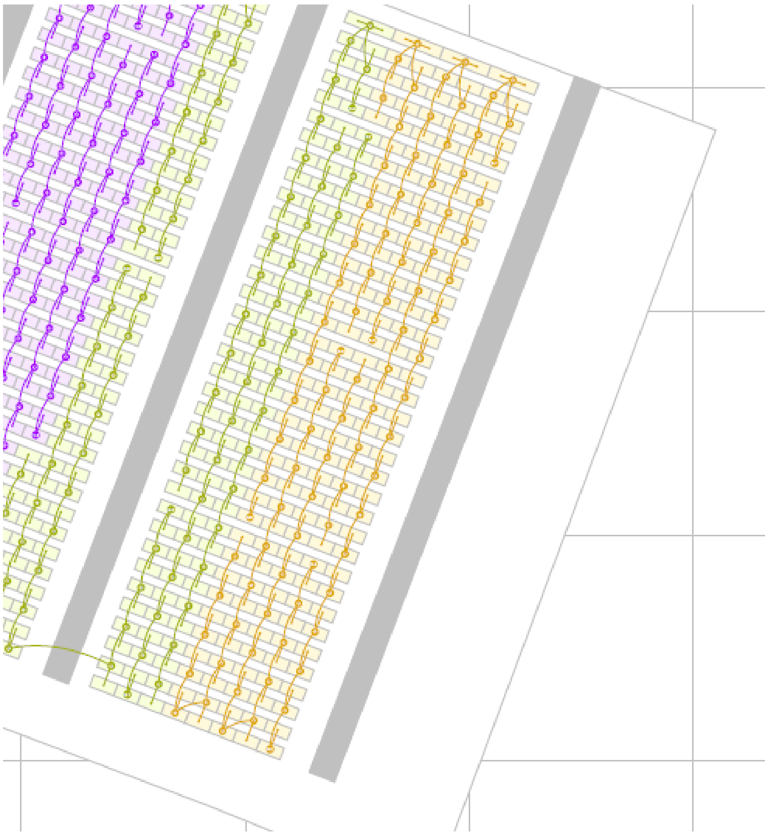


Figure 30: Detail of the vertical strings

4.4.2. Losses

Array losses include all the factors that lead to a reduction in the available power when compared to the nominal value of the module, as assessed by the manufacturer under standard conditions.

Also software used take into account a series of losses that affect the ideal efficiency, partially explained in a previous chapter and briefly reported here:

- shading losses: lead to a loss of radiation and therefore a loss of production;
- incident angle modifier (IAM): leads to a reduction in reflected light and, as a result, a decrease in the amount of irradiance that reaches the photovoltaic cells;

- MPPT efficiency losses: connected to the difference between the real conditions and the maximum power point;
- ohmic losses: referred to cables both in direct or alternative current, which are based on their section and length;
- LID losses: difficult to estimate for each module since it depends on the origin of the silicon wafers;
- dirt;
- aging losses: for our simulations is set equal to -0,55%/year, taken from the datasheet of the module, even if is a precautionary value since from real monitoring is showed that the effect of the degradation losses is lower.

In the *Figure 31*, it is possible to see a sort of Sankey diagram, in which are shown the losses considered and their effect on the energy reduction:

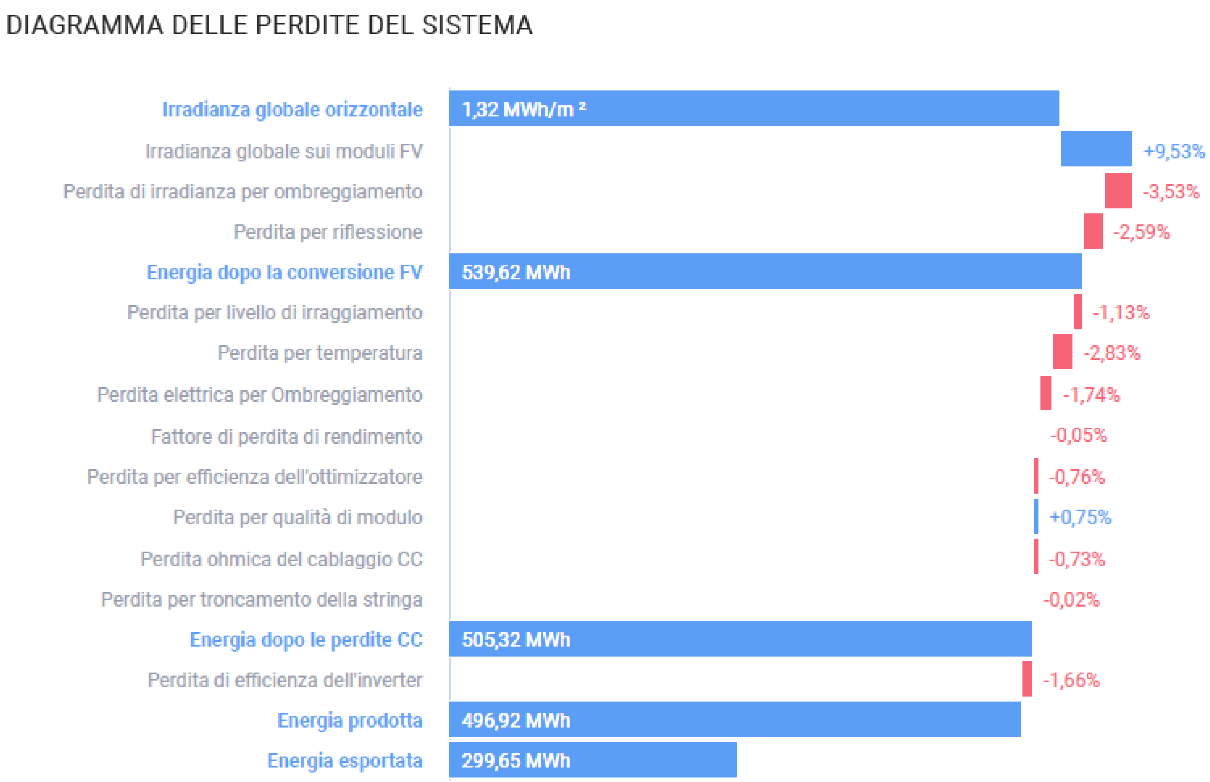


Figure 31: Diagram of the losses from Solar Edge Designer report (Appendix B)

After this introduction of how the software work, it is possible to start to show how the energetic and the economic analysis were carried out.

5. ENERGETIC ANALYSIS

In this chapter, it is shown the process behind the simulations for the energetic analysis, exploiting the two software mentioned before, which they work similarly but it was important to use both to have reliable data. In any case, these software were used only to develop and give back the self-consumption and the energy sold to the grid over the life cycle, while the data analysis and the comparison between the several simulations were done without using them.

For what concerns the scope of this chapter, the focus will be on the electric consumption, in order to give the possibility to the PV power plant to be fully exploited.

5.1. Input

The first important input to must have to carry out an energetic analysis is the annual load profile of the user, better if it is divided per hour. From it, in fact, it is possible to obtain useful information such as, for example, when is the main consumption period, what is the maximum annual peak power required or what is the daily trend of the energy consumed and how it changes according to the seasons.

Thankfully, these hourly data are available, since are registered from the programmable logic controller, PLC, on a .csv file, and they are communicated directly from the tax counter located inside the MT cabin outside the plant.

The current situation of the electric consumption load profile is the following reported in *Figure 32* and *Table 11*:

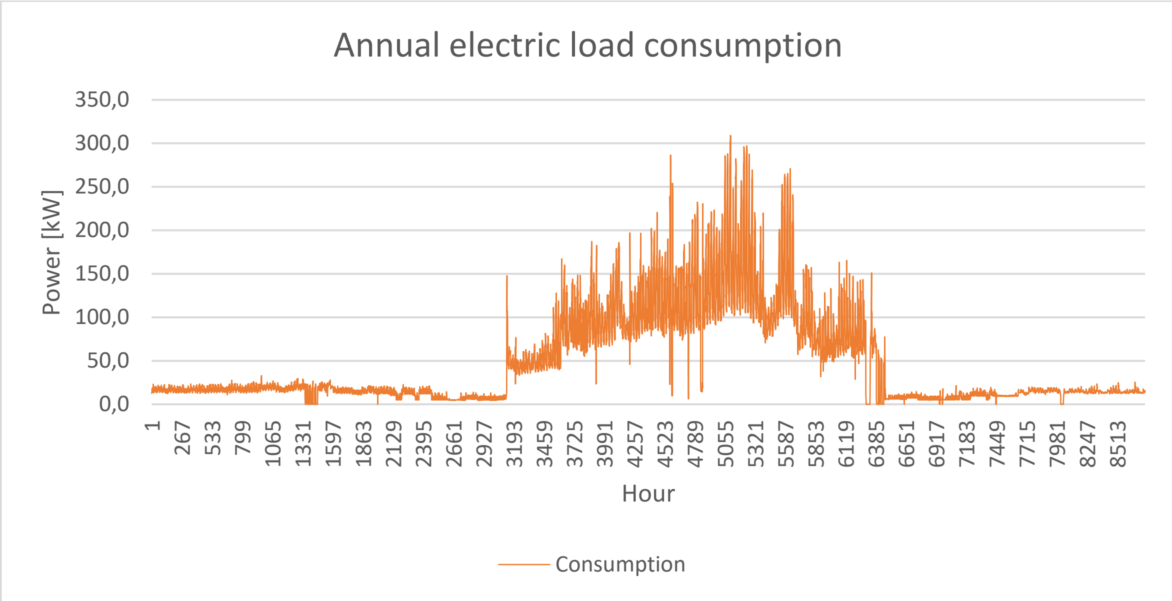


Figure 32: Annual electric load consumption trend of Telezip

MONTH	CONSUMPTION [kWh]	DAILY MEAN CONSUMPTION [kWh]
JANUARY	12715	410
FEBRUARY	12161	435
MARCH	11701	377
APRIL	6615	220
MAY	28377	915
JUNE	72141	2405
JULY	96290	3106
AUGUST	101946	3289
SEPTEMBER	43436	1498
OCTOBER	5556	185
NOVEMBER	9219	307
DECEMBER	10762	348
TOT	**410918**	

Table 11: Electrical annual consumption of Telezip

As shown above, the main electric consumption occurs during the summer period, when the chiller, with a nominal power of 300 kW, works to provide fresh water to shops and offices. Instead, during April and October, the consumption is relatively low because the plant is switched off to perform all the necessary maintenance; while, during the winter period, the electric consumption comes mainly from the energy consumed by the pumps, for water recirculation, and by the fan, used inside the combustion chamber of the boilers.

Still from *Figure 32*, it is possible to note that the maximum power required is 300 kW, according to the size of the chiller, even if it is not a common value, since the plant is currently underexploited. In the graph, some collapses of power are also present, that occur in the middle of the summer period, and that could be explained by power failures.

Another important aspect could be to see how the electric consumption is spread during a typical day in the month of August, where there are the highest peaks.

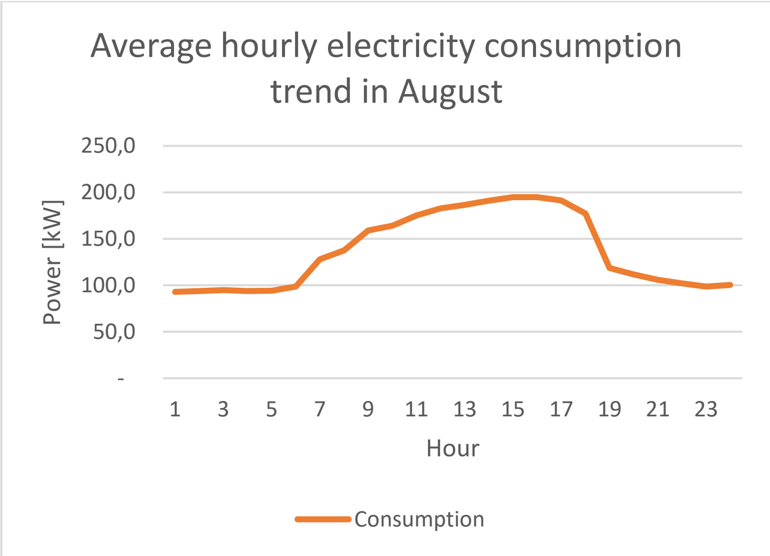


Figure 33: Average hourly electricity consumption trend in August

Figure 33 represents the average hourly electricity consumption trend in August. Knowing that the energy consumption of Telezip is directly dependent on the use of the service by its customers, it can be seen from the graph that the district cooling service is used from the 7 am up to 6 pm. In fact, most of the area supplied is made up of shops and offices, therefore there is not exceptional energy consumption outside that time slot, such as during the night or at weekends.

If, instead, the typical average hourly electricity consumption trend is taken in December, other considerations can be made.

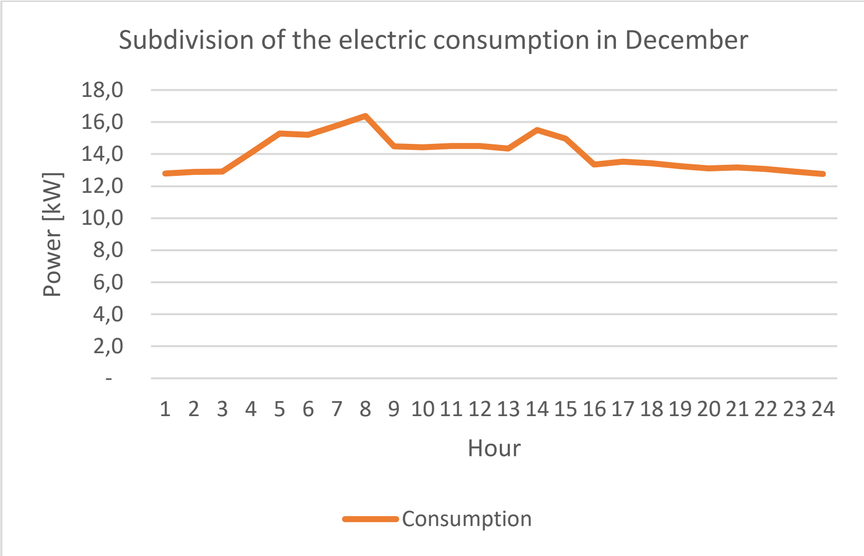


Figure 34: Typical average hourly electricity consumption trend in December

In fact, from *Figure 34*, it is possible to note that, in this case, the energy consumed is much lower compared before, the bell is no more present, because the chiller is switched off and only the boilers work, and small variations are present at 4 am and at 2 pm. These last ones could be explained by the ignitions of the combustion chambers to restore a set temperature value.

However, inside the energetic analysis, the annual load profile was supposed to increase by 1,59% every year, also equal to 10% every five years, over the entire life cycle of the PV plant. This incrementation is dictated by the knowledge of the potential of this plant from the point of view of thermal energy production. Therefore, the purpose was to stress, as much as possible, a plausible PV plant, supposing that, over the years, with the decrease of the energy costs and with a possible incrementation of the customers, the annual electric consumption could undergo a major increase.

In fact, annual electric consumption was supposed to increase from about 411 MWh, in year 0, to about 662 MWh, in year 25, which represents a growth of 61% from the beginning.

The increase in load profile is considered equal for all the months, even during outside summer period. This because, if there is an incrementation of the customers and consequently an increase in consumption, recirculation pumps and other auxiliary electric systems have to work more than now for all the year, in order to provide also the heating district service.

The variation is shown in the following figure:

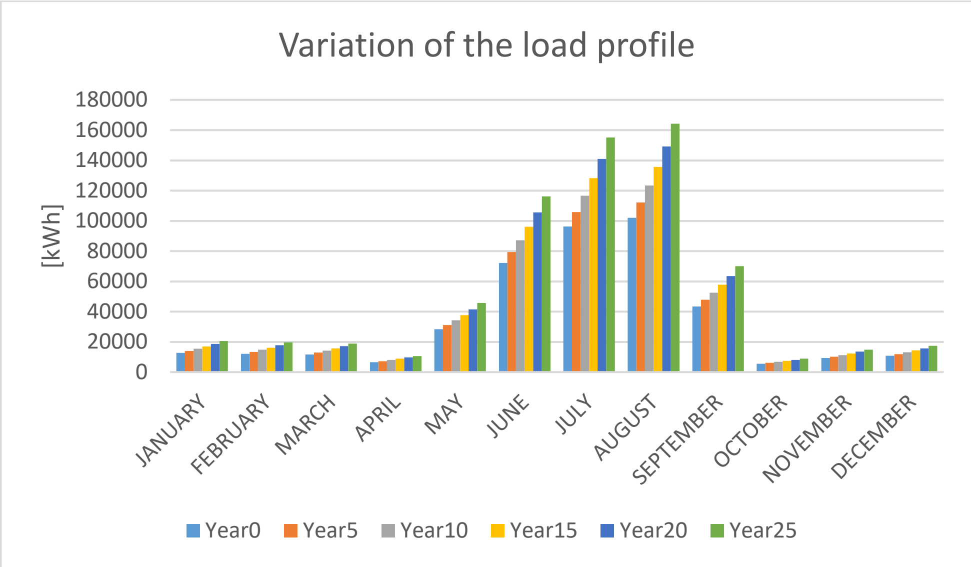


Figure 35: Monthly variation along the years of the electrical consumption

After having defined the consumption, it is necessary to illustrate also the production that will be generated from the photovoltaic plant.

Given the location, Corso Stati Uniti (PD), a module inclination of 15° and an azimuth angle of 21°, any PV plant of any size, placed on the roof considered, gives a producibility index of 1242 kWh/kWp, as reported in *Table 12*, in which the monthly energy production for 495 kWp PV plant is shown.

