POLITECNICO DI TORINO

Master's Degree in Energy and Nuclear Engineering

Master's Degree Thesis

Feasibility study and economic analysis of photovoltaic plant and CHP technology for a medium voltage user

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Academic Year 2021/2022

Abstract

The purpose of this master thesis is to analyse in detail the possible integration of two different technologies applied for an industrial plant, according to an energetic point of view and in terms of economic feasibility.
The first part is focused on the implementation of a renewable energy system, the photovoltaic one, whereas the second part aims to study the coupling of Combined Heat and Power technology with a photovoltaic plant.
The company Light Wire provided a design tool, which is employed for both scenarios and it allows easily to model the industrial structure and to dimension the PV plant.
Subsequently, the energy produced is estimated in both cases, by paying attention on that energy self-consumed, which will be able to reduce the electricity withdrawn from the network.
An economic evaluation must be performed for both, in order to understand what the major costs of this renewable technology are and, by computing some financing parameters, what the most cost-effective is.

Contents……………………………………………………………………………………………2

List of Figures

List of Tables

1. General Introduction

Renewables have grown rapidly in recent years, driven by policy support and sharp cost reductions for solar photovoltaics and wind power, particularly.
The electricity sector remains the brightest spot for renewables with the strong growth of solar photovoltaics and wind in the last years, building on the already significant contribution of hydropower. Electricity, though, accounts for only a fifth of global energy consumption, and the role of renewables in the transportation and heating sectors remains critical to the energy transition.
In sharp contrast to all other fuels, in 2020, renewable electricity generation rose about 7%, with wind and solar PV technologies together accounting for almost 60% of this increase.
The share of renewables in global electricity generation reached almost 29% in 2020, a record annual increase of two percentage points. However, the drop in electricity demand due to Covid-19 slowdown in economic activity and mobility is a key reason for this record.
Renewable power deployment as a whole still needs to expand significantly to meet the Net Zero Emissions by 2050 Scenario share of more than 60% of generation by 2030.
Yearly generation must increase at an average rate of nearly 12% during 2021-2030, almost twice as much as in 2011-2020. [1]

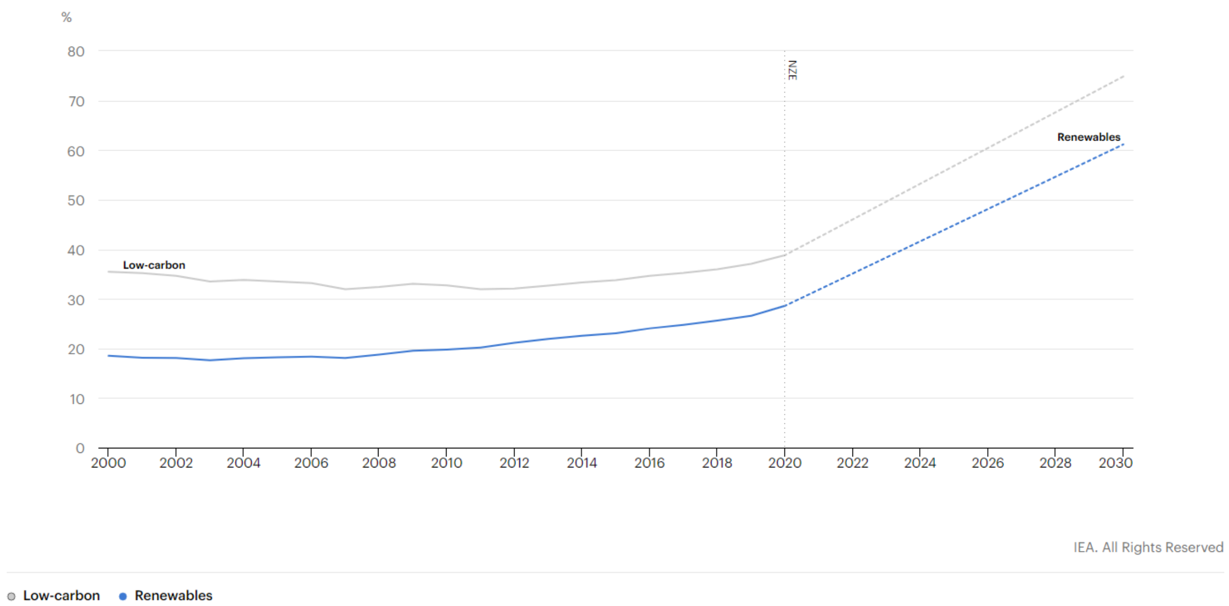


Figure 1.1: Renewables and low-carbon share in power generation in the Net Zero Scenario, 2000-2030 [2]

2. Introduction to Solar Photovoltaics

Solar PV worldwide

Solar PV generation increased a record 156 TWh (23%) in 2020 to reach 821 TWh. It demonstrated the second-largest absolute generation growth of all renewable technologies in 2020, slightly behind wind and ahead of hydropower. Looming policy deadlines in China, the United States and Vietnam spurred an unprecedented boom in PV capacity additions – a record 134 GW.

Solar PV is becoming the lowest-cost option for electricity generation in most of the world, which is expected to propel investment in the coming years.

However, the Net Zero Emissions by 2050 Scenario shows average annual generation growth of 24% between 2020 and 2030, which corresponds to 630 GW of net capacity additions in 2030. This almost fivefold increase in annual deployment until 2030 will require much greater policy ambition and more efforts from both public and private stakeholders, especially in the areas of grid integration and the mitigation of policy, regulation and financing challenges, particularly in emerging and developing countries.

The tracking status for Solar PV has therefore been changed from "on track" to "more efforts needed", reflecting the higher ambition of the Net Zero Scenario compared with last year's Sustainable Development Scenario [3]

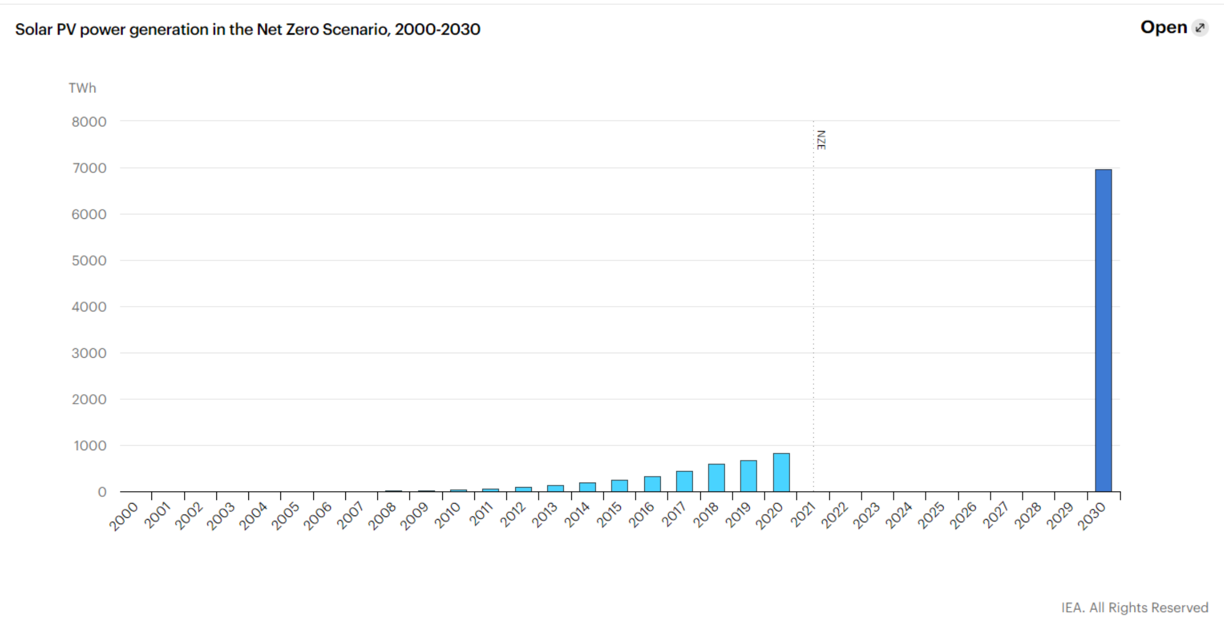


Figure 2.1: Solar PV generation in the Net zero scenario, 2000-2030 [3]