DATA FROM ZCS CONFIGURATOR				
Month	Output energy PV [kWh]	PR [%]	Producibility [kWh/kWp]	Power installed [kWp]
JANUARY	24 589	92,4	1242,3	495
FEBRUARY	30 355	92,7		
MARCH	53 576	91,7		
APRIL	63 523	90,4		
MAY	75 893	89,1		
JUNE	79 193	87,6		
JULY	82 960	86,8		
AUGUST	73 119	86,6		
SEPTEMBER	53 928	88,7		
OCTOBER	37 608	90,3		
NOVEMBER	23 080	90,7		
DECEMBER	18 537	91,1		
TOT	**616 361**			

Table 12: Monthly energy production of 495 kWp installed

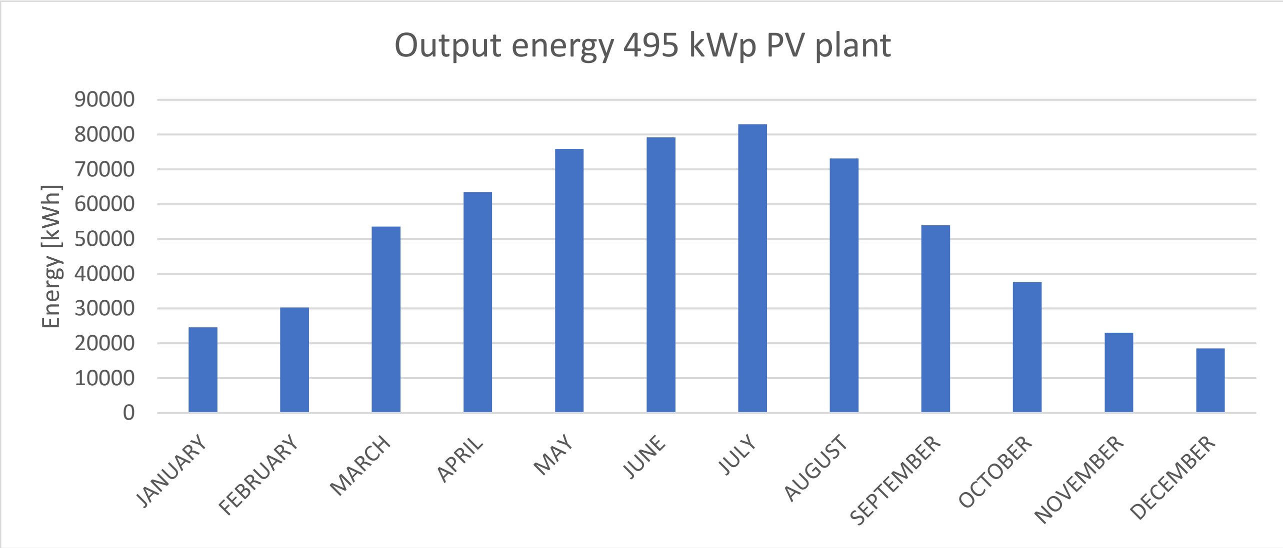


Figure 36: Monthly energy production trend for 495 kWp installed

Also in this case, some considerations were made to perform a more realistic analysis. In fact, in addition to the shadowing taken into account by the software, the degradation of the modules over the years was evaluated. As reported in the previous chapter, a degradation of – 0,55% of the nominal power per year was considered, as suggested by the module datasheet [20].

As can be seen in *Table 13*, the degradation is not negligible after 25 years of life of the module. In fact, at the last year, the nominal power is decreased by the 15% respect to the first year.

This aspect is more relevant when considering large power PV plants, as in this case. This is why some revamping of modules along the life cycle are often considered.

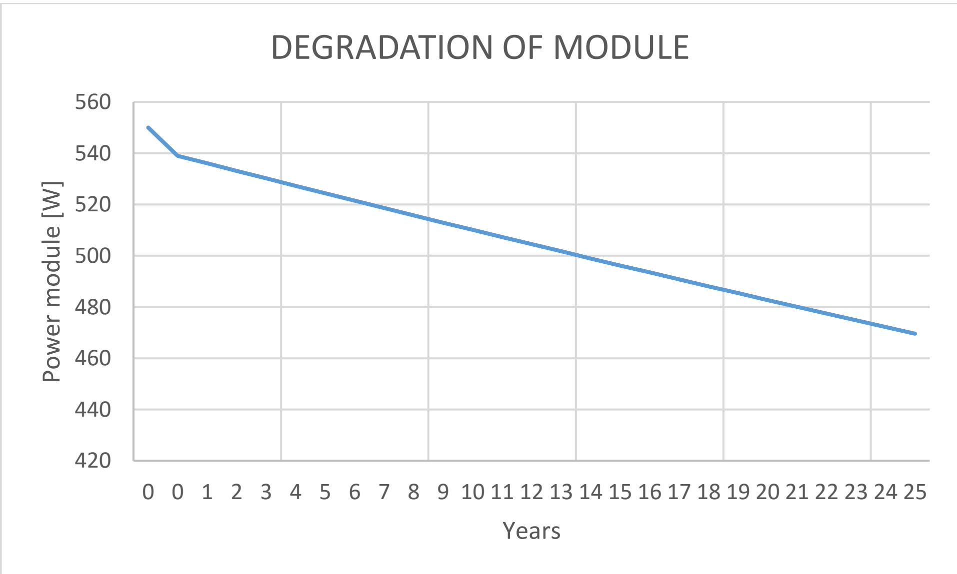


Figure 37: Degradation trend of the module Jinko Solar Tiger Pro 72HC 550W

DEGRADATION OF MODULE			
YEARS	% OF POWER	1-DEGRADATION	POWER MODULE [W]
0	100%	100%	550
0	98,00%	99,45%	539
1	97,46%	99,45%	536
2	96,92%	99,45%	533
3	96,39%	99,45%	530
4	95,86%	99,45%	527
5	95,33%	99,45%	524
6	94,81%	99,45%	521
7	94,29%	99,45%	519
8	93,77%	99,45%	516
9	93,25%	99,45%	513
10	92,74%	99,45%	510
11	92,23%	99,45%	507
12	91,72%	99,45%	504
13	91,22%	99,45%	502
14	90,72%	99,45%	499
15	90,22%	99,45%	496
16	89,72%	99,45%	493
17	89,23%	99,45%	491
18	88,74%	99,45%	488
19	88,25%	99,45%	485
20	87,77%	99,45%	483
21	87,28%	99,45%	480
22	86,80%	99,45%	477
23	86,32%	99,45%	475
24	85,85%	99,45%	472
25	85,38%		470

Table 13: Degradation along 25 years of the Jinko Solar module Tiger Pro 72HC 550 W

Instead, the variation in the monthly energy produced over 25 years is shown below:

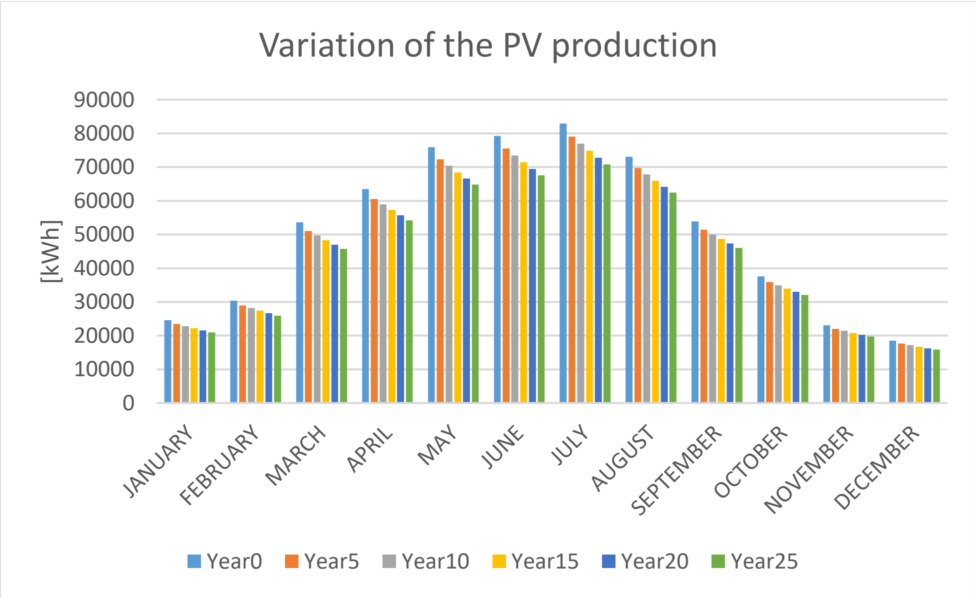


Figure 38: Variation of the PV production trend

Using historical weather data, the software also take into account the possibility of cloudy days, in which energy production is reduced, as shown in *Figure 39*.

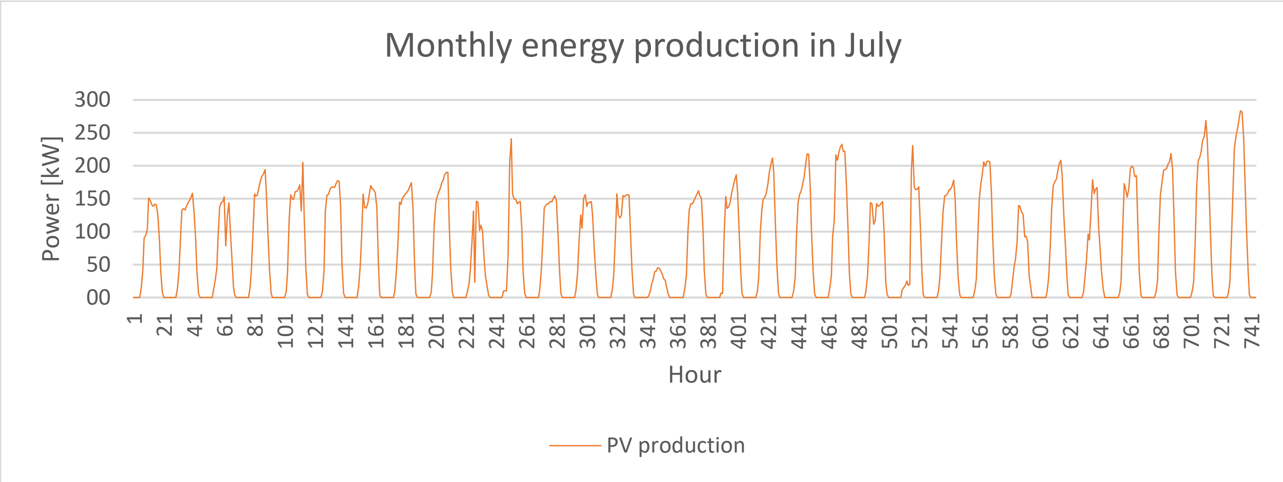


Figure 39: Monthly energy production in July of PV power plant of 400 kWp

As can be seen from *Figure 39*, despite the summer period under consideration, the bells are not perfect every day but, on the contrary, there are several oscillations due to clouds. This aspect makes the energy analysis even more trustworthy.

Before starting with the simulations, it is important to say that this electricity consumption study was done assuming only a constant increase in load consumption, because it would have been difficult, if not impossible, to try to change the usual consumption pattern of the district heating and cooling plant. In fact, its consumption strictly depends on that of its customers and, therefore, it would not have been reliable to predict one, all the more so considering that it could change from year to year.

5.2. Simulations

In this work, power sizes of the PV plant from 100 kWp to 800 kWp were considered.

The reason for this interval was that the aim was to test which type of power size best suited the energy demand of Telezip and, to do this, it was necessary to cover approximately all possible powers.

Certainly, for a given trigenerative district heating plant, supplying thermal energy to 87000 m^2, a larger PV plant is better, since it is energy-intensive, but it is not obvious that is also the same from an economic point of view. For this reason, PV plant of 1 MWp or more were not considered.

Another aspect that discouraged the consideration of larger PV power plant size was the fact that covering entirely the roof could be a problem, since it would then be impossible to use it as a car parking and thinking about creating shelters was too expensive. The cost of them, in fact, could have created a problem and made the business plan unsustainable.

In any case, the smartest way to exploit this type of PV project is to seek maximization of self-consumption, as this is the most profitable energy from the PV itself, and also because the purpose of renewable energy plants is to improve the simultaneity of production with consumption.

For this reason, the next step, in the energetic analysis, will be to compare the self-consumption obtained with the different situations.

5.2.1. <u>Self-consumed Energy</u>

After indicating the power sizes of photovoltaic plant considered, it is necessary to study their performances from an energetic point of view, taking into account, as mentioned, the increase of the consumption of Telezip and the degradation of the modules over the years.

Using the software and annual electricity load consumption, it is possible to obtain the annual self-consumed energy for each PV power plant considered.

From *Figure 40*, which represents the comparison of the self-consumed energy obtainable for each PV plant considered in this work, for each year from 0 to 25, it is already possible to obtain some important information. In fact, if one focuses on the first two rows, representing the self-consumed energy of 100 kWp and 200 kWp PV plants, one can note that it decreases over the years. The detail of the decrease can be seen from *Table 14*. This is strange because it is logical to think that as load consumption increases, self-consumption also increases if an amount of energy produced by the PV is still available, whereas here the opposite is the case.

This behavior can be explained by the fact that the powers considered are small, compared to the power required by the Telezip plant, and so it is not possible to make good use of the energy produced by these PV plants. In fact, during high energy demand months, such as summer period, 100 kWp and 200 kWp give all the energy produced for the self-consumption purpose already at year 0. So, when an increase in consumption is present, these PV plants cannot satisfy even more the demand, since it is already saturated from their side.

In addition to that, module degradation also plays an important role. Not by accident, in these two examples, the negative effect of the degradation decreases slowly the self-consumption part year by year, deleting the positive effect of the increased consumption.

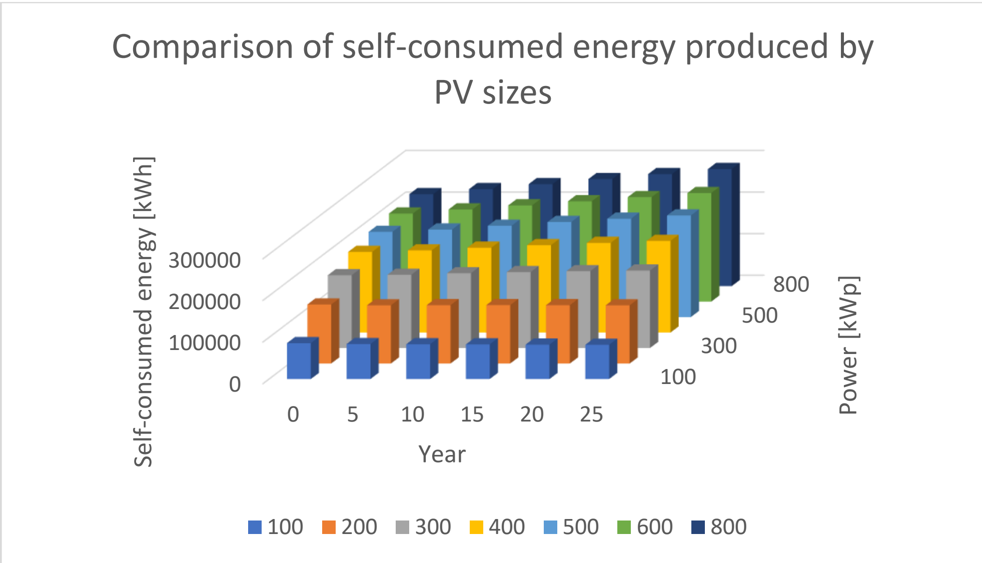


Figure 40: Comparison of energy production of PV sizes along the life cycle

SELF-CONSUMED ENERGY 0-25							
Power size	100 kWp	200 kWp	300 kWp	400 kWp	500 kWp	600 kWp	800 kWp
Year \ Energy	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	[kWh]
0	86169	141762	174923	193784	204632	211535	220904
5	84025	139849	175929	197435	210362	221389	232968
10	83572	140161	179718	203954	219503	231242	245031
15	83190	140352	182503	209973	228547	241096	257095
20	82658	140213	184680	215514	236395	250950	269158
25	82199	139768	186287	220177	244174	260803	281221

Table 14: Data of self-consumed energy for each PV power sizes

For what concerns the other power sizes, there is not so much to say, except that the self-consumed energy of 300 kWp remains approximately the same and that the ones of 600 kWp and 800 kWp, as forecastable, increase in a more pronounced manner.

Further skimming is possible if the percentage of the self-consumed energy is considered. This percentage represents the part share of self-consumed energy, coming exclusively from the PV plant, compared to the total energy required by the trigenerative plant. So for the specific case of 100 kWp at year 0, Telezip plant uses 21% of the energy coming from the PV plant and 79% of the energy coming from the grid to satisfy its electric energy demand.

To be precise, it is best to compare the percentage change in average self-consumed energy between the PV power sizes considered over 25 years. Obtaining this information can be important, as it provides a sensitivity to the self-consumed energy gain that a larger PV power plant can offer and thus whether or not it is worth adding more modules.