3. Introduction to Combined Heat and Power technology

The Cogeneration is a well-known technology, which is one among the most efficient for the energy production in industrial sectors, for electrical users and for heating purposes.
It allows to generate in only one process electrical and thermal energy, by reaching a high value of efficiency compared to the separate production of thermal and electrical energy.
Furthermore, it is possible to produce refrigerated water to be used in cooling mode during summer: it is the case of the Trigeneration.
In Italy there are over 1300 cogeneration units installed, for a total of about 13300 MW of power that produces about 17,5% of the total electricity demand.
Cogeneration systems are extremely flexible in power sizes, allowing them to be installed in many industrial and commercial contexts, even with relatively low electrical and thermal power loads. [4]

3.1. Functioning of Cogeneration

Normally, the production of electrical and thermal energy takes place through separate processes, using thermoelectric power plants and boilers. In each of these, a part of the primary energy, i.e. the fuel, is not converted into useful energy but it is lost (45% of the energy is wasted in the production of electricity). With cogeneration, both electrical and thermal energy are produced through a single process, recovering the heat that would otherwise be lost.
In this way, the overall efficiency of the system reaches on average 85% of the primary energy introduced, but it can exceed 90%. In practice, the same amounts of electricity and heat generated in separate processes are consumed using 30% less fuel. [4]

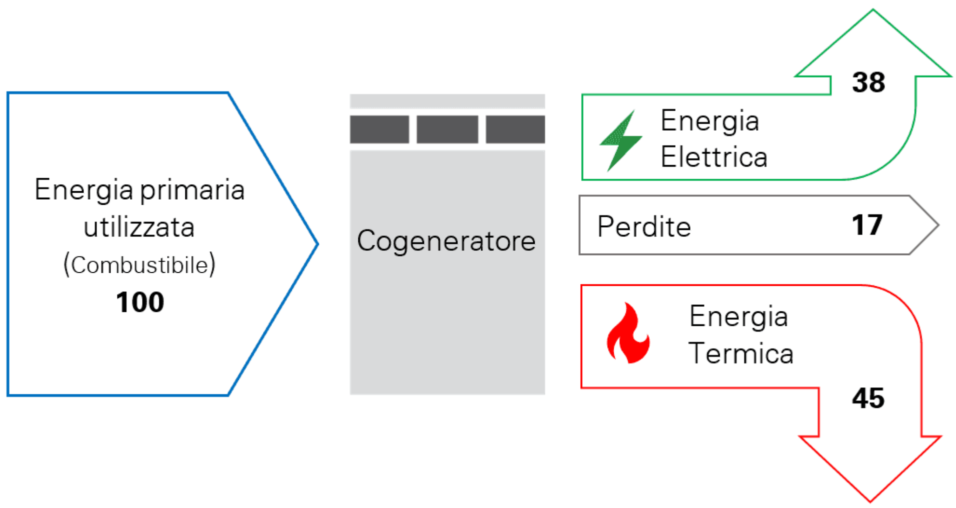


Figure 3.1: Example of energy balance for Combined Production [4]

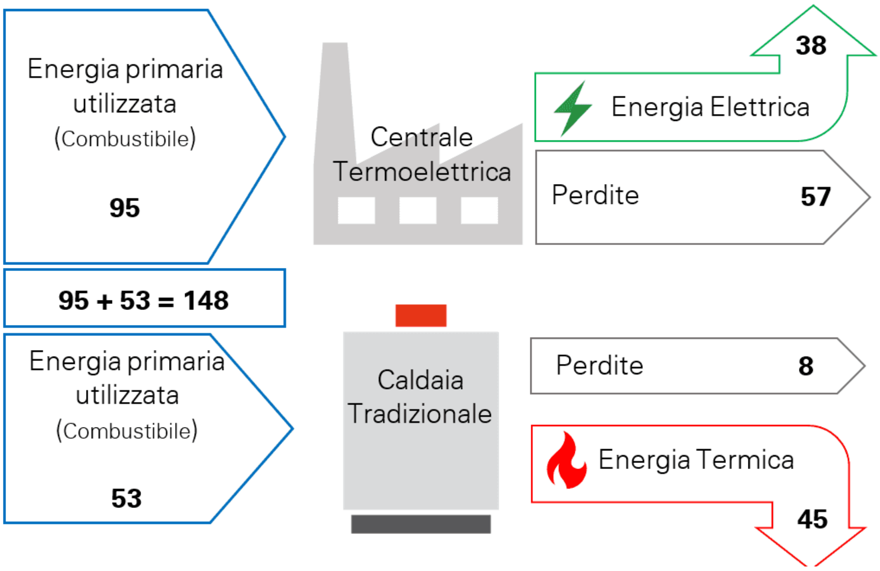


Figure 3.2: Example of Energy Balance for Separate Production [4]

<u>Base principle of Combined Heat and Power</u>

A cogeneration plant consists mainly of an engine, an alternator, a heat recovery system and a command-and-control panel.

The chemical energy of a fuel (it can be natural gas or a renewable source like biogas) is converted into mechanical energy by employing an engine. Then the machine drives an alternator, which can transform the mechanical energy of device into electricity.

The thermal energy produced by the engine and the flue gases is not wasted into the environment like in a traditional power plant, but it is recovered and introduced into the system.

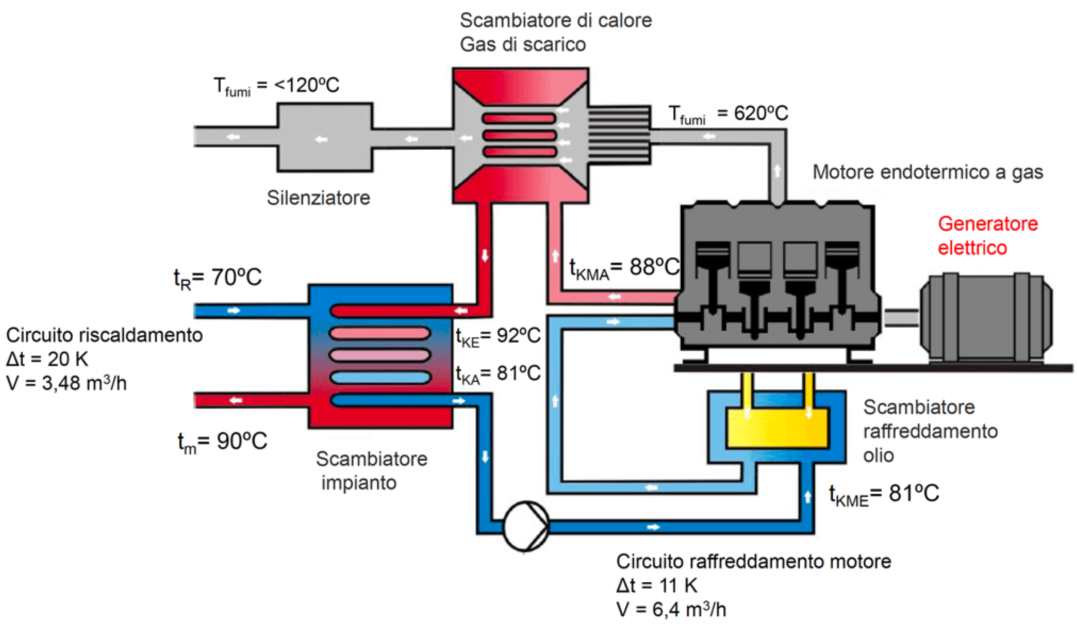


Figure 3.3: Technical scheme of a CHP system [4]

There are several primary generation technologies employed in a cogeneration system.
The common ones are:

- Internal combustion engine;
- Gas turbines and microturbines with heat recovery;
- Steam turbine;
- Combined cycles with gas turbine and steam turbine.