PERCENTAGE OF SELF-CONSUMED ENERGY							
YEAR	100 kWp	200 kWp	300 kWp	400 kWp	500 kWp	600 kWp	800 kWp
0	21,0%	34,5%	42,6%	47,2%	49,8%	51,5%	53,0%
5	18,6%	30,9%	38,9%	43,7%	46,5%	49,1%	51,0%
10	16,8%	28,2%	36,1%	41,0%	44,1%	46,7%	49,0%
15	15,2%	25,7%	33,4%	38,4%	41,8%	44,2%	46,6%
20	13,7%	23,3%	30,7%	35,8%	39,3%	41,8%	44,0%
25	12,4%	21,1%	28,1%	33,3%	36,9%	39,4%	42,0%
MEAN	**16,3%**	**27,3%**	**35,0%**	**39,9%**	**43,1%**	**45,4%**	**47,6%**

Table 15: Comparison of the percentage variation of the average self-consumed energy between the PV power sizes considered

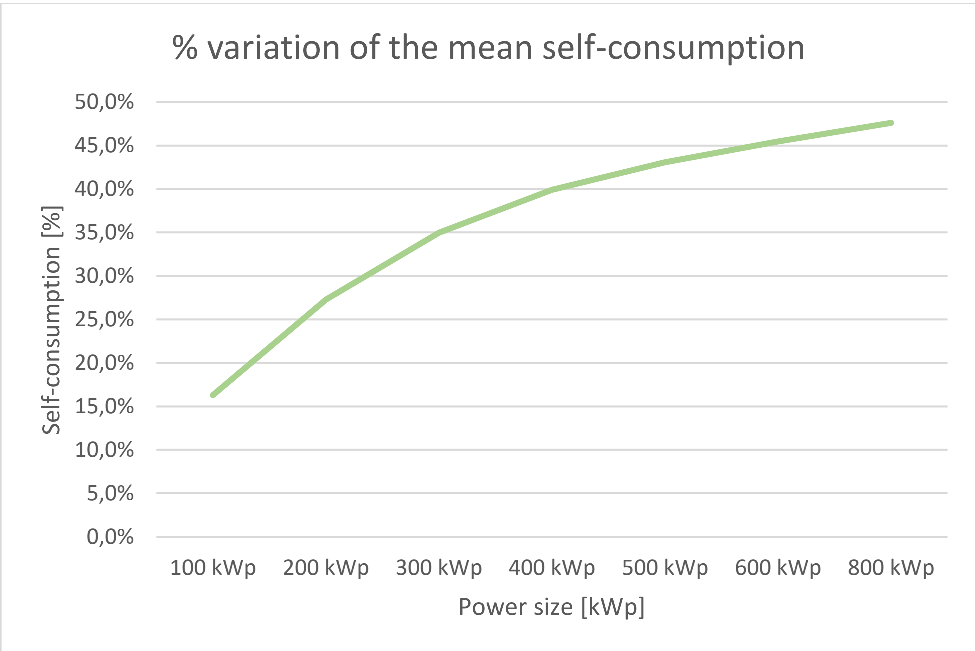


Figure 41: Trend of the increase of the self-consumed energy

As can be seen from *Table 15* and *Figure 41*, as the power size of the system increases, the slope of the curve tends to be flatter and flatter, so that there is no longer a significant gain in self-consumed energy. Therefore, it is possible to realize that, perhaps, it is not worth adding too much power for a small advantage, and this opinion will be endorsed and confirmed by the economic analysis.

So, at the end of these considered aspects, the best solutions from a self-consumption point of view seem to be the 400 kWp and 500 kWp PV power sizes.

Now, it could be interesting to compare these two solutions.

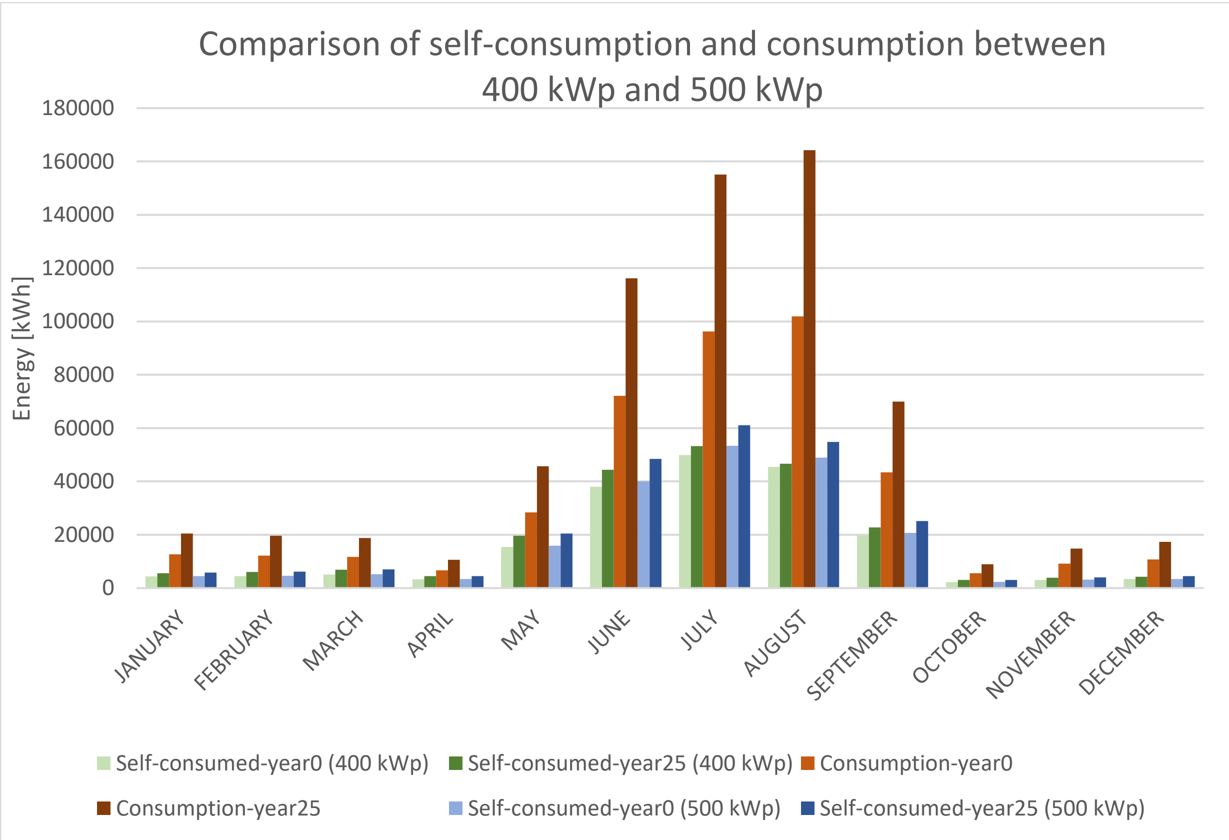


Figure 42: Comparison of self-consumption and consumption between 400 and 500 kWp

Figure 42 shows the comparison of the self-consumption versus consumption, between year 0 and 25, of the two best solutions.

As can be expected, the difference between the two solutions is more pronounced in the summer period, where the kWhs produced are more, whereas, in the rest of the year, the difference is very small. It is important to note that, although the annual bells of the PV production and Telezip consumption are very similar, most of the energy produced is not exploited and it is unfortunately sold to the net, as can be seen from the *Figure 43*, where the average energy performance of the 400 kWp PV plant is shown for the specific month of May. In fact, this situation occurs more often outside the summer period.

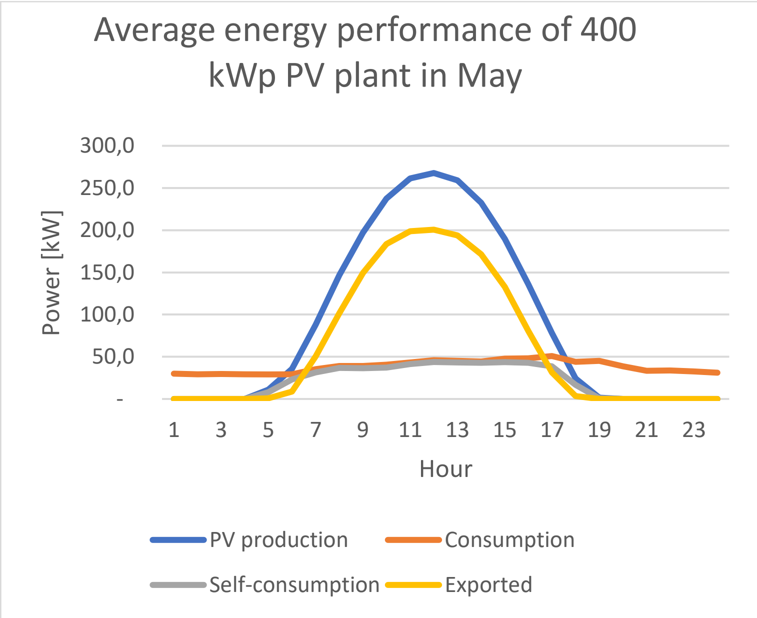


Figure 43: Average energy performance of 400 kWp PV plant in May at year 0

According to what said previously, the graph above shows clearly that the exported energy is the main part of the produced from the PV plant one, when the chiller is switched off.

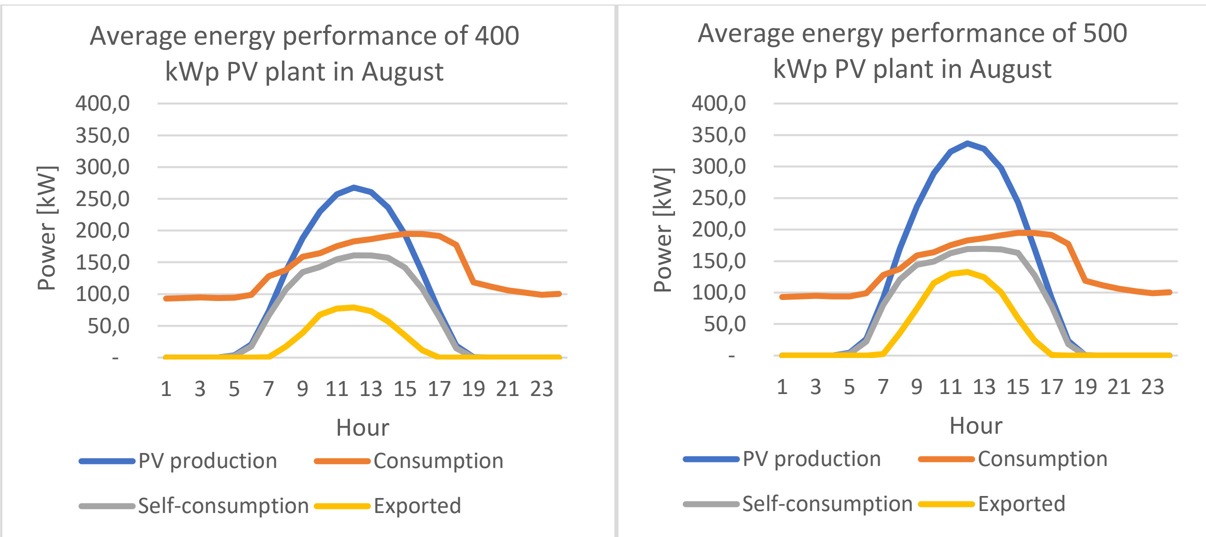


Figure 44: Average energy performance of 400 kWp (left) and 500 kWp (right) PV plants in August at year 0

However, *Figure 44* shows that the PV plant of 500 kWp has a better utilization of energy production. In fact, during the month of August, and similarly during the other summer months, the self-consumption curve is closer to the consumption curve.

In any case, as self-consumption is the highest remuneration system for the PV energy production, this is why simulations of 400 kWp and 500 kWp with a battery storage were carried out in order to increase it.

5.2.2. Simulations with battery storage

To carry out these simulations, an accumulation system of 69 kWh of energy storable is used. The storage system is subdivided into three racks of 23 kWh each one, which, in turn, contains 5 batteries connected in parallel of 4,6 kWh of energy available. The batteries are of the Solar Edge manufacturer, the same of the software used for the simulations.

Unfortunately, the software allows as maximum only three hybrid inverters connected to the same storage system and so, the configuration illustrated above was the only one to have the greatest accumulated energy.

Something interesting, that it is possible to note, is that during the non-summer nights the base load power consumption of Telezip, at year 0, is mostly constant at 30 kW or even lower, therefore the batteries could theoretically guarantee an autonomy of at least 2 hours after the sunset, if, at this precise moment, the batteries are totally charged. This base load value can be seen also from *Table 16*, where the average hourly consumptions of May and December, respectively, are shown.

MONTH	MAY	DECEMBER
HOURS	Consumption kW	Consumption kW
1	29,9	12,8
2	29,2	12,9
3	29,6	12,9
4	29,3	14,1
5	29,1	15,3
6	29,2	15,2
7	35,3	15,8
8	39,2	16,4
9	39,0	14,5
10	40,7	14,4
11	43,3	14,5
12	46,0	14,5
13	45,2	14,3
14	44,4	15,5
15	47,9	15,0
16	48,4	13,4
17	50,9	13,5
18	43,9	13,4
19	45,1	13,3
20	38,7	13,1
21	33,5	13,2
22	33,9	13,1
23	32,7	12,9
24	31,0	12,8

Table 16: Average hourly consumption of May and December of Telezip at year 0

It is important to specify that these simulations have not the aim to give back as result the best solution with storage, as wanted before, because now the intention is to see the difference between the same PV plant with and without accumulation system.

5.2.2.1. Simulation of 400 kWp with 69 kWh of storage

The first simulation is made on the PV plant of 400 kWp.

The following graphs illustrate the results obtained from the simulation and, in particular, *Figure 45* represents the comparison between self-consumption and consumption, at year 0 and 25, of the 400 kWp with battery storage, in order to see the behavior of the accumulation system during the year.

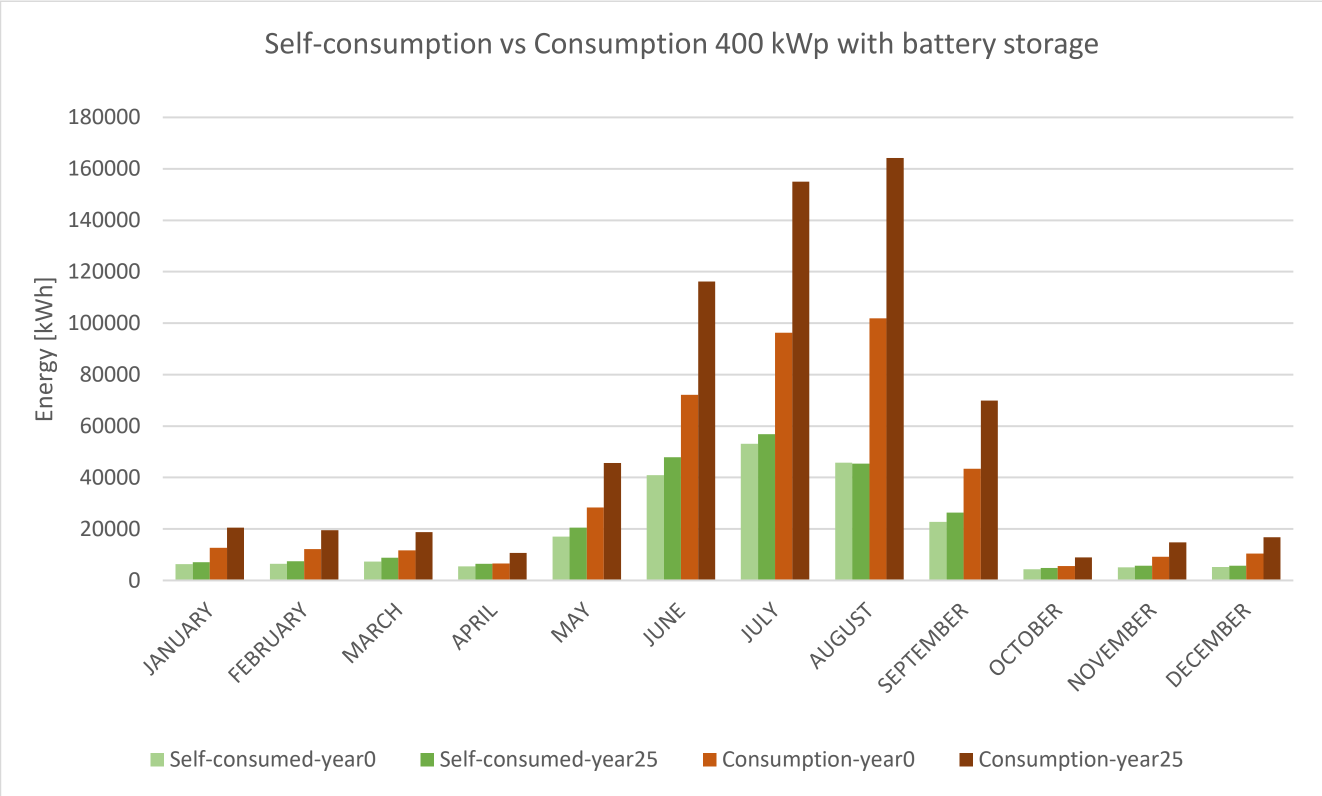


Figure 45: Comparison between self-consumption and consumption of 400 kWp with 69 kWh of battery storage

As it is possible to note from *Figure 45*, during April and October, where the Telezip plant is switched off, the self-consumption is approximately equal to the consumption, at year 0. The small difference between each other is given by the night, when the energy comes partially from the grid, as shown in *Figure 46*.

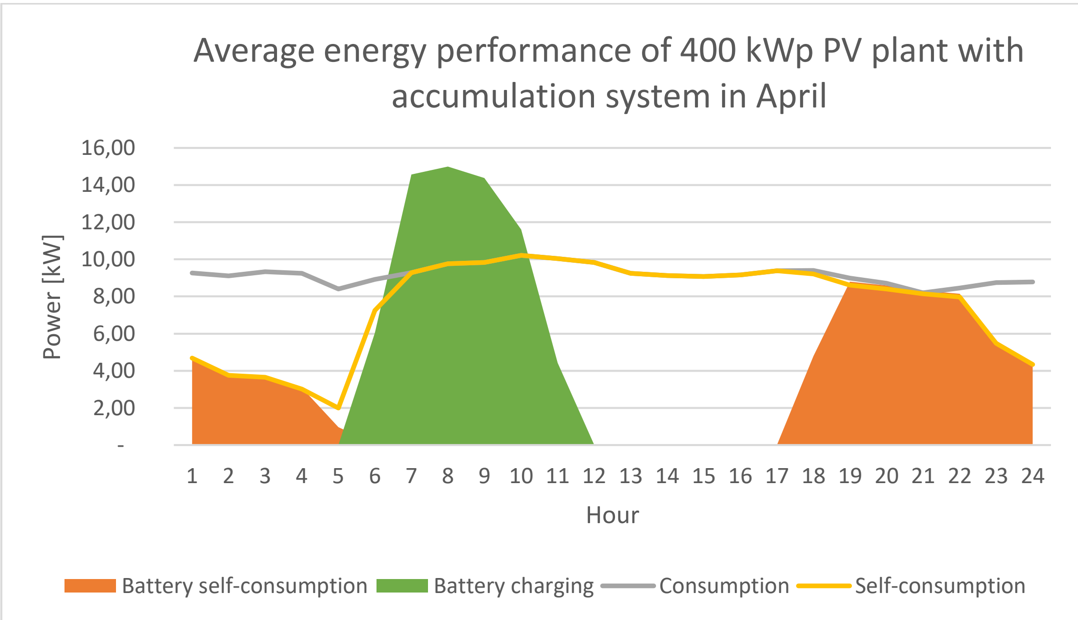


Figure 46: Detail of the average energy performance of 400 kWp PV plant with accumulation system in April

The graph above, in fact, shows the influence of the batteries on the total exploitation of the PV plant, in a favorable month as April, at year 0, when electricity consumption is not so high, and highlights what was said earlier.