Each type is characterized by a specific ratio between electrical and thermal power and it is suitable for certain power classes. The choice of technology and size of the cogenerator depends on the characteristics of the user in terms of thermal and electrical needs. [4]

Advantages of Combined heat and Power

- The simultaneous production of electricity and heat allows to achieve a higher level of efficiency compared to other energy production technologies (it can exceed 90%).
  This enables to consume less primary energy, with advantages on the costs of energy supply, and to reduce polluting emissions for the same amount of energy produced, thus determining environmental benefits.
- The CHP allows to reduce the energy consumption: for every kWh produced with cogeneration, 0,14 TOE, 160 m^3 of methane and 130 kg of diesel are avoided.
- Environmental sustainability: a minor fuel consumption with same useful effects.
  For every MWh generated we can avoid on average 500-600 kg of CO_2, 0.15 Kg of NO_x and 15 Kg of SO_x.
- A great energy independence from the suppliers thanks to self-consumption of heat and electricity.
- Peak Shaving effect, i.e. the reduction of peak loads from the network with a relative decrease in the cost items in the bill.
- Possibility of operating in trigeneration, using the excess heat to produce cooling energy that can be used for summer air conditioning or for industrial processes.
- Possibility of employing local renewable energy sources, like biomass, instead of fossil fuels.
- Use of the incentive mechanisms of the White Certificates, in case of high efficiency cogeneration, shortening the pay-back time.
- The generation of energy distributed throughout the territory avoids the construction of new power stations and transmission lines, also reducing grid losses. [4]

4. Case Study

4.1 General Information:

TRA.SMA S.p.A. is a private company born in 1994, certified ISO 9001 and ISO 14001.
It is located in the industrial area of Moncalieri (Turin) and it is the leader on the European market in production of copper wires for cable manufacturers.
The company enjoys state of the art production plants and control tools granting high quality standards, by respecting the environment.
Furthermore, in few years, it has been operating in order to meet its energy needs and heating supply.
For its production process, TRA.SMA exploits the cogeneration of electrical and thermal energy and this strategic approach has resulted in energy efficiency and eco sustainability.
The industrial plant covers a total surface of 13000 m^2 and it is divided into two structures, one of which is located in Moncalieri and the other one in Trofarello.
The two units are connected by a medium voltage line and a gas cogenerator is set in each of them.
The whole productivity is located in the Moncalieri building, whereas in Trofarello there are only the cogenerator and antifreeze pumps. [5]

Figure 4.1: View from top of Structure
Source: Google Earth

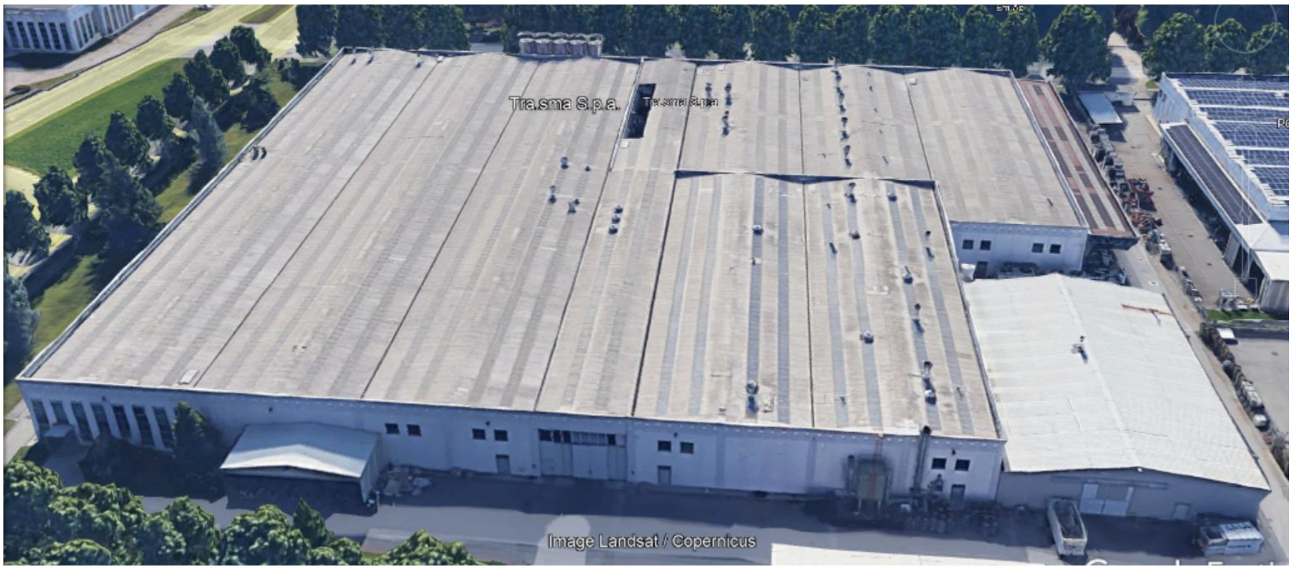


Figure 4.2: Side View of industry
Source: Google Earth

4.2. Distribution of the Electrical network

The figure below shows how the electrical energy is distributed within the industrial plant.

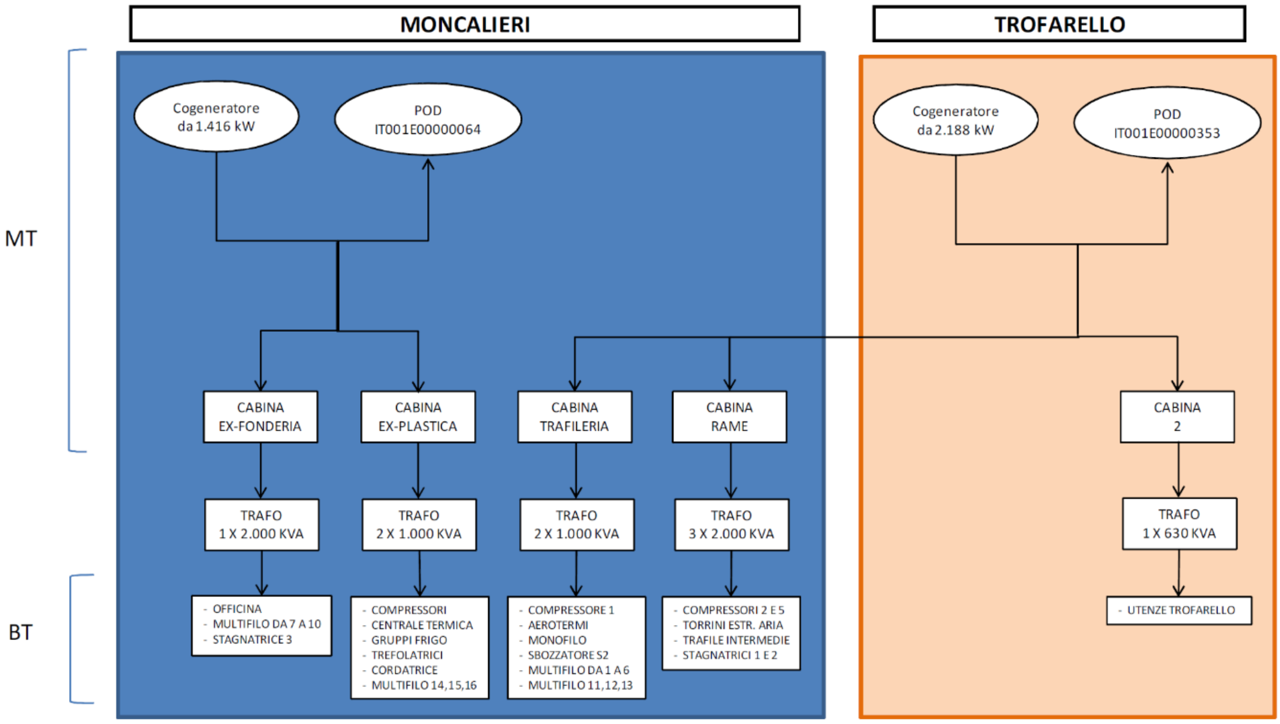


Figure 4.3: Electrical distribution of TRA.SMA

Each unit of industrial plant is supplied by its bidirectional point of delivery.
The Moncalieri part receives electricity from a cogeneration plant which has a prime mover with a rated power of 1416 kWe and from a certain POD.

Whereas the plant in Trofarello receives electrical energy from a cogeneration unit with a prime mover with a nominal power of 2188 kWe and from another POD.
The energy produced and purchased by Plant in Moncalieri is consumed within the sectors called "*ex fonderia*" and "*ex plastica*" and released into the network in case of excess of electricity. The quantity of energy produced and bought, instead, by plant in Trofarello is partially consumed inside "*cabina 2*" and partially is transferred to the Moncalieri building for powering the part "*cabine trafileria e rame*" by releasing the surplus of electricity into the grid.

4.3. Natural Gas Distribution and Thermal Energy

The natural gas purchased by Tra.sma is almost entirely employed for powering the Cogeneration units. The primary energy coming from the natural gas is converted into thermal energy inside the cogenerator itself, and this thermal energy is used in the form of hot water for heating the offices and in part of the productive spaces.