As can be seen, during the nights of April, the batteries can totally cover the consumption from 7 pm to 10 pm. While, for the rest of the night, as the batteries state of energy decreases, the energy supplied by the storage system slowly decreases too, until 6 am, when the PV power plant begins to produce. In this latter time slot, besides, part of the energy is supplied by the grid, as the batteries cannot totally cover the consumption.

From 5 am to 12 am, instead, the batteries are completely recharged, since 400 kWp plant produces more than what need from trigenerative plant.

Obviously, increasing the load consumption, the accumulation system does not have better performances compared to the ones at year 0: in fact, at the end of the life cycle of the PV plant and in the same considered month, the batteries can no longer cover the load consumption in the early hours of the night, as they did before.

Another important information from *Figure 45* is that in August, when the highest consumption is recorded, there is no visible advantage in batteries use over the years, despite the increase of the consumption. The reason could be that the accumulation system is undersized and the mean energy consumed in this month, after sunset, is greater than the energy stored, and then supplied, by the batteries, as shown in *Figure 47*. In fact, the accumulation system considered can provide a maximum discharge power of 15 kW, a negligible value compared to the about 200 kW requested at 6 pm.

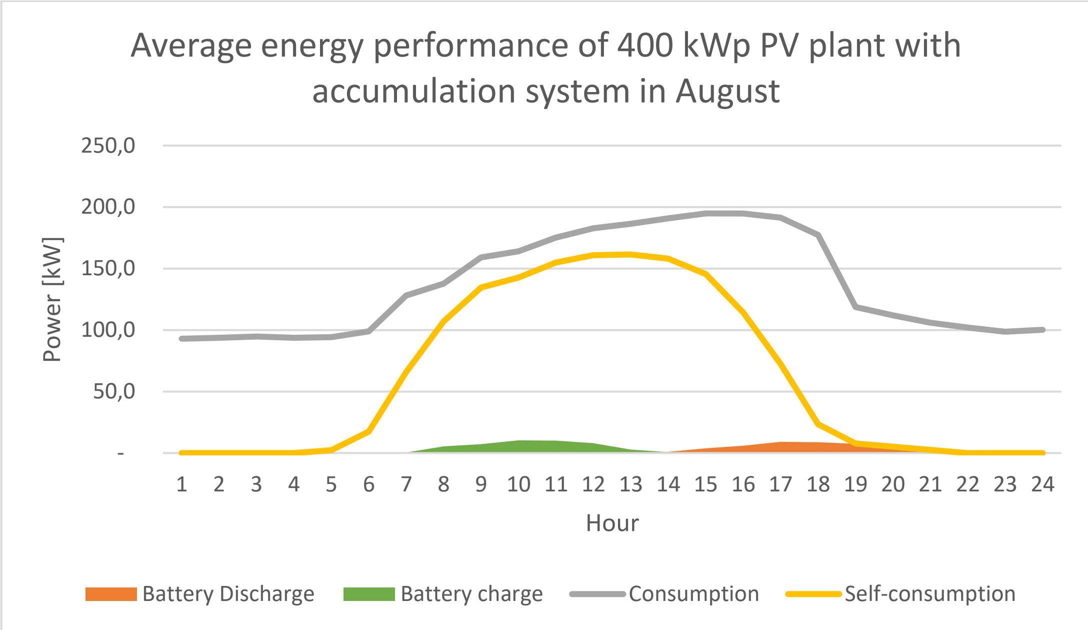


Figure 47: Average energy performance of 400 kWp PV plant with accumulation system in August

Instead, *Figure 48* shows the comparison of the same size PV plant with and without batteries, in order to show if there is an advantage or not in adding them.

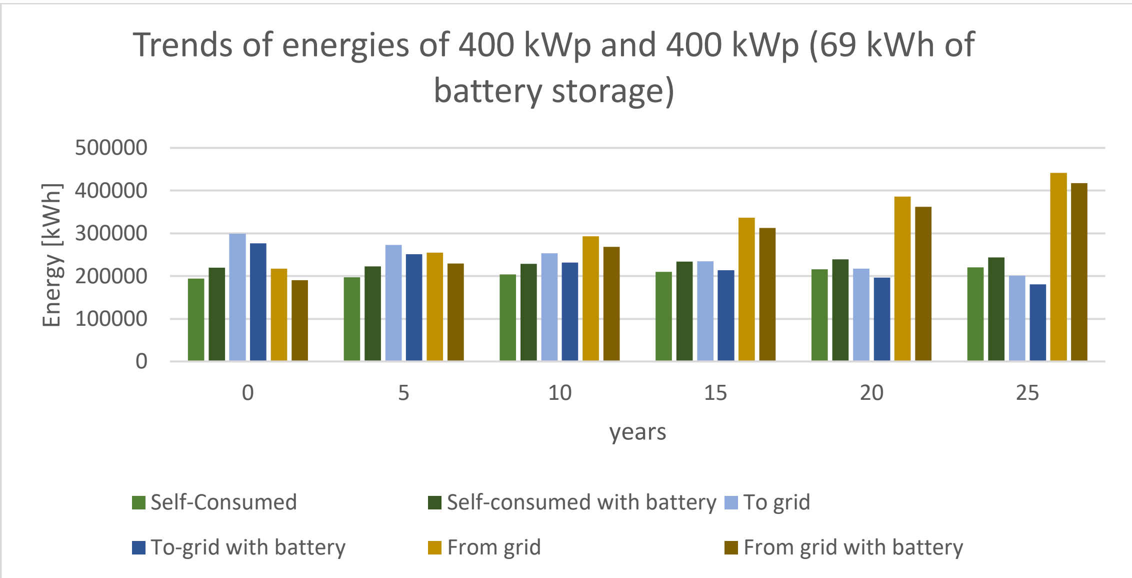


Figure 48: Comparison between 400 kWp and 400 kWp with storage

Predictably, it can be seen from the above graph that the self-consumption of the photovoltaic system, with batteries, is always greater than in the other case, over the years. This is due to the possibility of storing an amount of energy that can be used when the photovoltaic system can no longer produce. But, in any case, this increase in self-consumption is not so significant, especially during the summer period, as seen before. In the case of accumulation system, this also affects the energy imported from and exported to the grid, which are lower than in the case of a normal PV plant.

Another piece of information, obtained from the above graph, is that the energy sold to the grid has decreased over the years in both cases. This is still due to the fact that, as consumption increases, there is a better utilization of the energy. However, the decrease of the energy sold is not compensated by an equal increase of the self-consumption.

Below the variation of the percentage of the self-consumption with an accumulation system is shown:

YEARS	% SELF-CONSUMPTION	% SELF-CONSUMPTION WITH BATTERY
0	47%	54%
5	44%	49%
10	41%	46%
15	38%	43%
20	36%	40%
25	33%	37%

Table 17: Percentage variation of the self-consumption of 400 kWp plant

5.2.2.2 Simulation of 500 kWp with 69 kWh of storage

The second simulation made is on the PV plant of 500 kWp.

As before, the same graphs are shown to illustrate the results with the equal purposes and in order to drawing conclusions.

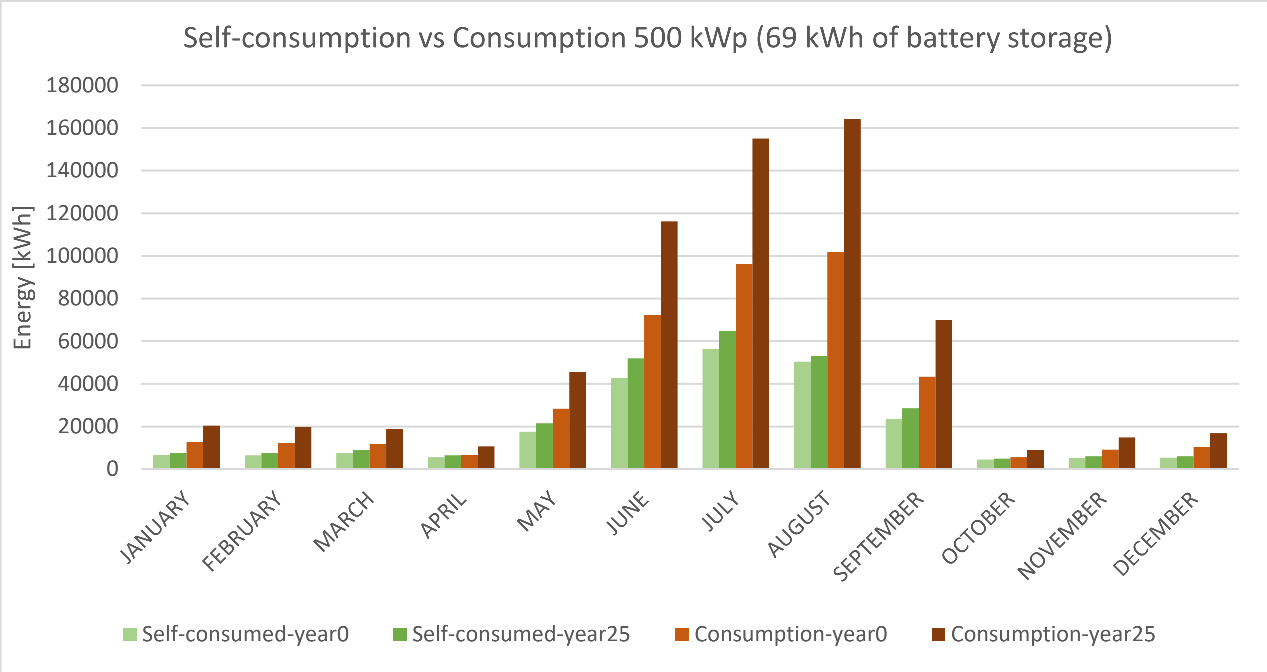


Figure 49: Comparison between the self-consumption and consumption of 500 kWp with 69 kWh of battery storage

The trends in *Figure 49* are the same as in the 400 kWp case and, as can be imagined, the results are approximately equal, as the behavior of the PV plant and Telezip plant does not change.

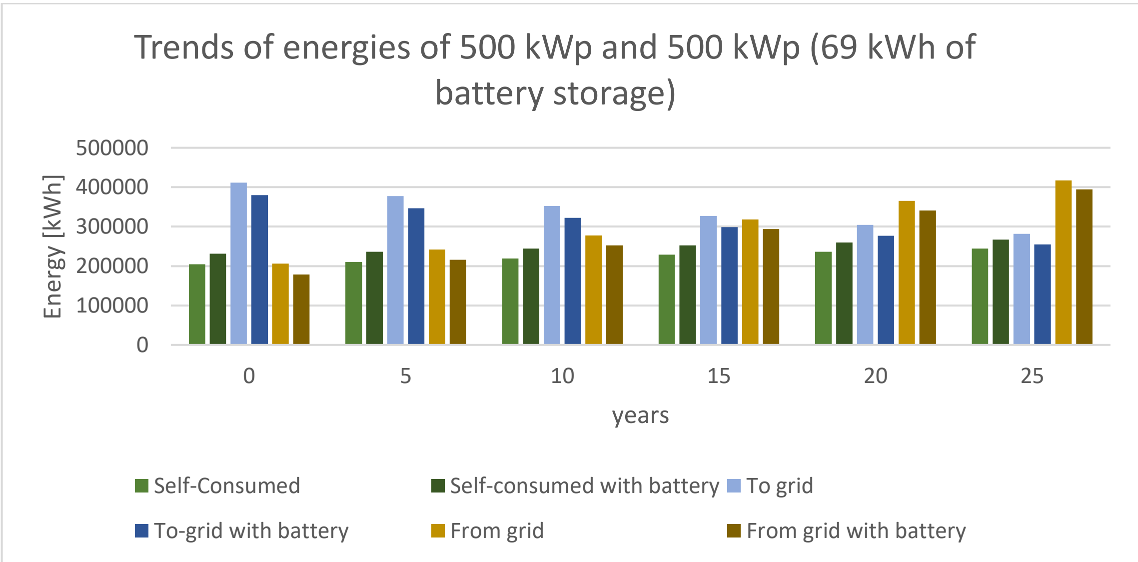


Figure 50: Comparison between 500 kWp and 500 kWp with storage

An interesting thing to note from *Figure 50* is that the self-consumed energy is greater than, or at least equal to, the energy imported from the net for the first 10 years of the considered life cycle. This concept is shown below, where the variation of percentage of the self-consumption with an accumulation system is shown:

YEARS	% SELF-CONSUMPTION	% SELF-CONSUMPTION WITH BATTERY
0	50%	56%
5	47%	52%
10	44%	49%
15	42%	46%
20	39%	43%
25	37%	40%

Table 18: Percentage variation of the self-consumption of 500 kWp plant

In fact, it should be noted that, in the presence of the storage system, the percentage of self-consumption is more than half up to about 10 years.

If, in any case, a comparison is made with *Table 17* and *Table 18*, it can be seen that the greatest variation in the percentage of the self-consumption, compared to the consumption of the Telezip plant, is achieved with the smaller plant.

5.3 Conclusions of the energetic analysis

From this energetic analysis is possible to draw, as preliminary result, that the best solutions, in terms of gain from self-consumption, compared to total consumption and the life cycle utilization, are 400 kWp and 500 kWp PV power plants.

Another insight gained from this chapter is that the accumulation system can be very useful during plant shutdown periods, as the energy consumed can mainly come from the PV plant and batteries. However, during periods of increased energy demand, storage cannot be of much help because it is undersized in these cases.

Furthermore, it is important to consider that the benefits, that the accumulation system could generate, are mainly relate to night-time consumption. Knowing that the base load power consumption, during non-summer nights, is less than 30 kW, this means that Telezip needs at least an accumulations system of 150 kWh of storable energy to be independent from the grid for half of the night. A storage system of this size is not negligible from an economic point of view.

This is why it is now important to go a step further, analyzing photovoltaic systems from another point of view, to see which is the most profitable solution.

6. ECONOMIC ANALYSIS

Having identified, in the previous chapter, configurations of PV power plant that seem to be better than the others considered, from the energetic point of view, it is now the time to carry out the economic analysis, to confirm or not what has been said before.

The analysis was conducted considering several costs and assumptions, with the aim of being as reliable as possible, which they will be explained in the course of this chapter.

Since the main objective is to find the best solution, it is necessary to compare the PV plants considered and, to this end, usual economic indices, such as PB, NPV, IRR, LCOE and others, were taken into account.

6.1. Operative costs

Before starting, it is important to explain which costs have been considered for all the PV power plants and why they have been included.

The main cost of a project comes from its development, in fact finances are concentrated mainly in this part of the process, even more when considering a renewable energy project, since there are basically O&M and revamping costs after installation.

For all simulations, several different costs were considered within the development costs, such as:

- installation cost: which, in turn, it depends on:
    - location of the PV plant: roof-added or free-standing;
    - inclination of the floor: horizontal, inclined or with domes;
    - floor covering: cement, gravel or tar paper;
    - structures: triangular, with ballasts, with pylons and so on;
    - size of the PV power plant: scale economies are possible for larger plants, especially for the purchase of modules and inverters in large quantities;
    - construction of BT/MT cabin: in this case, it is not necessary since the already existing one of Telezip could be exploited;
- work direction: considered fixed for all sizes and amounting to 3000 €, which it takes into account all the costs for the feasibility studies and site start-up;

- deeds: which includes all the costs incurred for land acquisition, notary deeds and servitudes required for the passage of cables over private properties required for connection;
- connection: which depends principally on two factors: the power of the PV plant and the distance from the nearest cabin of MT or HT. Its economic value is the minimum connection cost sustained by the grid operator and it is include in the *Testo Integrato delle Connessioni Attive*, TICA [24], which establishes technical and economic terms and conditions for the connection of electricity production plants to the grid. The connection cost is obtained from the following formula:

$$min \begin{cases} A = CP_A P + CM_A P D_A \dfrac{D_{aerial}}{D_{tot}} + 2CM_A P D_A \dfrac{D_{cable}}{D_{tot}} + 100 \ \ [€] \\ B = CP_B P + CM_B P D_B \dfrac{D_{aerial}}{D_{tot}} + 2CM_B P D_B \dfrac{D_{cable}}{D_{tot}} + 6000 \ \ [€] \end{cases}$$

  where:

  - P_A and P_B are the difference between the PV power plant and the committed power, which in this case is equal to 626 kW, represented by the power of the two cogenerators. So, since this value has to be positive, the cost of the TICA is only 100 € until 600 kWp of PV power plant;
  - D_{cable} is the real length of the connection line built in underground cable;
  - D_{aerial} is the real length of the connection line built in airline;
  - D_A is the linear distance from the nearest MT cabin and equal to 70 m;
  - D_B is the linear distance from the nearest HT cabin and equal to 2 km;
  - CP_A equal to 35 €/kW;
  - CM_A equal to 90 €/kW*km;
  - CP_B equal to 4 €/kW;
  - CM_B equal to 7,5 €/kW*km.

The last item considered, in the development cost, is an extra budget, 5% of the installation cost, to be covered in case of problems of any type.