4.4. Analysis of consumption of Tra.sma

Before dimensioning correctly, a future plant that exploits renewable sources, the first step to do is studying the real electricity consumption of industrial plant.
In this case it was possible analyse the consumption by means of the knowledge of electrical bills of 2019 given by the user, before the energy impact due to global health emergency.
The electrical bills are generally divided into 3 time slots: F1, F2 and F3.

- F1 time slot involves the electrical consumption during the week, Saturday and Sunday not included, from 8 to 19. The national holidays are not included. It's the most expensive time slot.
- F2 includes the electrical consumption in the time interval Monday-Friday from 7.00 to 8.00 and from 19.00 to 23.00 plus Saturday from 7.00 to 23.00, excluding national holidays.
- F3 time slot involves electrical consumption Monday-Saturday from 00.00 to 7.00 and from 23.00 to 24.00, Sunday and holidays included 24/7. It's the cheapest time slot. [6]

As it was said before, the company covers its energy needs by employing a Cogeneration unit. However, the latter is not always sufficient to reach the energy request.
Therefore, in this case, the electrical energy is withdrawn from the network through the point of delivery.
The actual electrical and thermal consumption of the plant is summarized in the following table.

MONCALIERI					
Month	**Natural Gas consumption [Sm^3]**	**Electricity produced [kWh_e]**	**Electricity Self-consumed [kWh_e]**	**Energy Sold [kWh_e]**	**Electricity purchased [kWh_e]**
January 2019	158968	607476	533724	73752	59851
February 2019	159402	611193	562552	48641	117487
March 2019	182218	699806	627314	72492	63743
April 2019	144118	555190	533432	21758	64870
May 2019	140864	545793	502494	43299	221601

June 2019	136321	536182	455710	80472	109609
July 2019	169562	659795	648708	11087	96032
August 2019	42400	165322	137096	28226	38240
September2019	162353	633625	578964	54661	75892
October 2019	157998	618324	540055	78269	33447
November2019	167026	651789	410887	240902	33567
December 2019	81694	317462	237434	80028	50498
Total	**1702924**	**6601957**	**5768369**	**833588**	**964837**

Table 4.1: Natural gas consumption and Electricity produced in 2019

In our case study we are focusing on Moncalieri site consumption, since the structure covers a larger area to be exploited for the installation of a new renewable energy system and it involves almost all the company's production processes.

Let's suppose, for the target of analysis, to remove the Cogeneration unit to understand the real energy consumption of building if the whole electricity is withdrawn from the grid.
If the electricity self-consumed by company is added to the electricity withdrawn by the network, we could obtain the "real" electrical consumption of industrial plant.

Month	F1 [kWh]	F2 [kWh]	F3 [kWh]	Electrical Consumption [kWh]
January 2019	213687	201816	178073	593575
February 2019	244814	231213	204012	680039
March 2019	248780	234959	207317	691057
April 2019	215389	203423	179491	598302
May 2019	260674	246192	217229	724095
June 2019	203515	192208	169596	565319
July 2019	268106	253212	223422	744740
August 2019	63121	59614	52601	175336
September 2019	235748	222651	196457	654856
October 2019	206461	194991	172051	573502
November 2019	160003	151114	133336	444454
December 2019	103655	97897	86379	287932
Total	2423954	2289290	2019962	**6733206**

Table 4.2: Electrical consumption of industry without cogeneration unit

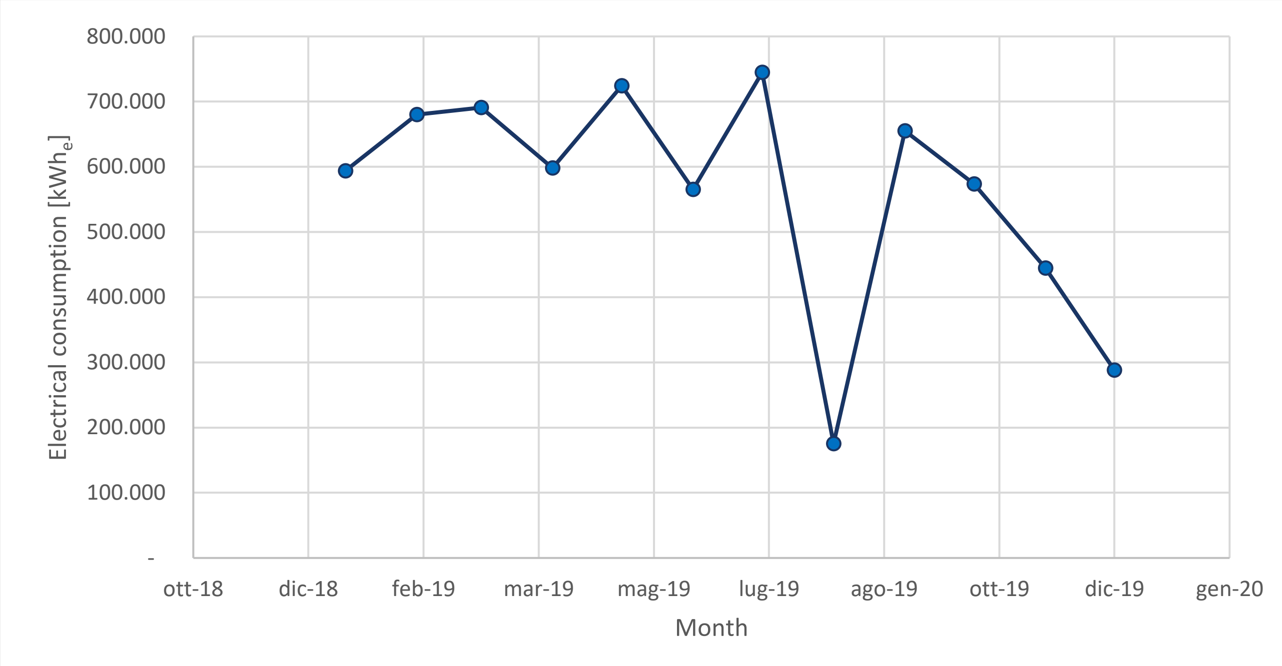


Figure 4.4: Behaviour of Electricity Consumed

As it can be seen from the graph, the electricity consumption of users is generally very high, and the trend is not constant during the year.
In the first months of the year, the values of electricity produced fluctuate between 570 and 730 MWh. The maximum peak is achieved in July, whereas the lowest consumption is highlighted in August when the company is closed for the summer holidays.
Then, there was a decline between October and December, the latter due to the closure during the Christmas period.

4.5. Structure Modelling

The design tool employed for the development of the project can create a photovoltaic template for residential and industrial structure. In this case the latter will be chosen.
Before modelling the PV plant, let's start from the two-dimensional modelling of the entire surface covered by the structure.
Then we estimate roughly the height of the building, the surface and inclination of the roof to obtain a three-dimensional model.
If it is possible, we should compare the estimated values with the tool with planimetry of structure, in order to have a more detailed measure.
One characteristic to be taken into account is the amount of energy radiated from the Sun on the surface. This value is called Irradiance and the tool gives this information by expressing it in percentage.
For this reason it is very important to estimate as correct as possible the inclination roof.
Basically if the value is below the 80%, not locating the module there would be better because it will produce a little amount of energy and most of it will be lost.
Furthermore, it is also important to check for the presence of shading around the building.

There are several trees located in southerly and westerly direction, but they do not contribute to obstacle the roof, since they are not high enough to shade it.
The same consideration can be done for nearby industries.
The only shading that it can be observed is the shadow created by two parts of the same structure since the first one is higher than the second one.

Feature		Unit of measure
Length	113,16	m
Surface	15137	m^2
Height	10	m
Roof Inclination	6	°
Azimuth for layer n°1	182 with North reference	°
Azimuth for layer n° 2	2 with North reference	°

Table 4.3: Characteristics of Roof

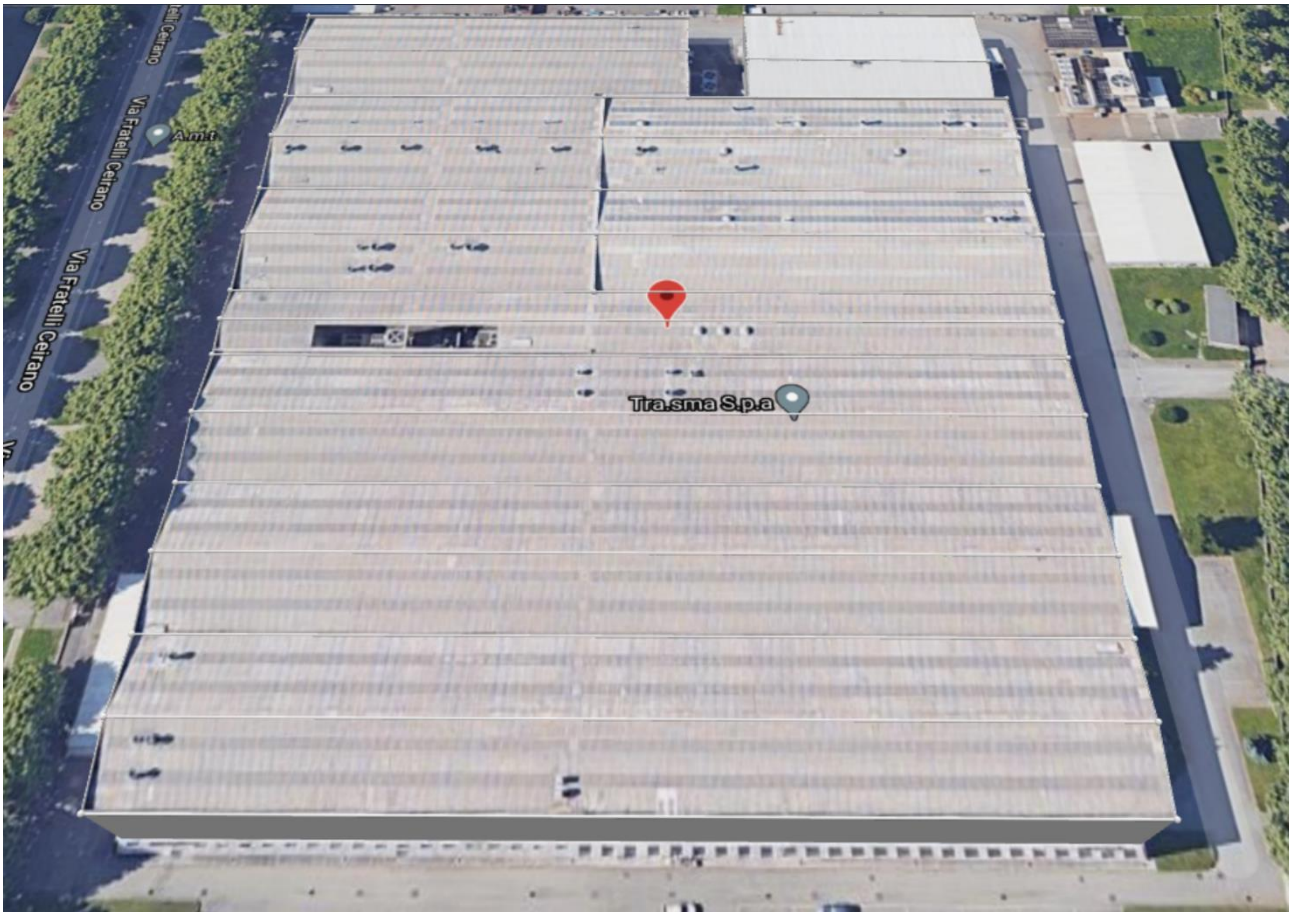


Figure 4.5: Model structure in 3D - top view

Figure 4.6: Model structure in 3D - side view

Figure 4.7: Inclination of layer 1

Figure 4.8: Inclination of layer 2
Source [7]

5. Scenario 1: Installation of a Photovoltaic Plant

5.1. Features of PV module

Once we have designed the entire structure, it is fundamental to choose the PV panel as reliable as possible, to be inserted on the roof, depending on the technology available on the market.
Nowadays the market is covered by monocrystalline Silicon, which is currently the most efficient technology, so we might choose this one for the calculations, in order to have higher performance.
There are many brand producers of PV modules, e.g. LG electronics, Viessmann, Suntech, JA Solar, Trienergia, etc….
Let's choose for our purpose the Suntech one.
A photovoltaic panel is characterized by several important features:

a. Efficiency

It is an important value defined as the ratio between the rated electrical power produced by PV module and the amount of irradiated Power from the Sun over the panel's surface.

$$\eta = \frac{P_{rated}}{I_{STC} * Area} = \frac{I_{MPP} * V_{MPP}}{I_{STC} * S_{PV}} = \frac{540\ W}{1000\ W/m^2 * 2{,}584\ m^2} = 20.9\ \%$$

The rated power is given by the product of

- the current delivered in the maximum power point I_{MPP};
- the voltage applied to the panel at maximum power point V_{MPP}.

These two values are listed in the electrical characteristics of the module in the data sheet.
I_{STC} is the solar irradiation incident on the module in standard test condition. It is equal to 1 kW/m^2.
The module, made of monocrystalline silicon, has a high value of efficiency compared to amorphous and polycrystalline silicon. Therefore, according to the mathematical formula, the module will cover a small area of the roof of building.[8]

b. Temperature Coefficient

All photovoltaic panels decrease their performance as the operating temperature increases. Especially in areas with high summer temperatures this parameter can make the difference.
Each manufacturer enters in the technical data sheet the temperature coefficient through which it indicates the loss of performance for each additional degree of temperature.
For poor quality modules the coefficient is about 0.5% per degree centigrade, this value can improve up to 0.25% per degree centigrade, for good quality panels.
The Suntech module can be classified as a good quality PV panel.

c. Tolerance on Rated power

It represents the maximum deviation in percentage with respect to the rated power declared by module. The tolerance is always indicated with a positive value (or zero) and a negative value (or zero). The best PV panels are those which have the tolerance shifted towards the positive value, maintaining the same other characteristics.

For Suntech module the tolerance is 0/0,926 %.

d. Fill Factor

It is a nondimensional parameter, related to the shape of solar cell.

It measures the degree of purity and the correct exploitation of the Silicon wafer that the module is made of.

It is a number between 0 and 1 and the closer it is to 1, the better is the quality of the module, the lower will be the losses and the aging factors.

Moreover, the determination of this number determines how much the I-V Characteristic curve deviates from the I-V Characteristic curve of an ideal pure solar cell.

$$FF = \frac{P_{rated}}{I_{sc} * V_{oc}} = \frac{540}{13{,}89 * 49{,}54} = 78{,}5\ \%$$

The value of fill factor shows again the great performance of the panel chosen for the analysis. [9]

e. Power warranty

Photovoltaic panels are subjected to a decline in their performances through years, usually about 1 % per year. Consequently, the module should preserve, after 10 years, a minimum power of 90 % of installed power and, after 20 years, a minimum power of 80 %.

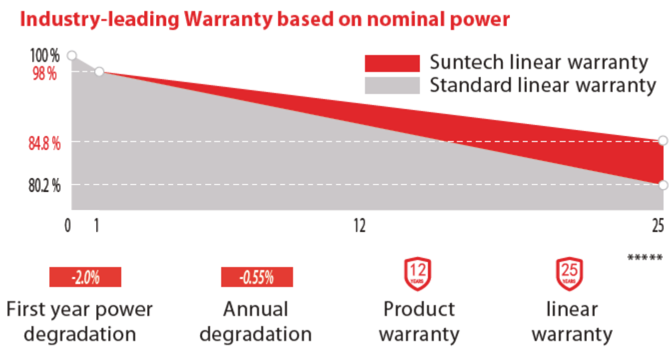


Figure 5.1: Linear warranty of Suntech module

f. Normal Operating Cell Temperature

It is defined as the equilibrium temperature of solar cells inside a PV module.

Since the PV module works at different environmental conditions rather than standard conditions at T_{cell} = 25 °C, it's needed to introduce the NOCT value to calculate the influence of Temperature over the Power.

It is measured when:

- The irradiance is 800 W/m^2
- The ambient temperature is 20 °C
- The wind speed is 1 m/s

$$T_{cell} = T_{Amb} + G_p * \frac{(NOCT - 20)}{800}$$

The typical NOCT must be in the range 40-50 °C
Low NOCT values correspond to a good capacity of the solar cells to dissipate heat towards the outside [10]

g. Mechanical resistance

The panels must be able to withstand the mechanical stresses caused by atmospheric agents, such as snow, wind and hailstorm, without being damaged.
Every module can withstand a certain weight in Kg/m^2 or Pascal. Higher is the resistance, lower will be the risk of damaging of the panel during years.