After having explained all the costs included up to the finishing of the site and the connection of the PV plant, there are other important costs that cannot be overlooked and that are present throughout the life cycle of it.

These are called annual fixed costs and they are:

- rent: if the company does not purchase the land, it must pay a rent to the landowner to develop, and then exploit, the PV plant. Based on the company's experience, this annual cost is assumed to be ten times the power size of the PV plant, expressed in €;
- O&M contract: which includes all the costs for routine maintenance, module cleaning, security service, remote control and all the forms that the company has to fill out for GSE, Customs, Revenue Agency, Arera and so on. The cost of O&M services changes depending on the size of the installation, in fact as the power size increases there is a small scale economy. A different argument is made when considering PV plants with accumulation system, in fact, for these, the maintenance of the batteries must also be considered;
- insurance: which is increasingly important due to the fact that extraordinary weather events are no longer rare and it is essential to be insured. At the suggestion of the company, this cost is also assumed to be eight times the power size of the PV plant, expressed in €.

Size [kW]	Development cost [€]	O&M contract [€/year]	Insurance [€/year]	Rent [€/year]	Battery
100	116.490,00 €	1.400,00 €	800,00 €	1.000,00 €	No
200	224.540,00 €	2.400,00 €	1.600,00 €	2.000,00 €	No
300	321.190,00 €	3.600,00 €	2.400,00 €	3.000,00 €	No
400	425.520,00 €	3.200,00 €	3.200,00 €	4.000,00 €	No
500	510.890,00 €	4.000,00 €	4.000,00 €	5.000,00 €	No
600	611.380,00 €	4.800,00 €	4.800,00 €	6.000,00 €	No
800	817.642,40 €	6.400,00 €	6.400,00 €	8.000,00 €	No
496	571.700,39 €	4.761,60 €	4.464,00 €	4.960,00 €	Sì
396	486.330,39 €	3.801,60 €	3.564,00 €	3.960,00 €	Sì

Table 19: Summary of the costs for each PV plants

Table 19 shows all the costs incurred for each simulation. It is important to note that, for the last two PV plants, 496 kWp and 396 kWp, the cost of the batteries is also included in the development cost, which is 16 972,00€ per rack of storage system [25]. The total cost of the batteries amounts to 50 916,00€.

In any case, the annual fixed costs, reported in *Table 19*, refer to year 0, in fact they increase over the life cycle of the PV plant, since an inflation of 1% per year has been considered.

Now, all the fixed costs have been illustrated and explained, but other aspects and assumptions need to be mentioned.

In fact, it is supposed that Telezip does not have the financial capability to develop this PV project without third-party intervention. This is why the PV plant is initially projected and installed by Forgreen and then sold to Telezip with a margin, as it is treated as a customer. Consequently, all the costs, shown in *Table 19,* already include a 20% increase.

In turn, Forgreen asks the bank for a loan of half the development cost of the PV plant, which is granted with a 5% annual interest rate and 12 years.

Interests are calculated on the outstanding debt and not on the annual instalment, so they are very high in the first years.

Provisions have been considered for extraordinary maintenance or replacement of the inverters, amounting to 12% of the development costs and spread over 10 years, and for the change of the batteries every 10 years, if there is a storage system.

6.2. Revenues

After having explained all the costs, it is now important to talk about the revenues that these PV plants can generate over their life cycle.

The revenues, that a PV power plant can generated over its life cycle, can be derived mainly from two ways of using of the energy produced:

- self-consumption: direct use of the PV energy production avoiding consumption from the grid, which could be considered passive income, as it is an avoided cost;
- sale of electricity: excess and unused energy is sold to the grid, which is, instead, an active income.

There is also another income similar to self-consumption, if an accumulation system is present.

As mentioned in *Chapter 3*, the company used to refer to future electricity prices, reported on the EEX.com, to forecast its future revenues.

The same is therefore done here, as can be seen in *Figure 51*:

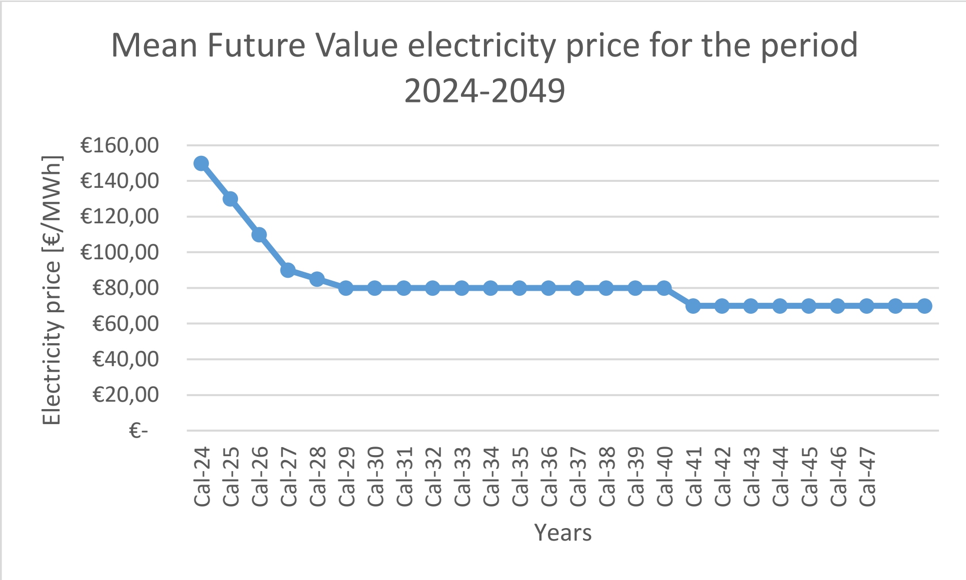


Figure 51: Trend of the electricity price futures (Data present on 28/07/2023)

As can be clearly noted from *Figure 51*, the electricity price is expected to decrease over the years, with an initial rapid decline followed by a flatter and longer period, in which the price is assumed to be constant at around 70/80 €/MWh.

However, a more detailed study was done on the future electricity price value, available from EEX. In fact, knowing that the electricity price varies constantly every hour throughout the day, the desire was to find a more precise remuneration price based on the hours of the day and the type of energy, if self-consumed, sold to the net or coming from the accumulation system.

To better understand, *Figure 52* shows the average hourly trend of electricity price during the time period of October ’22 – September ’23. The graph illustrates also how dramatic the economic situation of the energy sector was during the end of 2022 and the beginning of this year, where the price of electricity was more than twice as high as usual, as already mentioned in previous chapters.

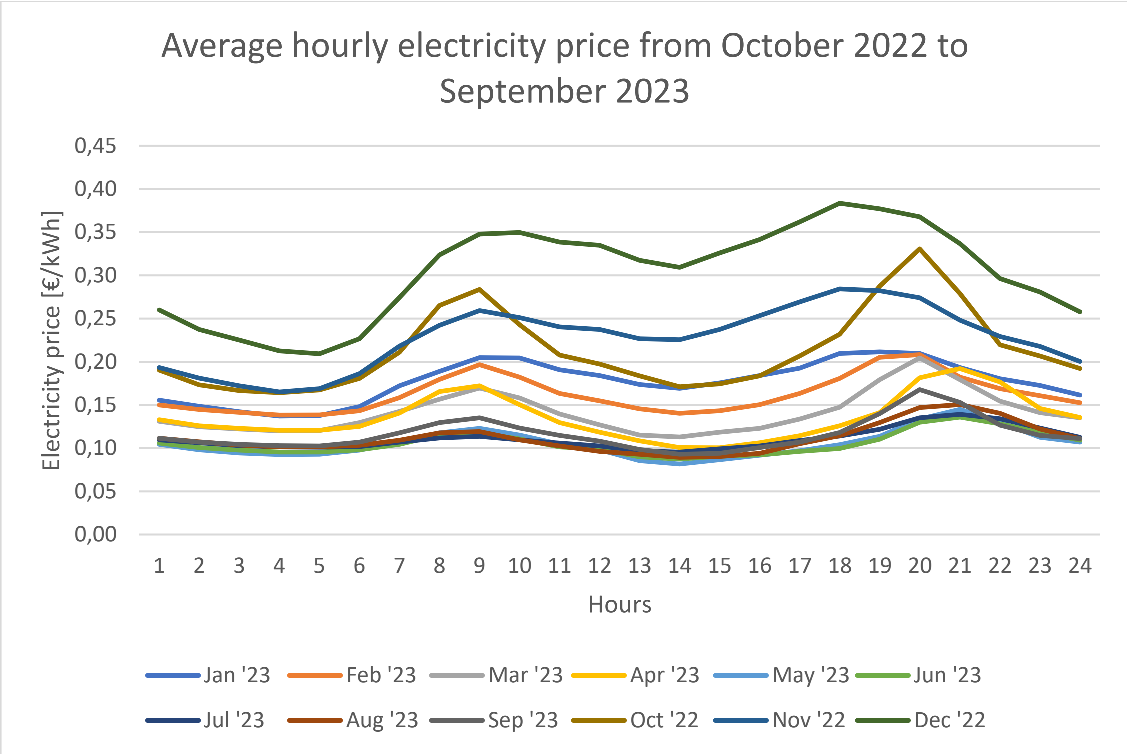


Figure 52: Average hourly trend of electricity price from Oct '22 to Sept '23

The graph above clearly shows how the price of electricity changes a lot during the day and also the months, so it could be not entirely correct to assume one single price value as remuneration, for the three different energies mentioned before. In fact, self-consumption mostly takes place from 11 a.m. to 4 p.m., when the price tends to be lowest, while self-consumption from accumulation system takes place in the late evening, when the price tends to be highest, so the unitary value of remuneration may be different.

A similar comment can be made about the sale of energy to the grid, which takes place in a narrower slot of the day respect to the self-consumption. This implies that its remuneration price may be higher than that of self-consumption, as it is less affected by low electricity prices in the first morning and afternoon.

However, as already mentioned, since the PV plant is not incentivised, the remuneration of electricity sold to the grid would be equal to the hourly zonal PUN, but it is considered constant and equal to 80 €/MWh to be conservative throughout its life cycle. Obviously, if the data available from EEX are correct, revenues will be higher than those assumed for the first 5 years, but, in the event of a different negative situation, there will be some margin.

Now, some steps were taken to calculate a more precise and reliable remunerative electricity price for future years:

- historical hourly data of the PUN were obtained from GME [12], considering only the last past year;
- from these data, the average hourly electricity prices were calculated for each month of the same year;
- monthly and quarterly future electricity price data of 2024 were taken from EEX [26];
- the 2024 average hourly electricity prices were calculated by scaling the 2023 values to the future electricity prices of 2024.

This step was carried out month by month.

After this process, the same graph shown in *Figure 53* was obtained, but referring to the year 2024, and the same was done for the following years until 2049.

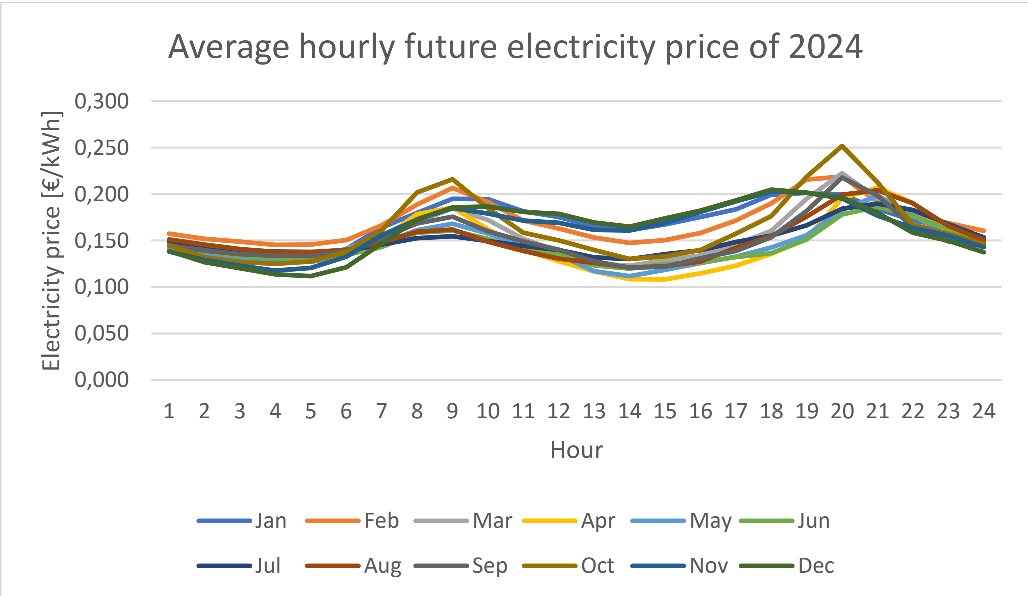


Figure 53: Average hourly trend of electricity price of 2024

Thus, by multiplying the hourly electricity price by the energy produced, in the same time slot, and then adding up the products, the annual revenue could be calculated. Then, the annual average electricity price remuneration, for each income type, could be found dividing the annual revenues by the annual production.

As the process is not easy to understand, the summary table of the 400 kWp PV plant with accumulation system is shown in *Table 20*:

	Revenues from:					
	Battery Discharge	Self-consumption	Exported		YEAR	
MONTH	[€]	[€]	[€]		2024	
1	383 €	1 151 €	1 886 €			
2	375 €	1 134 €	2 747 €			
3	396 €	1 171 €	4 713 €			
4	322 €	804 €	5 837 €			
5	324 €	2 392 €	5 939 €			
6	305 €	5 648 €	3 088 €			
7	319 €	7 633 €	2 323 €			
8	239 €	6 302 €	1 664 €			
9	334 €	3 294 €	3 266 €			
10	383 €	746 €	3 773 €			
11	373 €	918 €	2 078 €			
12	375 €	956 €	1 576 €			
Annual revenues	4 129 €	32 148 €	38 891 €			
Annual energy [kWh]	23168	219915	272556			
Annual average remunerative electricity price [€/kWh]	0,178	0,146	0,143		0,156	Annual future electricity price expected by EEX [€/kWh]

Table 20: Resume table of average electricity price for each revenue of the 400 kWp with accumulation system

Table 20 highlights the difference between the future annual electricity price expected by EEX and the remunerative annual price of electricity for the self-consumption, sale of electricity to the grid and self-consumption from batteries.

As can be seen, the unitary electricity price for self-consumption from accumulation system is higher than the others because it occurs in the late evening, when the price tends to be greatest, as mentioned before. *Table 20* shows also the difference between the remunerative electricity price for self-consumption and for sale of electricity to the grid, in favour of the latter, confirming the assumption formulated above.

However, even if the single values can differ from the EEX value, their mean is approximately equal to this last one.

In addition, it is important to specify that very similar, even more equal, remuneration price of electricity values have been obtained also for the others PV power plants considered.

In any case, when revenues from self-consumption are considered, it is necessary to add also the cost of the charges at the wholesale price of electricity. These charges have been assumed constant for all the 25 years and equal to 90 €/MWh and they take into account:

- costs for transport and meter management;
- system expenses;
- taxes;
- Value Added Taxes (VAT).

SIZE [kWp]	Total revenues 0-25 [€]	Battery
100	441 392,06 €	No
200	815 477,93 €	No
300	1 147 928,57 €	No
400	1 447 680,71 €	No
500	1 726 014,93 €	No
600	1 991 054,87 €	No
800	2 501 167,77 €	No
496	1 776 797,10 €	Yes
396	1 513 811,49 €	Yes

Table 21: Resume of the revenues for each PV plant after the whole life cycle

In *Table 21* is present the summary of the total revenues, given by the sum of self-consumption from batteries or not and sale of electricity to the grid, for all the PV plants considered.

Logically, as the PV power size increases, also the revenues follow the same trend, as more energy is produced and utilised.

But something interesting can be seen if the focus is concentrated on comparing the revenues of PV plants with accumulation system and the corresponding types without batteries. In fact, even if the difference is small, revenues from the PV plants with storage are higher than those of the same PV size plants without, because self-consumption, which is more remunerated, is better exploited.

6.3. Indices

6.3.1. Payback Period

One of the indices used for this economic analysis is the Payback Time Index, also known as the Payback Period, which is an index used to evaluate the time it takes, for an investment, to generate an amount of income, or savings, that equals the initial investment. This index is expressed in years. The shorter the payback period, the quicker the investment recovers its initial outlay.

To obtain this index result, it is important to take into account the income statement of the PV plant for the whole life cycle. In fact, from the income statement, it is possible to obtain the income cash flow, net of the provision for extraordinary maintenance and replacement, which is used to calculate the Payback time.

The income statement provides a summary of the revenues, expenses, gains and losses of the PV plant over its life cycle.

The first step, included in the income statement, is to calculate the EBITDA, i.e. Earnings Before Interest, Taxes, Depreciation and Amortization, and it is calculated through:

$$EBITDA = TOTAL\ REVENUES - OPERATIONAL\ COSTS$$

where, in particular, total revenues are those obtained from the self-consumption and sale of energy to the grid, while operational costs are the sum of rent, insurance and O&M services.

After that, it is possible to obtain the income cash flow simply by subtracting the financial charges, due for funding request, from the EBITDA.

By introducing and then subtracting provisions, the total net cash flow is obtained, which is useful for calculating how long the return on the investments takes.

Year			Income cash flow	Investment	Cash flow	Total cash
	Investment cost	Refund financing	Net income + depraciation +/- taxes	Plants and straordinary mantainances	Total cash flow	Final Cash
2024	- 425.520,00 €	- €	49.414,41 €	- 425.520,00 €	49.414,41 €	49.414,41 €
2025		17.730,00 €	46.238,33 €		28.508,33 €	77.922,74 €
2026		17.730,00 €	43.018,97 €		25.288,97 €	103.211,71 €
2027		17.730,00 €	39.756,33 €		22.026,33 €	125.238,04 €
2028		17.730,00 €	39.420,50 €		21.690,50 €	146.928,55 €
2029		17.730,00 €	39.073,05 €		21.343,05 €	168.271,59 €
2030		17.730,00 €	39.714,54 €		21.984,54 €	190.256,13 €
2031		17.730,00 €	40.354,94 €		22.624,94 €	212.881,07 €
2032		17.730,00 €	40.994,23 €		23.264,23 €	236.145,30 €
2033		17.730,00 €	41.632,41 €	- €	23.902,41 €	260.047,72 €
2034		17.730,00 €	42.269,47 €	- 51.062,40 €	- 26.522,93 €	233.524,79 €
2035		17.730,00 €	42.905,39 €		25.175,39 €	258.700,17 €
2036		17.730,00 €	43.540,15 €		25.810,15 €	284.510,33 €
2037		- €	43.287,26 €		43.287,26 €	327.797,59 €
2038			43.033,20 €		43.033,20 €	370.830,79 €
2039			42.777,95 €		42.777,95 €	413.608,74 €
2040			42.521,51 €		42.521,51 €	456.130,25 €
2041			40.146,55 €		40.146,55 €	496.276,79 €
2042			39.877,12 €		39.877,12 €	536.153,91 €
2043			39.606,46 €	- €	39.606,46 €	575.760,37 €
2044			39.334,56 €		39.334,56 €	615.094,93 €
2045			39.061,40 €		39.061,40 €	654.156,32 €
2046			38.786,97 €		38.786,97 €	692.943,29 €
2047			38.511,26 €		38.511,26 €	731.454,55 €
2048			38.234,25 €		38.234,25 €	769.688,80 €
2049			37.955,94 €		37.955,94 €	807.644,75 €

Table 22: Cash flow of 400 kWp PV plant

The summary of the cash flow of 400 kWp PV plant is shown in *Table 22*, for the entire life cycle. As can be seen, the second column represents the total development cost of the project, which is then amortised over 25 years, while the third column identifies the annual loan rate, having assumed a 12 years payback period, and the fifth column represents the different provisions mentioned earlier.

The lasts two columns, on the other hand, are respectively the total net incomes and the cumulated incomes, which is the sum of the final cash metaphorically present in the bank account of the PV plant project, year by year.

In particular, in the last column, the rows coloured in red indicate that the project has not yet returned on its initial investment, which can be associated with the number of years that the PV plant takes to return on it. In this case, for example, the 400 kWp PV plant has a PB period of 7 years.

It is important to note that the PB period is based, and counted, only on the part of the development cost not financed.

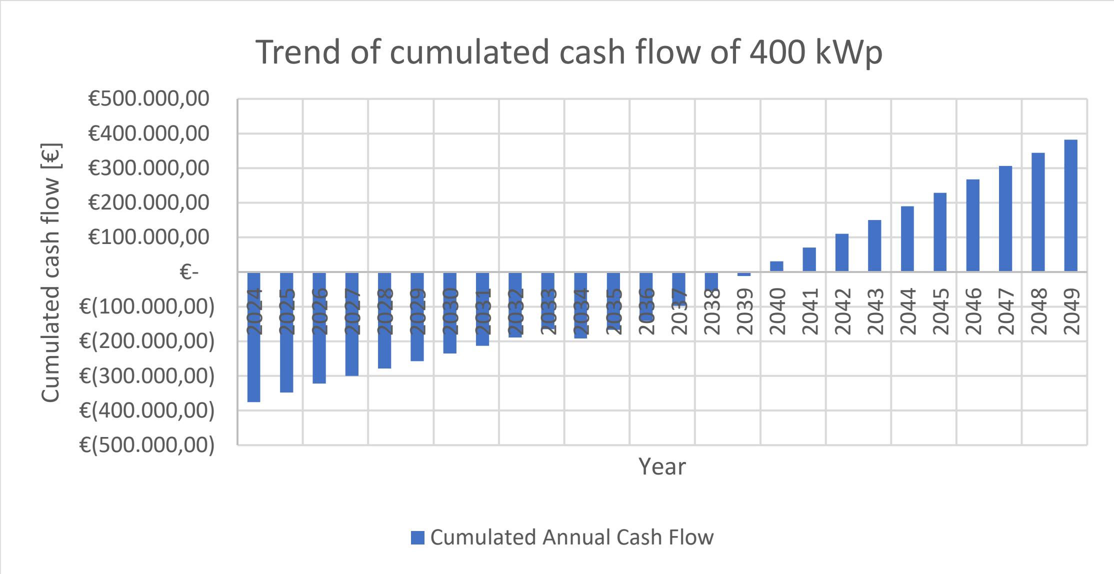


Figure 54: Trend of the cumulated cash flow of 400 kWp plant

In contrast, here, in *Figure 54*, the trend of the cumulated cash flows based on the total development cost is shown. In fact the PB period is longer than before, which is 16 years.

It is important to note how the cash output, due to extraordinary maintenance or replacement of the inverters, affects the trend in 2034. In fact, this exit changes the positive trend, postponing the return period on the investment. However, at the end of the life cycle, the PV plant gives back about the initial development cost as final cumulated revenue.

After having explained the process behind the calculation of the PB period, based on the cumulated cash flow, it is possible to do a comparison between all the PV plants considered.

SIZE [kWp]	PB period [year]	Battery
100	5	No
200	6	No
300	7	No
400	7	No
500	8	No
600	10	No
800	13	No
496	13	Yes
396	13	Yes

Table 23: Comparison of PB period of the PV plants

As can be seen from *Table 23*, the lowest PB period is given by the 100 kWp PV plant, for two reasons:

- its initial investment cost is smaller than the others;
- since the energy produced by the PV plant is approximately negligible compared to the energy required by the Telezip plant, the percentage of self-consumption is greater than that of the others. Due to the fact that the self-consumption is more profitable, the investment returns earlier.

Another thing, that can be noted, is the difference of PB time between PV plants up to 500 kWp of size and the other two of 600 kWp and 800 kWp. The PV plant of 800 kWp, in fact, takes 13 years to pay back half of the investment cost, which is not financed.

In this case, the reason is given by the higher initial development cost and the following outcome of the provision.

A comparison on the PB period could be made also between the PV plants with an accumulation system and their relative types without it. The difference is very marked, in fact, the PB is about twice as high for PV plants with accumulation system, as expected.

In fact, in terms of costs and the need for replacement every 10 years, the impact of the accumulation system on the business plan of the PV plants is very high and it is also aggravated by the increase in the cost of the O&M services, since the batteries also require regular maintenance.

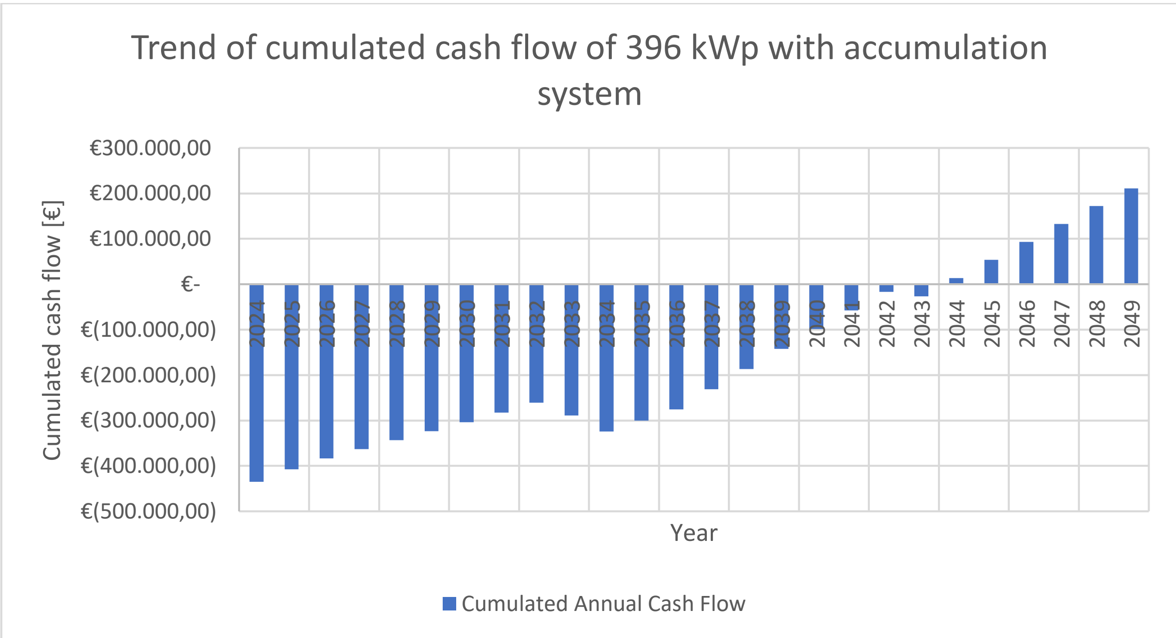


Figure 55: Trend of the cumulated cash flow for PV plant of 396 kWp with 69 kWh of accumulation system

From *Figure 55*, can be seen how the outcomes of the replacement of the batteries affect, in a deeply way, the cumulated cash flow compared to the case represented in *Figure 54*. In particular, the second replacement, at year 2043, postpones of one year more the return on the investment, since it is programmed when the cumulated cash flow are close to reach the positive.

PV plant with an accumulation system are, therefore, not so encouraging and this is one of their many weaknesses.

In any case, the PB period index has its pros and cons and must be considered in addition to the other indices:

- simplicity and speed of the calculation method;
- it gives a primary measure of risk;
- time is not valued;
- it does not take into account the availability that occurs after the recovery of the investment.

6.3.2. Net Present Value

Another index used is the Net Present Value, which is a financial metric used to evaluate the profitability of an investment or project. It represents the difference between the present value of cash inflows, revenue or benefits, and the present value of cash outflows, costs or investments, over a specified time period, typically the life of the investment or project.

It is calculated with the following formula:

$$NPV = -I_0 + \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} \quad [€]$$

where:

- NPV: Net Present Value;
- I_0: initial investment cost;
- n: number of years considered, in this case 25 years;
- t: year t-th;
- CF_t: cash flow at year t;
- r: discount rate, in this case equal to 2%.

SIZE [kWp]	NPV [€]	Battery
100	83.057,46 €	No
200	134.730,32 €	No
300	166.423,02 €	No
400	195.465,70 €	No
500	211.779,36 €	No
600	192.111,17 €	No
800	128.487,01 €	No
496	45.595,97 €	Yes
396	47.352,33 €	Yes

Table 24: Resume of the NPV for each PV plant

As can be seen from *Table 24*, even if it seems logical to think that the NPV increases with the power size of the plant, the highest one is obtained with the PV plant of 500 kWp.

In fact, from this result, it is obtained that the power size of 600 and 800 kWp are not profitable as the smaller power size plants from the costs-revenues point of view.

This result can be explained by the fact that the 500 kWp PV plant offers the best compromise between costs, including provisions and annual costs, and PV energy production, which represents the only income source. According to this scheme, in fact, smaller PV power plants cannot produce enough energy, even though they have lower annual costs; on the other hand, larger PV power plants produce an enormous amount of energy, but they also have higher annual costs.

PV plants with accumulation system show the worst results, because their NPV is strongly influenced by provisions for batteries replacement.

Also NPV index has its pros and cons:

- pros:
  - it incorporates time value of money;
  - it can accommodate different discount rates to represent the risk associated with the investment;
  - simple way to determine if a project delivers value;
- cons:
  - its accuracy depends on quality of inputs;

- it may be not useful for comparing projects of different sizes, as the largest projects typically generate highest returns;
- for very long-term life cycle, it may not accurately account for the risk and uncertainty of the project.

6.3.3. *Internal Rate of Return*

A further useful index is the Internal Rate of Return, also known as IRR, which is the discount rate, expressed in percentage, that makes the positive discounted cash flows equal to the investments, making the NPV equal to zero at the end of the whole life cycle considered of the PV plant.

The IRR is often used inside economic analysis in order to make a comparison between investments with different initial costs and understand the feasibility and the profitability of them.

The reading key of the IRR is that, the more its percentage value is high, the more the investment seems worth. This is due to the fact that a high value means to have more margin on the financing interest or on the inflation, because it means that a great interest rate is necessary to make null the investment.

The equation of the IRR is the following:

$$0 = \sum_{t=0}^{N} \frac{CF_t}{(1 + IRR)^t} \quad [€]$$

where:

- CF_t: cash flow at year t;
- N: life cycle of the PV plant, expressed in years.

Since the relationship is not linear in the unknown variable, the only viable resolution method, to find the correct IRR, is to use an iterative process.

Below the IRR of each PV plants considered in this analysis are shown:

SIZE [kWp]	IRR [%]	Battery
100	20,8%	No
200	18,1%	No
300	16,2%	No
400	14,7%	No
500	13,9%	No
600	12,3%	No
800	10,1%	No
496	9,8%	Yes
396	10,2%	Yes

Table 25: Comparison of different IRR for each PV plant

As it is possible to note from *Table 25*, the IRR decreases with the increase of the power size of the PV plant. This is because, of course, the larger the power, the higher the costs and so it is predictable that the cash flows will be used primarily to repay the investment, and only after this purpose has been achieved, they begin to generate a profit. This is in contrast to what happens with the first three PV plants, where the costs are relatively low and the cash flows start to work before that.

In any case, it has already been stated in the energetic analysis that, up to 300 kWp, the PV plant is not worthwhile for Telezip, according to the increase in energy demand.

On the contrary, for what concerns the IRR of the PV plants with accumulation system, it can be noted that these values are quite negative with respect to the others. All the more reason, then, that it is not so convenient to use accumulators today, due to the impractical costs of the batteries and their short life.

Also IRR index has its pros and cons as well as the other indices:

- pros:
  - it takes into account the time value of money, similar to NPV;
  - it provides an objective criterion for evaluating investment projects: if the IRR is greater than the required rate of return of capital, the project is generally considered acceptable;
- cons:
  - its accuracy depends on quality of inputs;

- it does not account for risk or variability in future costs;
- it does not account for the project size: relying solely on the IRR method tends to favour the smaller project, overlooking the potential for the larger project to generate considerably greater cash flows and, potentially, more substantial profits.

6.3.4. Levelized Cost Of Electricity

The Levelized Cost Of Electricity, internationally recognised as LCOE, is used in the energy industry for assessing and comparing the cost of generating electricity from different sources or technologies. It calculates and gives back as result the per-unit cost of electricity produced over the entire life cycle of a power plant, in this case PV power plant.

Ideally, this value represents the minimum price at which the electricity, produced by the PV plant, is required to be sold in order to return on the total costs over its life cycle.

As reported below, it is obtained from the ratio of the summatory of the discounted costs and the summatory of the discounted energy production of the PV plant:

$$LCOE = \frac{Total\ Lifetime\ Costs}{Total\ Lifetime\ Energy}$$

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + AC_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad \left[\frac{€}{kWh}\right]$$

where:

- I_t: investment at year t-th;
- AC_t: annual fixed costs;
- F_t: annual fuel cost (null for the PV plant);
- E_t: annual energy production;
- r: discount rate;
- n: life cycle of the plant.

As the others economic indexes considered before, also the LCOE has its strengths and weaknesses here reported:

- strengths:
    - it allows for straightforward comparisons between different energy generation technologies by standardizing the cost of the electricity production;
    - it accounts for the entire life cycle;
    - it accounts for the degradation of the production of the modules;
    - it is not affected from the revenues, so starting from an estimate of the costs it is able to have a measure of the competitiveness of the technology;
- weaknesses:
    - it could oversimplify complex energy projects;
    - small weight is given to variable costs in the long period, as in the case of strong price fluctuations or poorly regulated markets;
    - the co-existence of different technologies in the same market is not taken into account.

However, as far as our simulations are concerned, the LCOE formula is slightly different from the previous one, since the specific case of the photovoltaic plant is now illustrated:

$$LCOE_{pv} = \frac{\sum_{t=1}^{n} \frac{I_t + AC_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t\,(1-d)^t}{(1+r)^t}} \quad \left[\frac{€}{kWh}\right]$$

where the addition factor, d, represents the degradation factor of the modules.

For the calculation it is used:

- degradation of the modules, d, equal to -0,55 %, already explained in previous chapter;
- discount rate, r, equal to the Weighted Average Cost of Capital, WACC, which refers to the average discount rate weighted between the remuneration of the debt capital and the equity capital, and equal to 5% in this case;
- life cycle of the plant equal to 25 years.

Below, LCOE of all the simulations are reported:

SIZE [kWp]	LCOE [€/kWh]	Battery
100	0,086	No
200	0,082	No
300	0,08	No
400	0,076	No
500	0,074	No
600	0,074	No
800	0,074	No
496	0,09	Yes
396	0,094	Yes

Table 26: Comparison of all LCOE of the PV power plants

As can be seen from *Table 26*, the LCOE decreases as the size of the plant increases, due to economies of scale in costs and increased energy production. However, starting from the 500 kWp PV power plant, a decrease in LCOE is not more visible.

Interesting to note how LCOE changes with the PV power plants with the accumulation system, which is about 0,02 €/kWh more compared to the better compatible plants.

But, after having obtained these values of LCOE, it is important to understand and verify if they are reliable or not and in line with the global trend.

To do this, the report *"Renewable Power Costs in 2022"* [27] by the International Renewable Energy Agency (IRENA) is used as a reference, which lists all the average global costs for renewable energy sources in the main countries.

For the specific case of the solar energy source, the report only considers utility-scale photovoltaic plants, therefore plants above a certain power size.

However, taking into account some economies of scale for raw materials and O&M services due to the larger scale of the plants, the report can also provide important information for the PV plants included in this work.

In fact, has reported by IRENA, in the last 12 years, the global average LCOE of utility-scale PV plants declined by 89%, from 0,445 USD/kWh to 0,049 USD/kWh. On a global scale, the range of LCOE costs is becoming increasingly narrower. In 2021, the costs of the most affordable and most expensive projects spanned from 0,031 USD/kWh to 0,127 USD/kWh.