Module SUNTECH 540S-C72/Vmh		Unit of measure
Typology	**Monocrystalline Silicon**	
Rated Power @STC	**540**	[W_p]
Tolerance	**0/0,926**	[%]
Lenght	**2,279**	[m]
Width	**1,134**	[m]
Surface	**2,584**	[m^2]
Efficiency	**20,9**	[%]
Weight	**29,1**	[kg]
N° of cells	**144**	
Short circuit current Isc	**13,89**	[A]
Open circuit voltage Voc	**49,54**	[V]
Current at MPP Impp	**12,94**	[A]
Voltage at MPP Vmpp	**41,75**	[V]
Temperature coefficient Pmax	**-0,36**	[%/°C]
Temperature coefficient Isc	**0,05**	[%/°C]
Temperature coefficient Voc	**-0,304**	[%/°C]
NOCT	**42**	[°C]
Tolerance of power	**0/+ 5**	[W]
Fill Factor	**78.5**	[%]

Table 5.1: Summary of PV module characteristics

5.2. PV modules Configuration

Thanks to the tool, we can choose the orientation of module (horizontal or vertical) and its position (lying on the roof, inclined with the respect to the roof).
The PV module cannot be installed randomly over the surface, but it is necessary to make some considerations.

- The distance between each panel is at least 2 cm, because a clip must be inserted between them.
- The module should be installed parallel to the corrugated roof profile to permit the insertion of minirails, that are little devices usually inserted perpendicular to the profile structure.
- The PV module cannot be installed above a skylight for fire prevention and safety reasons.
- It would be better if the module is not placed on the surface that has an irradiance lower than 80 %.
- The module must be far from a chimney and side part of the roof.
- The total power installed by PV plant must be below the available power at the smart meter. Hence, it is important to check if the power installed by PV arrays does not overcome that value of power.

In our project all Photovoltaic panels will be arranged on the rooftop.
Since the roof of the building is full of several skylights, the surface cannot be completely covered by PV strings. Moreover, most of panels will be arranged in horizontal position whereas only some of them will be placed vertically.
The imagine below displays the configuration of the whole PV plant obtained by considering the previous factors.

Figure 5.2: Arrangement of PV arrays

Figure 5.3: Top view of whole PV plant

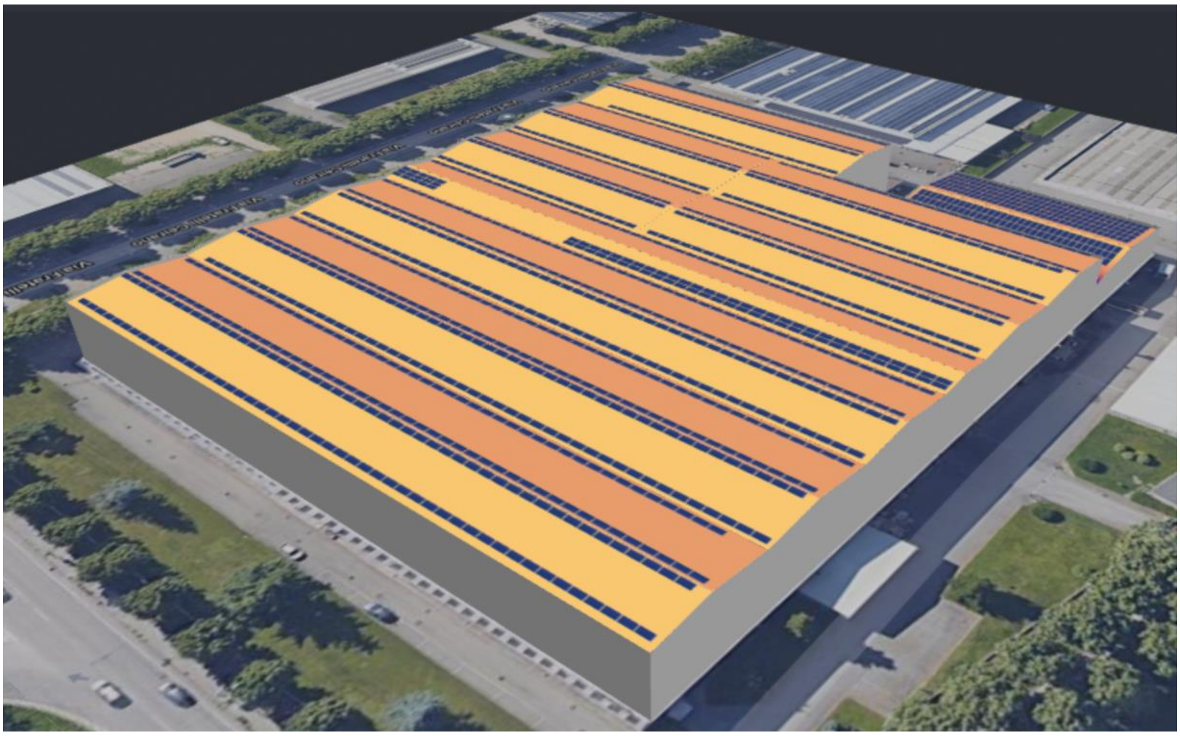


Figure 5.4: Irradiation captured by the modules

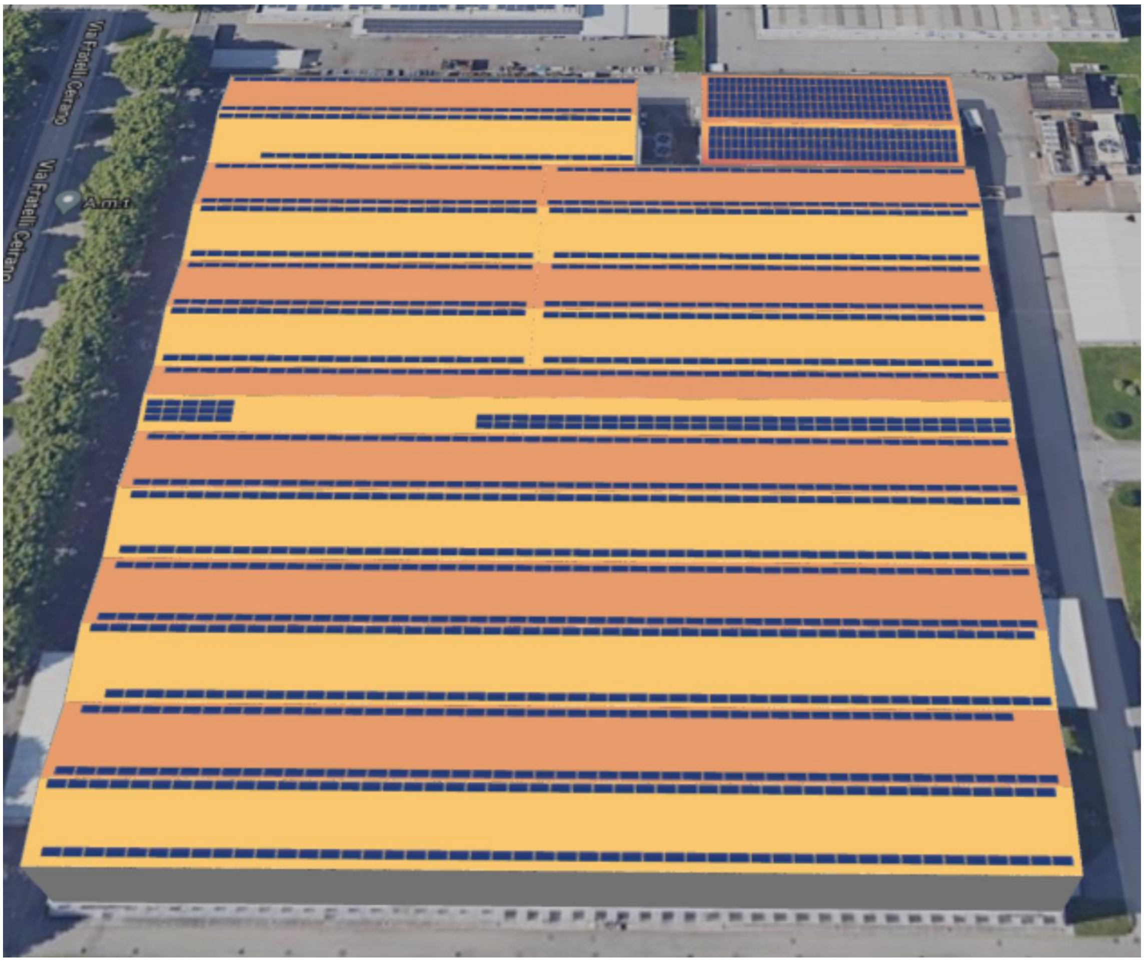


Figure 5.5: Irradiation – Top view

Figure 5.6: Detail of the PV configuration

The immagines 5.4, 5.5, 5.6 show the percentage of Irradiance on the rooftop: it's possible to see that in the yellow zone the irradiance is at 89%, in the orange part the irradiance is 81 %, whereas in the violet part the radiated energy is so low (it reaches 45 %) that installing a PV arrays there will not convenient anymore.