By 2022, this range had tightened to a level between 0,030 USD/kWh and 0,120 USD/kWh, indicating significant reductions of 87% and 78% for the 5th and 95th percentile values, respectively, compared to the figures from 2010. The reason for this rapid decline is explained by the fact that the total installed costs and O&M services costs fall down, while the capacity factor of PV increases.

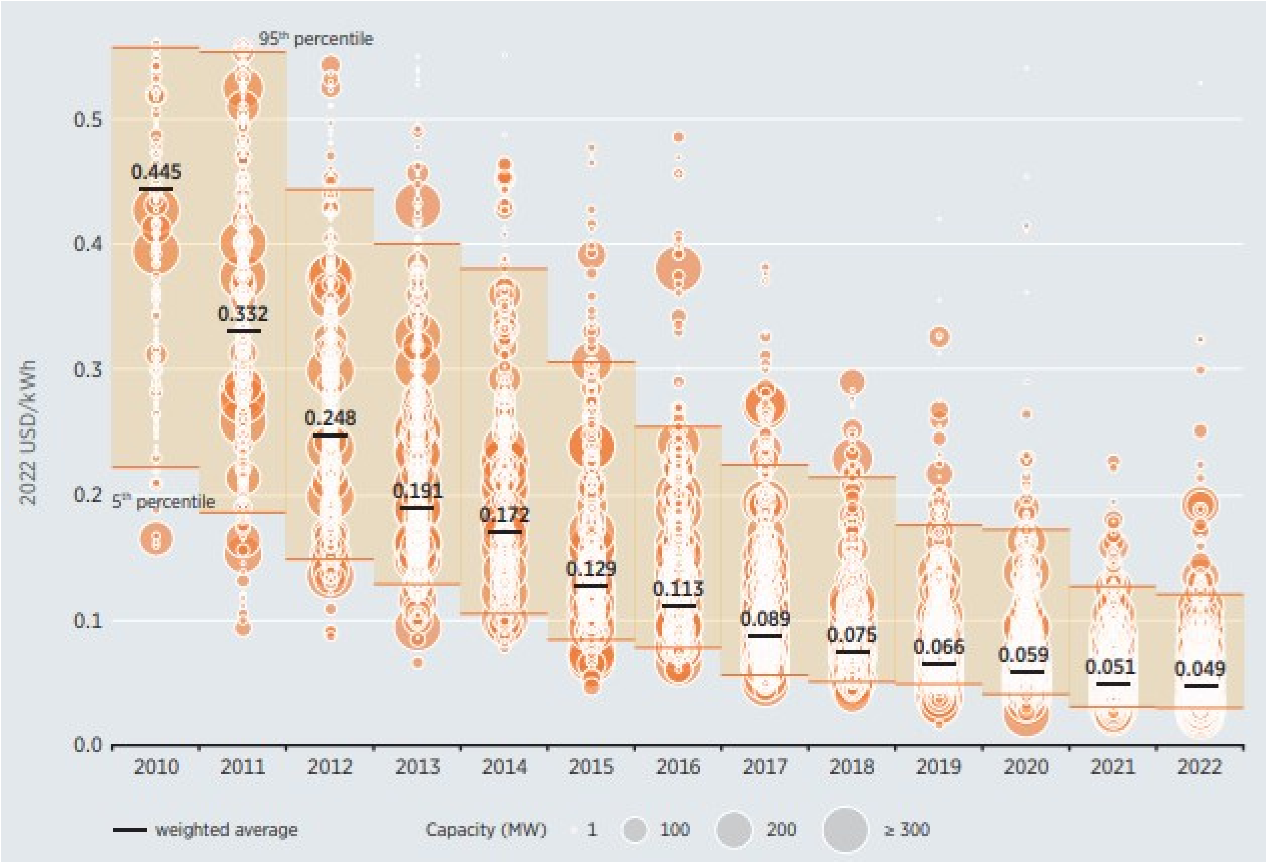


Figure 56: Global utility-scale solar PV project LCOE and range, 2010-2022 [27]

As it is possible to see from *Figure 56*, the actual global weighted average LCOE of utility-scale PV plants in 2022 is 0,049 USD/kWh, equivalent to about 0,047 €/kWh.

Now, knowing that LCOE of larger PV power plants is 50 €/MWh, it is possible to say that the LCOE results obtained from the simulations carried out in this work are very reliable, since the case of 500 kWp is amounting to 74 €/MWh. In this case, there is also another point to be taken into account, such as the fact that the global PV companies, that are able to project utility-scale plants, have huge financial resources, which allow them to avoid relying on third parties for the project development, except for some banks for financing.

6.4. Conclusions of the economic analysis

Having presented all these indices and how the various simulations behave for each one of them, it is now possible to draw some conclusions about the economic analysis.

To better understand the situation, a summary table is illustrated below:

SIZE	Total Cost of plant	Per-unit total cost of plant	Total Annual Cost 0-25	Total revenues 0-25	PB period	ROI	IRR	NPV	PI	LCOE	Battery
[kWp]	[€]	[€/kWp]	[€]	[€]	[year]	[%]	[%]	[€]	-	[€/kWh]	
100	116.490,00 €	1.164,90 €	94.482,02 €	441.392,06 €	5	7,15%	20,84%	83.057,46 €	0,71	0,086	No
200	224.540,00 €	1.122,70 €	177.153,79 €	815.477,93 €	6	6,63%	18,10%	134.730,32 €	0,60	0,082	No
300	321.190,00 €	1.070,63 €	265.730,68 €	1.147.928,57 €	7	6,26%	16,18%	166.423,02 €	0,52	0,08	No
400	425.520,00 €	1.063,80 €	307.066,57 €	1.447.680,71 €	7	6,00%	14,73%	195.465,70 €	0,46	0,076	No
500	510.890,00 €	1.021,78 €	383.833,21 €	1.726.014,93 €	8	5,80%	13,88%	211.779,36 €	0,41	0,074	No
600	611.380,00 €	1.018,97 €	460.599,85 €	1.991.054,87 €	10	5,32%	12,34%	192.111,17 €	0,31	0,074	No
800	817.642,40 €	1.022,05 €	614.133,14 €	2.501.167,77 €	13	4,57%	10,14%	128.487,01 €	0,16	0,074	No
496	571.700,39 €	1.152,62 €	418.838,80 €	1.776.797,10 €	13	4,14%	9,79%	45.595,97 €	0,08	0,09	Yes
396	486.330,39 €	1.228,11 €	334.395,49 €	1.513.811,49 €	13	4,21%	10,22%	47.352,33 €	0,10	0,094	Yes

Table 27: Summary table of the economic analysis

As can be seen from the table above, other indices have been considered but not explained in the economic analysis, such as ROI, Return On Investment, and PI, Profitability Index.

The choice is dictated by the fact that both indices do not add any other useful information, as well as the fact that ROI is strongly influenced by the initial investment, making smaller investments more attractive, even if the potential profit is lower, and that PI does not take into account for the size of the project, similar to IRR.

Therefore, these latter indices have not been explained in detail so as not to be redundant.

Although *Table 27* allows to compare the PV plants considered, the choice of the best PV plant is a complicated one, as there is a different PV plant that prevails over the others for each economic index.

In fact, the energetic and economic analysis are used by the companies to make investment decisions, but on the basis of a priori opportunities and priorities fixed.

So it is not possible to find the best single solution, but there is a solution that better suits the purposes set. For example, in this case, it does not make sense to install PV plants up to 300 kWp, because the energy demand of Telezip is very important. On the other hand, PV plants with an accumulation system do not show a significant energy gain, which makes the storage itself useless, as also the economic indexes, which do not meet the good performance requirements.

As for the 600 kWp and 800 kWp sizes, although they have some positive aspects, such as higher revenues and lower LCOE compared to the others, they are not fully satisfactory.

Consequently, the situation is alike to the energetic analysis, where the PV plants that seem to suite better the initial purposes were the cases of 400 kWp and 500 kWp.

At this point, the choice come down to what the company is willing to do: if it is not a problem to have a higher debt and PB period, but to obtain a higher NPV after the whole life cycle, the choice will be in favour of the 500 kWp PV power plant.

On the other hand, if the company does not want to take certain risks or it has already enough capital committed, it will opt for the 400 kWp plant.

Conclusion

The current global climate change and energy crisis have shown the importance of exploiting renewable energy sources and have confirmed the PV as one of the most reliable and competitive technologies on the market, like wind, to replace fossil fuels.

On the other hand, PV technology development has also highlighted its limits and weaknesses, such as the non-programmability and discontinuity of the production, even if some solutions have emerged to overcome these problems, like storage systems. However, as the PV plant is very versatile and can be implemented in several different situations, such as on roofs, on shelters, on the ground and so on, it has to be exploited, even more so in this last period and in view of the future objectives set by the European Union to reach carbon neutrality.

For this reason, ForGreen company wanted to carry out an energetic and economic feasibility study of a photovoltaic system integrated with a trigeneration district heating plant, exploiting an industrial roof currently used as parking lot.

The study was developed in different steps:

- preliminary sizing of the PV plant;
- comparison between several PV plant sizes, from an energetic point of view;
- additional comparison between PV plant with and without accumulation system of the same size;
- economic analysis of the considered configurations.

The sizing of the PV plant was carried out using the Solar Edge Designer software for what concerns the correct positioning of the modules to avoid possible shadings, since it gives the possibility to recreate a reliable configuration of the place and makes available an irradiance map. While the ZCS Configurator software was used to find the best array-inverter matching, since it focuses on the voltage and current limits of the inverter.

After defining the available area, PV plant sizes between 100 kWp and 800 kWp were considered, in order to verify which of these solutions would best suit the energy demand of the trigenerative district heating and cooling plant for the next 25 years. The load was assumed to increase by 10% every 5 years, in order to make the study as realistic as possible and considering that the district heating and cooling plant is currently underexploited.

Then, implementing the annual load profiles of the trigenerative plant within the software, the amounts of self-consumption and sale of electricity were obtained for each PV plant and year of the whole life cycle. From these results, it was possible to draw some conclusions on the energy analysis, obtaining that the most suitable PV sizes were 400 kWp or 500 kWp. In fact, smaller PV capacities could not be sufficiently exploited by the plant, while larger PV capacities did not lead to a noteworthy gain.

However, a problem of incredible amount of sale of energy for most of the year emerged from the simulation; for this reason, a double comparison was made between the same PV sizes, 400 kWp and 500 kWp respectively, but with an accumulation system of 69 kWh.

Unfortunately, the maximum capacity of the battery storage, allowed by the software used, was undersized compared to the energy required by the plant on a typical night. Therefore, the storage did not result in a useful gain during the months of highest consumption of the district heating plant.

After obtaining preliminary results from the energetic analysis, the economic analysis was carried out. Several costs and assumptions were taken into account in order to make a reliable study, such as installation and development, deeds and connection costs but also insurance annual cost and a financing of 50% of the total cost.

For what concerns revenues, different considerations were made:

- self-consumption revenues: future price of electricity, made available by EEX, were used;
- sale of electricity revenues: a constant remuneration of 80 €/MWh for the whole life cycle was assumed.

In addition, a more detailed study on the future hourly electricity price showed that the remuneration for self-consumption from batteries was higher than the value of EEX of 2 cents/kWh, confirming that energy from the accumulation system was more profitable. The reason for this was that this energy was exploited in time slots with high electricity prices.

In any case, the economic comparison between the several PV plants was made examining different indices, such as PB, NPV, IRR and LCOE, obtaining that the most cost-effective plants were 400 kWp and 500 kWp, as well as in the energy analysis. In fact, these two PV sizes showed the best NPV and LCOE values, respectively:

- 400 kWp shows a NPV equal to 195 465,70 € and an LCOE equal to 0,076 €/kWh;
- 500 kWp shows a NPV equal to 211 779,36 € and an LCOE equal to 0,074 €/kWh.

On the other hand, PV plants with accumulation system manifested the worst results for each economic indices considered, for example their payback time was about twice that of the system of the same sizes without batteries.

In conclusion, the study has established that the most suitable PV plants are 400 kWp and 500 kWp, although the increase of the consumption over the years, and that the battery storage is currently not a useful solution due to its high cost and frequent need for replacement.

It is important highlight that the PV production leads to further lower exploitation of the water/Li-Br absorption cycle for the cooling part.

According to this, possible future improvements can be added at this work.

In fact, it can be interesting to evaluate what limits and conditions lead to an advantage in using the PV plant instead of the absorption cycle for cooling supply and vice versa.

To achieve this purpose, it would be necessary to make a more detailed study on the hourly consumption of Telezip plant in order to have a clear view of the start and end times of the use of the cooling service. This step would allow to determine in which time slots it is not possible to exploit the PV plant.

Then, it would be important to know the real efficiency of the cogeneration-absorption cycle process, to determine how much fuel, natural gas in this case, would be used. Consequently, several simulations on the right production configurations would be necessary to implement, in order to know how much electric energy to produce with cogenerators to have enough thermal energy in excess, exploited then by the absorption cycle. A possible combined work between the absorption cycle and the chiller, given that both use helpful products of the cogenerators, thermal energy in excess and electric energy produced, respectively, could be implemented.

However in this latter case, the whole efficiency might be very low and the process worthless.

Furthermore, an economic analysis should be conducted to verify the cost-effectiveness of each possible configurations, considering different future electricity price scenarios.

Something, that should not be overlooked, is the expected decrease of the accumulation system costs, accompanied by a probable improvement in their useful life. This could heavily influence the choice.

Appendix A

Forgreen Spa Sb in Via Torricelli 37

Progetto 500 kWp **Data** 08/29/2023
Riferimento
Descrizione
Indirizzo Corso Stati Uniti, 1, 35127 Padova PD, Italia
Latitudine 45,3997322 **Longitudine** 11,9313110 **Altitudine** 10,14

	Campo FV 0
Tipo di installazione	Free
Inclinazione	15,00°
Azimut	21,00°
Produttore	Jinko Solar
Modello	JKM550M_72HL4-V
N. moduli	900
Potenza totale	495 kWp
Temperatura Minima	-5,5 °C
Temperatura Massima	62,98 °C

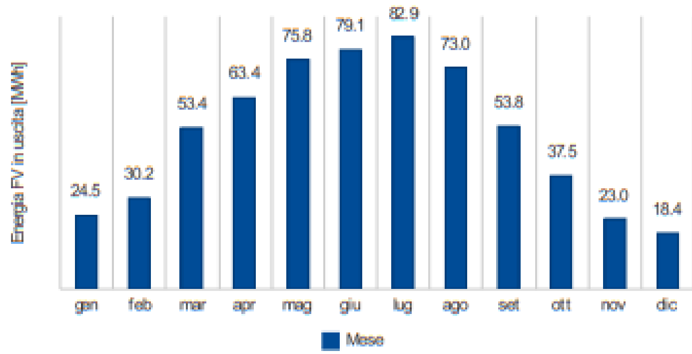
Campo FV 0

Potenza nominale	**550,00 W**	Tensione circuito aperto Voc	**49,62 V**
Corrente di cortocircuito Isc	**14,03 A**	Tensione nominale Vmp	**40,90 V**
Corrente nominale Imp	**13,45 A**	Coefficiente di temperatura Voc	**-0,28 %/°C**
Coefficiente di temperatura Isc	**0,05 %/°C**	Coefficiente di temperatura Pmax	**-0,35 %/°C**

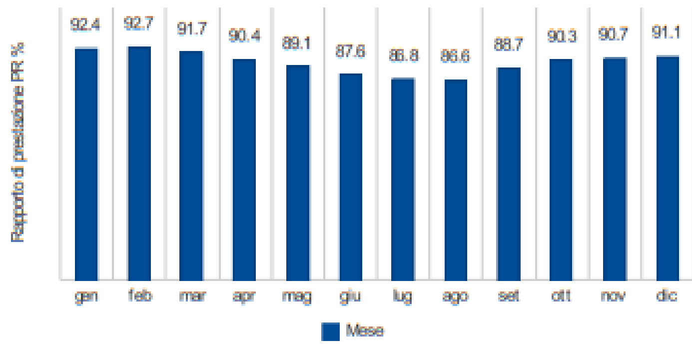
Riepilogo

Produzione energetica annua	**614,95 MWh**	Produzione specifica	**1.242,32 kWh/kWp**
Potenza nominale CC	**495,00 kWp**	Potenza nominale CA	**500,00 kWp**
Irraggiamento orizzontale	**1.253,59 kWh/m²**	Irraggiamento inclinato	**1.441,84 kWh/m²**
Fornitore dati meteo	**Meteonorm**	Performance Ratio PR	**89,09%**

Produzione energetica annuale



Performance Ratio PR



Inverter 1, 2, 3, 4, 5

Modello	3PH 100KTL-V4-3PH 100KTL-V4
Potenza nominale CA	100 kW
Tensione nominale	625 V
Numero canali MPPT	10
Numero totali di moduli	180
Potenza CC installata a STC	99 kW

	MPPT 1	MPPT 2	MPPT 3	MPPT 4
Campo FV	Campo FV 1	Campo FV 1	Campo FV 1	Campo FV 1
Moduli per stringa	18	18	18	18
Numero di stringhe in parallelo	1	1	1	1
Numero totali di moduli	18	18	18	18
Potenza installata massima MPPT [kW]	9,9	9,9	9,9	9,9
Potenza massima di canale MPPT [kW]	20	20	20	20
PPV(inst),MPPTi/PMMPTMAX	0,50	0,50	0,50	0,50
PPV(inst)/PACR	99,00%			
PPV(inst)/PACMAX	90,00%			
Tensione di ingresso massima inverter	1100	1100	1100	1100
Tensione di attivazione	200	200	200	200
Range operativo MPPT a massima potenza	500 - 850	500 - 850	500 - 850	500 - 850
Voc_max stringa a circuito aperto @Min.Temp	969,44	969,44	969,44	969,44
Voc_min stringa a circuito aperto @Max.Temp	798,18	798,18	798,18	798,18
Vmp_Max tensione stringa @Min.Temp	799,07	799,07	799,07	799,07
Vmp_Min tensione stringa @Max.Temp	657,91	657,91	657,91	657,91
Massima corrente Isc per canale	50	50	50	50
Corrente CC Isc @Max. Temp	14,29	14,29	14,29	14,29
Corrente massima Imp	40	40	40	40
Corrente massima Imp @Max. Temp	13,70	13,70	13,70	13,70
Battery model				
Storage system				
Enabled for Storage	False			