5.3. Electrical Design

Once all the Photovoltaic modules have been arranged on the rooftop, we move on to the next phase of the project, which is the electrical design of the renewable plant.
During this step, we have to connect the PV strings with a fundamental component of a PV plant, the inverter and, then, with the power optimizer.

5.3.1. Characteristics of the Inverter

The PV panels produce electrical energy in DC form, whereas the industrial user needs an electricity in AC.
The inverter is an electrical device able to convert the direct current (DC) coming from PV panel to alternate current (AC), at a certain voltage and frequency, with the purpose of powering those devices that work with AC.
A good inverter must have the following features:

- The inverter efficiency, i.e. the energy percentage converted into alternating current, has to be higher than 96 %.
- The device must maximize the energy withdrawal from photovoltaic field.
- Possible compatibility with other components, such as electrical storages.
- Monitoring and control of the operation and performance of the system. [11]

There are mainly 2 types of inverters:

- One-phase Inverter
  It is employed in domestic context where the alternating current is in one phase and for the PV plants that require low installed power.
- Three-Phase Inverter
  It is the most suitable if we want to install a large PV plant (with a high installed power) for covering the energy consumption of a medium voltage user.
  This kind of inverter combines sophisticated digital control technology with efficient power conversion architecture to achieve superior solar harvesting and best-in-class reliability. [11]

The design tool provided by Light Wire offers several types of inverters.
We can manually connect each PV string with a type of inverter, selected arbitrarily, or alternatively the tool automatically proposes a possible lacing configuration.
Let's choose the second option because it is a faster solution when lot of PV modules must be connected.
The inverter connected at PV array are two:

- Solaredge SE 82,8 K
- Solaredge SE 90 K

3 phase Inverter Solaredge SE 82,8 K		Unit of measure
Input		
Maximum Power in DC (@STC) Inverter/Unit	**111750/37250**	[W]
Maximum Voltage in DC, V_{DC}	**1000**	[V]
Rated Voltage in DC, V_{DC}	**750**	[V]
Maximum Current in DC, I_{DC}	**3x40**	[A]
Output		
Maximum Power in AC, P_{AC}	**82800**	[VA]
Frequency	**50/60 ± 5%**	[Hz]
Europe efficiency	**98 %**	
Power Factor	**1**	
3 phase Inverter Solaredge SE 90 K		**Unit of measure**
Input		
Maximum Power in DC (@STC) Inverter/Unit	**135000/45000**	[W]
Maximum Voltage in DC, V_{DC}	**1000**	[V]
Rated Voltage in DC, V_{DC}	**750**	[V]
Maximum Current in DC, I_{DC}	**3x43,5**	[A]
Output		
Maximum Power in AC, P_{AC}	**90000**	[VA]
Frequency	**50/60 ± 5%**	[Hz]
Europe efficiency	**98 %**	
Power Factor	**1**	

Table 5.2: Inverter DC/AC features

5.3.2. Power Optimizers

Another important component for the electrical design of a PV system grid-connected is the Power Optimizer.

The SolarEdge Power Optimizer is a DC/DC converter, which connects to each solar module in a PV system, turning them into smart modules. By constantly tracking the Maximum Power Point (MPP) of each individual solar module, Power Optimizers can increase system energy production, potentially growing revenues and shortening system ROI.

By attaching the Power Optimizer to each solar module, it is easy to monitor system performance, track and resolve issues at any point along a string with surgical precision.

Each Power Optimizer is equipped with industry-leading safety mechanisms designed to automatically reduce modules' high DC voltage to a safe level whenever the inverter or grid power is shut down, for maximum protection of people and property.

The power optimizers are selected automatically by the tool after the choice of the inverter. [12]

Power Optimizers P800p		Unit of measure
Quantity	1244	
Input		
Rated Power in DC P_{DC}	**800**	[W]
Maximum Voltage in DC, V_{DC}	**83**	[V]
Maximum Current in DC, I_{DC}	**7**	[A]
Range MPPT	**12,5-83**	
Output		
Maximum Current I_{DC}	**18**	[A]
Maximum Voltage V_{DC}	**80**	[V]
Europe Efficiency	**98,6 %**	
Power Optimizers P1100		**Unit of measure**
Quantity	99	
Input		
Rated Power in DC P_{DC}	1100	[W]
Maximum Voltage in DC, V_{DC}	125	[V]
Maximum Current in DC, I_{DC}	14	[A]
Range MPPT	12,5-105	[V]
Output		
Maximum Current I_{DC}	18	[A]
Maximum Voltage V_{DC}	80	[V]
Europe Efficiency	98,6 %	

Table 5.3: Main feature of Optimizers

5.4. Productivity of PV plant

After having dimensioned the solar photovoltaic system in terms of installed power, it is now essential to estimate step-by-step the energy production of the PV plant **E_{AC}**.

The productivity can be estimated as follows:

$$E_{AC} = H_g * \eta_{STC} * S_{PV} * PR$$

Where:

- Hg: global in-plane Irradiation $\left[\frac{kWh}{m^2 * month}\right]$
- η_{STC}: nominal efficiency of PV panels [-]
- S_{PV}: total area covered by PV generator [m^2]
- PR: performance ratio [-] [10]

Global Solar Irradiation

The solar energy captured by the surface H_g can be assessed by employing a tool called Edilclima. Particularly the software needs 2 input parameters

- the inclination of module, i.e. the tilt angle β.
- the orientation of module, i.e. the azimuth angle γ.

The inclination of panel is always the same but, during the structure modelling, two azimuth angles have been found.

Therefore, we will end up with more than one global irradiation per month.

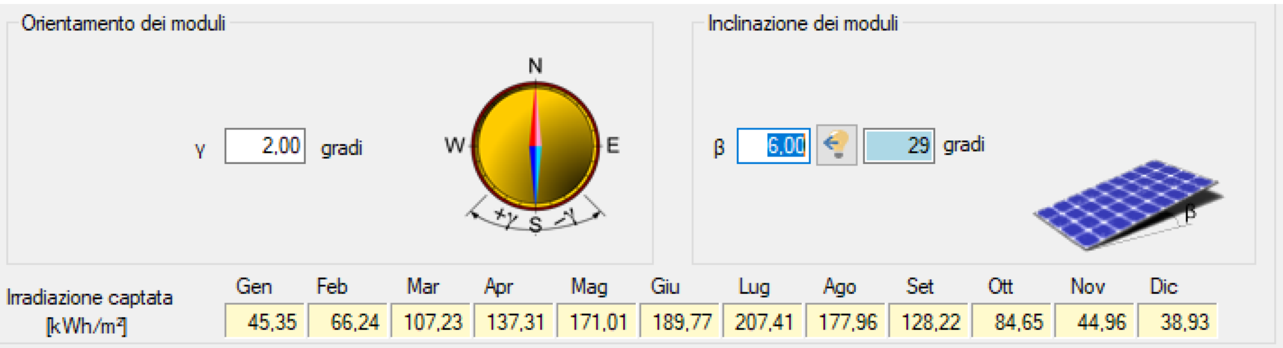


Figure 5.7: Irradiation [β = 6°, γ = 2°]

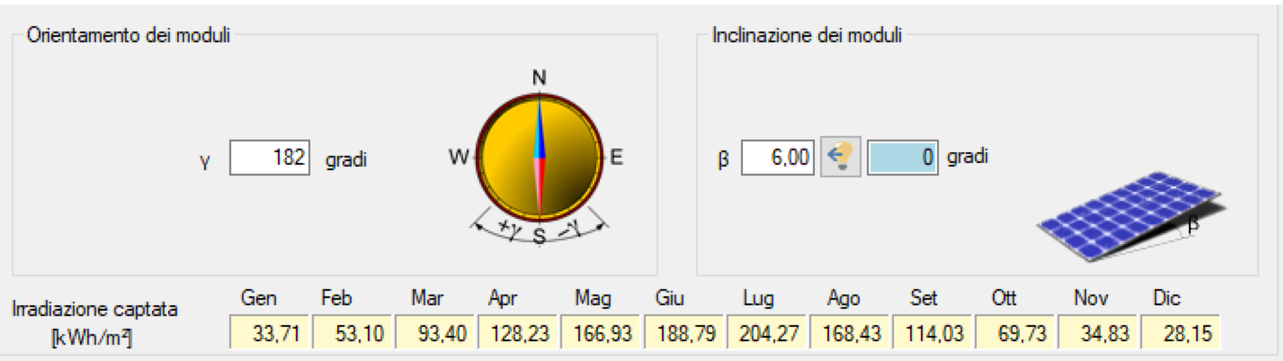


Figure 5.8: Irradiation [β = 6°, γ = 182°]

As we can see, when the value of azimuth is given, the software also suggests the optimal value of beta. It should be 29 ° with γ = 2° and 0° with γ = 182 °.