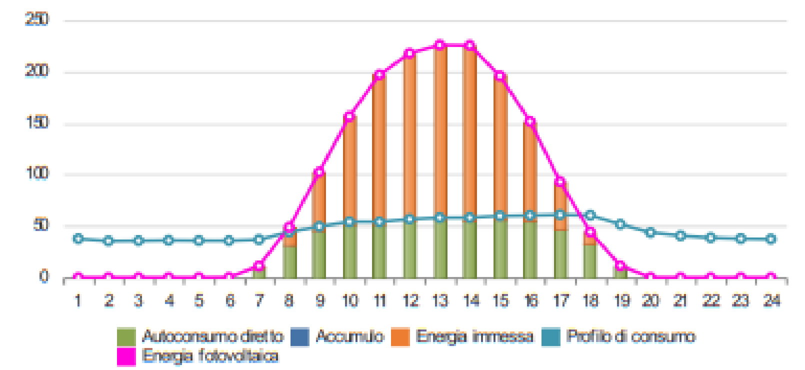
	MPPT 5	MPPT 6	MPPT 7	MPPT 8
Campo FV	Campo FV 1	Campo FV 1	Campo FV 1	Campo FV 1
Moduli per stringa	18	18	18	18
Numero di stringhe in parallelo	1	1	1	1
Numero totali di moduli	18	18	18	18
Potenza installata massima MPPT [kW]	9,9	9,9	9,9	9,9
Potenza massima di canale MPPT [kW]	20	20	20	20
PPV(inst),MPPTi/PMMPTMAX	0,50	0,50	0,50	0,50
PPV(inst)/PACR	99,00%			
PPV(inst)/PACMAX	90,00%			
Tensione di ingresso massima inverter	1100	1100	1100	1100
Tensione di attivazione	200	200	200	200
Range operativo MPPT a massima potenza	500 - 850	500 - 850	500 - 850	500 - 850
Voc_max stringa a circuito aperto @Min.Temp	969,44	969,44	969,44	969,44
Voc_min stringa a circuito aperto @Max.Temp	798,18	798,18	798,18	798,18
Vmp_Max tensione stringa @Min.Temp	799,07	799,07	799,07	799,07
Vmp_Min tensione stringa @Max.Temp	657,91	657,91	657,91	657,91
Massima corrente Isc per canale	50	50	50	50
Corrente CC Isc @Max.Temp	14,29	14,29	14,29	14,29
Corrente massima Imp	40	40	40	40
Corrente massima Imp @Max.Temp	13,70	13,70	13,70	13,70
Battery model				
Storage system				
Enabled for Storage	False			

	MPPT 9	MPPT 10
Campo FV	Campo FV 1	Campo FV 1
Moduli per stringa	18	18
Numero di stringhe in parallelo	1	1
Numero totali di moduli	18	18
Potenza installata massima MPPT [kW]	9,9	9,9
Potenza massima di canale MPPT [kW]	20	20
PPV(inst),MPPT/PMMPTMAX	0,50	0,50
PPV(inst)/PACR	99,00%	
PPV(inst)/PACMAX	90,00%	
Tensione di ingresso massima inverter	1100	1100
Tensione di attivazione	200	200
Range operativo MPPT a massima potenza	500 - 850	500 - 850
Voc_max stringa a circuito aperto @Min.Temp	969,44	969,44
Voc_min stringa a circuito aperto @Max.Temp	798,18	798,18
Vmp_Max tensione stringa @Min.Temp	799,07	799,07
Vmp_Min tensione stringa @Max.Temp	657,91	657,91
Massima corrente Isc per canale	50	50
Corrente CC Isc @Max. Temp	14,29	14,29
Corrente massima Imp	40	40
Corrente massima Imp @Max. Temp	13,70	13,70
Battery model		
Storage system		
Enabled for Storage	False	

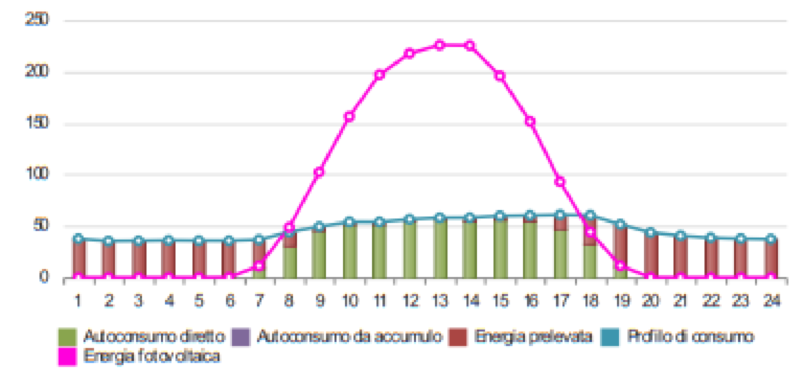
Autoconsumo

Consumo energetico annuo	410.594,14 kWh	Resa energetica annua	614.950,95 kWh
Autoconsumo da FV	205.546,24 kWh	FV a batteria	0,00 kWh
Consumo da storage	0,00 kWh	Feed-in griglia	409.404,72 kWh
Energia comprata	205.047,90 kWh	Autoconsumo da FV	33,42%
Quota di autosufficienza energetica	50,06%	Capacità della batteria	0,00 kWh

Produzione media annua

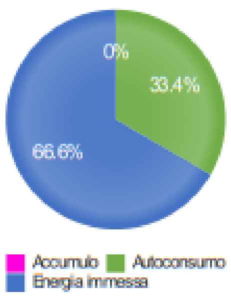


Consumo medio annuo

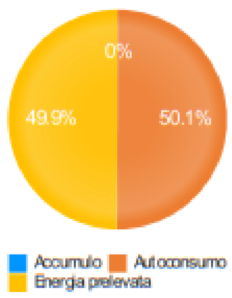


Powered by Azzurro configurator

Produzione



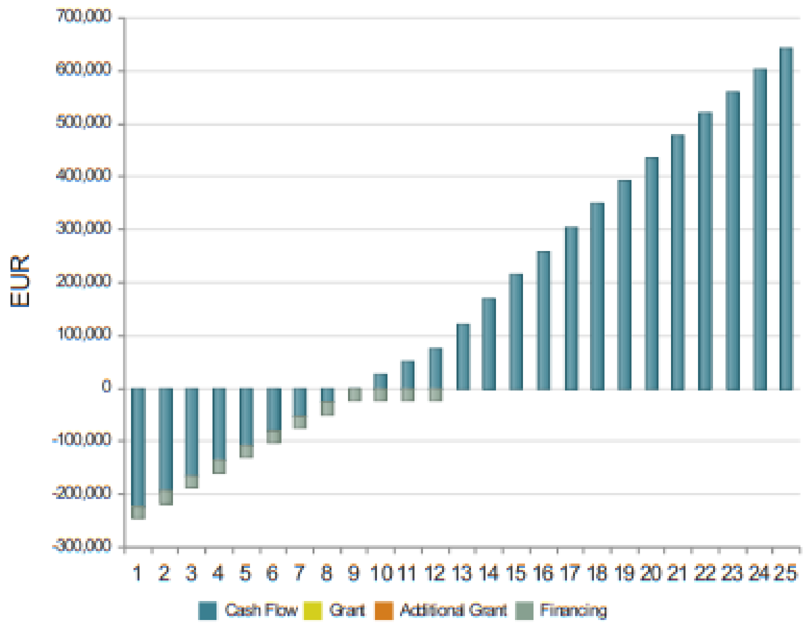
Consumo



Ritorno dell'investimento

Periodo analisi ROI	25 years	Investimento totale	EUR 509741,09375
Costo batteria	EUR 0	Decadimento batteria	0 % annuale
Sovvenzione	EUR 255445	Periodo Analisi	12 Anni
Incremento % annuo prezzi	1%	Rata di interesse mensile	1%
Prezzo acquisto dell'energia	0,17 EUR/kWh	Tariffa incentivante	0 EUR/kWh
Durata incentivo	0 Anni	Ricavo da incentivo	0,08 EUR/kWh
Totale Ricavi	EUR 642 820	Tasso di rendimento annuale	0,9%

Risparmio effettivo

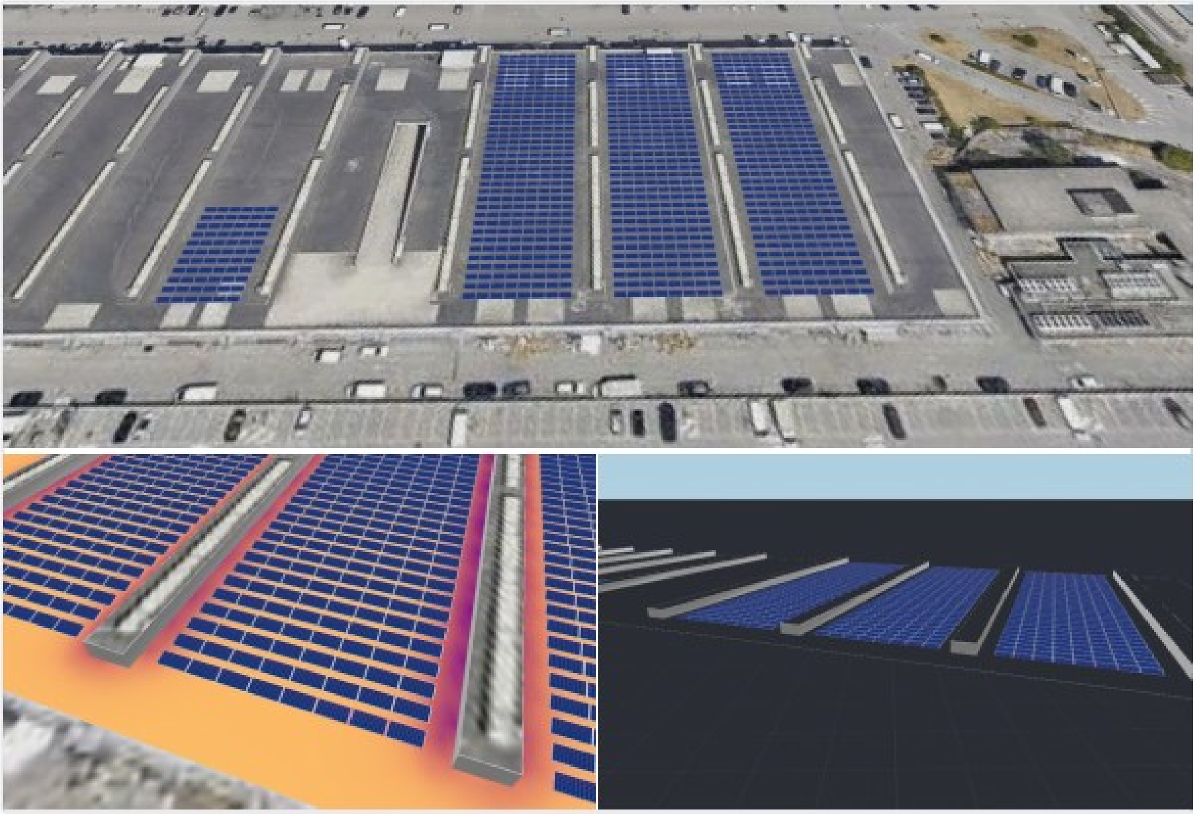


Appendix B

solaredge | REPORT DESIGNER | Pag. 1 di 5 ID impianto: 935811867792826

TELEZIP - 500 KWP

Corso Stati Uniti 1, Padova, 35127, Italy | Telezip | 22 set 2023



PANORAMICA DEL SISTEMA

906 Moduli FV | 5 Inverter | 456 Ottimizzatori

RISULTATI DELLA SIMULAZIONE

Potenza CC Installata	Potenza Massima CA Ottenuta	Produzione Annuale Di Energia	Emissioni Di CO2 Evitate	Alberi Equivalenti Piantati
498,30 kWp	450,00 kW	625,10 MWh	160,03 t	7.350

Potenza CC Massima Ottenuta	Sovradimensionamento CC/CA	Potenza Attiva CA Max	PR Rapporto Di Performance	Indice Di Performance
498,30 kW	100 %	499,50 kW	86 %	1.254 kWh/kWp

solaredge | REPORT DESIGNER | Pag. 2 di 5 ID impianto: 935811867792826

TELEZIP - 500 KWP

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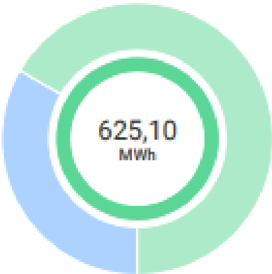
PRODUZIONE DEL SISTEMA

Produzione totale - 100 %
625,10 MWh

Autoconsumo - 33 %
208,65 MWh

Esportata - 67 %
416,45 MWh

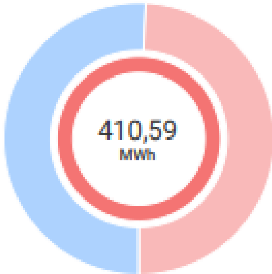


CONSUMO

Consumo totale - 100 %
410,59 MWh

Autoconsumo - 51 %
208,65 MWh

Importata - 49 %
201,94 MWh



TELEZIP - 500 KWP

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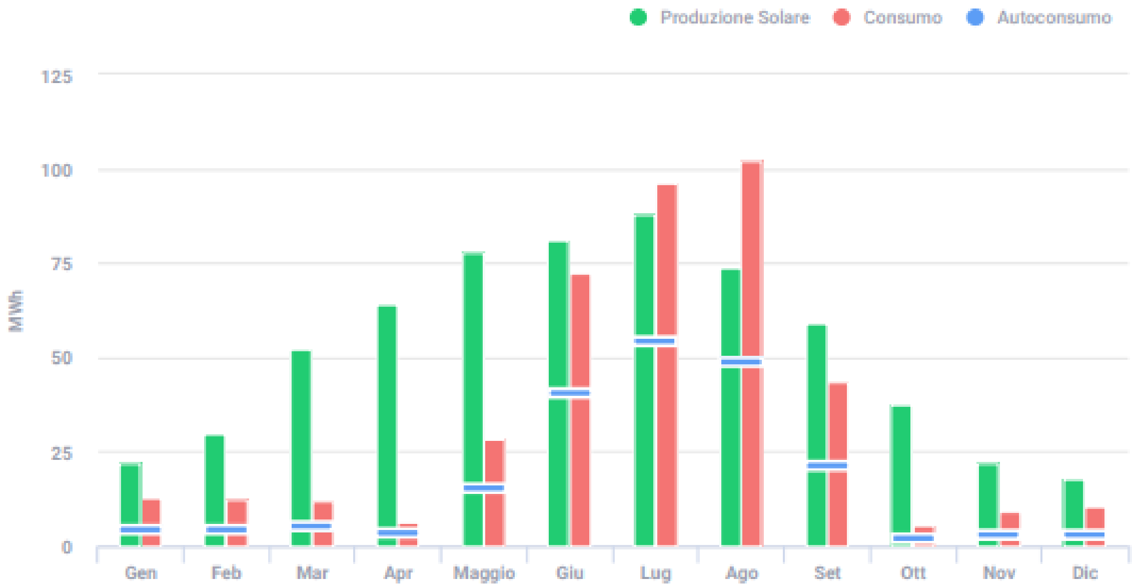
ENERGIA MENSILE STIMATA



Energia totale tagliata: -0%

	Mese Produzione Solare (kWh)	Consumo (kWh)	Auto-consumo (kWh)	Energia troncata (kWh)
Gen	21.960	12.715	4.539	-
Feb	29.880	12.160	4.627	-
Mar	52.173	11.701	5.359	-
Apr	64.032	6.616	3.577	-
Mag	77.823	28.377	15.607	-
Giu	81.053	72.141	40.872	-
Lug	87.904	96.290	54.593	-
Ago	73.677	101.946	48.893	-
Set	59.047	43.435	21.602	-
Ott	37.351	5.556	2.311	-
Nov	22.149	9.219	3.259	-
Dic	18.049	10.437	3.411	-

TELEZIP - 500 KWP

Corso Stati Uniti 1, Padova, 35127, Italy | Telezip | 22 set 2023

MODULI FV

# Modulo	Modello	Potenza di picco	Tipo di supporto	Orientamento	Azimut	Inclinazione
906	JinkoSolar Holding Co. Ltd., JKM-550M-72HL4-V Tiger Pro 72HC	498,3 kWp			201°	15°
Totale: 906		498,3 kWp				

DISTINTA MATERIALI (BOM)

Componenti	Codice Prodotto	Quantità	Prezzo (€)	Totale (€)
SE100K Manager		5		
S1200		456		
JKM-550M-72HL4-V Tiger Pro 72HC		906		

TELEZIP - 500 KWP

Corso Stati Uniti 1, Padova, 35127, Italy | Telezip | 22 set 2023

DIAGRAMMA DELLE PERDITE DEL SISTEMA

PARAMETRI DI SIMULAZIONE

LUOGO & RETE

Fuso orario	CEST (Rome)
Stazione meteo	Padua (4,35 km distanza)
Altitudine stazione	11 m
Stazione sorgente dati	Meteonorm 7.1
Rete	400V L-L, 230V L-N

FATTORI DI PERDITA

Ombre vicine	Abilitato
Albedo	0,20
Sporcizia/Neve	0%
Effetto Angolo di Incidenza (IAM), ASHRAE b0 Param.	0,05
Fattore di Perdita termica Uc (cost.) montaggio complanare	20
Fattore di Perdita termica Uc (cost.) montaggio inclinato	29
Fattore di perdita per LID	0%
Indisponibilità del sistema	0%

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