Rated efficiency of PV panels η_{STC}

We have already defined and evaluated this important value when we have discussed about the characteristic of the module.
Differently from the efficiency founded previously, for the assessment of productivity, we implement the Net Area in the mathematical formula.
Hence the new η in standard test condition is higher, precisely 22 %, because we consider only the part of module which can capture and convert the solar energy into electricity.

PV module		Unit of measure
Peak power	540	[W_p]
Net area	2,46	[m^2]
Gross area	2,58	[m^2]
Efficiency	22	[%]
Specific power	209	[W_p/ m^2]

Table 5.4: Module main features

Surface area covered by the modules S_{PV}

Another quantity to insert in the formula of Productivity is the total area covered by all PV panels.
It is obtained easily by multiplying the area of a single module with the number of PV panels arranged on the rooftop.
Since the modelled photovoltaic system covers a large area of the roof of the structure, a very high surface of panels is expected.

The product of the last two characteristics for the number of PV panels arranged on the top gives the overall power installed by the renewable plant.

		Unit of measure
n° of modules	**1442**	-
Total Power installed by PV plant	**778,7**	[kW_p]

Table 5.5: PV plant main characteristics

Performance Ratio

This is the last input parameter to determine the productivity of PV plant.
The formula of PR includes different sources of losses:

- Tolerance with respect to Standard Test Condition data and intrinsic mismatch of modules current-voltage characteristics.
- Dirt and reflection of the frontal glass.
- Different solar spectrum compared to the reference solar spectrum (AM = 1.5) and low irradiance levels (< 400 W/m^2).

- Wiring, blocking diodes, fuses and breakers.
- Over-temperature (or under-temperature) compared to 25°C.
- Non-uniform illumination on all modules (shading effect).
- MPP tracker and DC-AC conversion of the inverter.

$$PR = \eta_{mis} * \eta_{d-r} * \eta_{sp-IG} * \eta_{wir} * \eta_{temp} * \eta_{shad} * \eta_{PCU}$$

The design value of Performance Ratio is usually 0,75 but real values are in the range 0,55-0,85 depending on the losses previously described.

In our calculations, we are not able to come up with a precise value of PR since every value of formula is obtained experimentally.

Therefore, we made an assumption of this parameter for each month by considering a higher value of irradiation over the module corresponds to a smaller value of PR because the increasing of the Temperature causes a reduction in the panel performances (it's a loss).[10]

Month	Irradiation on the module surface [kWh/m²] Field n°1	Irradiation on the module surface [kWh/m²] Field n°2	Performance Ratio [%]
January	45,35	33,71	77%
February	66,24	53,10	76%
March	107,23	93,40	76%
April	137,31	128,23	75%
May	171,01	166,93	75%
June	189,77	188,79	75%
July	207,41	204,27	74%
August	177,96	168,43	75%
September	128,22	114,03	75%
October	84,65	69,73	75%
November	44,96	34,83	76%
December	38,93	28,15	76%
TOTAL	**1399,04**	**1283,6**	

Table 5.6: Global Irradiation and Performance ratio

The Energy Productivity achieved is indicated in the next table.

Month	Productivity on the module surface [kWh] Field n°1	Productivity on the module surface [kWh] Field n°2	Total Productivity [kWh]
January	18574	6406	24979
February	26777	9959	36736
March	43347	17517	60865
April	54776	23733	78510
May	68220	30896	99116
June	75704	34942	110646
July	81638	37303	118941
August	70993	31174	102167
September	51150	21105	72255
October	33769	12906	46675
November	18175	6532	24707
December	15737	5280	21017
TOTAL	**558860**	**237754**	**796614**

Table 5.7: Energy production of PV system

5.5. Self-consumption of PV plant

Introduction to Self-consumption

Self-consumption consists in the possibility to consume locally, e.g at home, in office, in an industrial plant, the electrical energy produced by the renewable plant (PV system, cogeneration system, etc…) to meet the energy needs. It is a concept that plays an important role in the debate on the development of prosumers.
The prosumer is an electricity consumer who aims at produce electricity to support own consumption. The term is based on the combination of producer and consumer, and it is largely used nowadays.
Producing and consuming the electricity generated by a renewable plant on the same site means contributing actively to the energy transition and sustainable development of the country, promoting energy efficiency and the development of renewables.[13]

Self-consumption in Italy

- Self-consumption is allowed for all PV system sizes.
- For systems below 200 kW (and even 500 kW for plants installed starting from 2015), Italy has switched in 2009 from a net-metering mechanism to the so-called “Scambio Sul Posto (SSP)”. The SSP can be seen as a hybrid solution between a self-consumption system (real-time self-

consumption) with some netbilling features (for the calculation of the "energy quota" and the "service quota"). After the end of the FiT law, net billing is the only scheme left.
Above the 500 kW limit, a pure self-consumption scheme is used.

- In all cases, the electricity self-consumed reduces the energy injected into the grid (the self-consumed energy is never fed into the grid).
- With the SSP, the electricity fed into the grid is remunerated through an "energy quota" that is based on electricity market prices and a "service quota" that depends on the cost of grid services (transport, distribution, metering and other extra charges). Without SSP, the market prices apply for the electricity injected into the grid.
- Grid costs linked to self-consumed electricity are compensated for all plants under SSP scheme. For system bigger than 20 kW, a fee is added to the bill to compensate partially the saved grid costs.
- New rules have introduced the so-called "Sistema Efficiente di Utenza" (SEU), a system where one or more power production plants, operated by a single producer, are connected through a private transmission line to a single end user located on the same site.[13]

Advantages of Self-consumption

A business that chooses to self-consume or share the electricity with a PV plant has many economic and environmental benefits.

- *Saving on electricity bill*: the more energy is self-consumed, the more the costs of the variable components of an electricity bill decrease.
- *Enhancement of the energy produced or shared*: producing energy with a plant can represent a source of income thanks to the incentive mechanisms managed by the GSE, i.e. the Exchange on the spot, the Dedicated Withdrawal, the Minor Islands DM and the FER-1 DM, the service for the enhancement and incentive of shared electricity for groups of self-consumers and communities.
- *Tax concessions for photovoltaic systems.*
- *Reduction of environmental impact*: thanks to energy produced by PV plant, the carbon dioxide and other greenhouse gases emissions are avoided. [13]

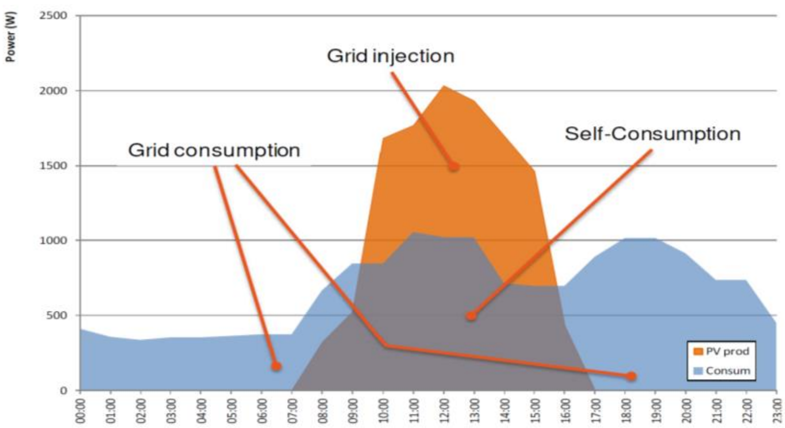


Figure 5.9: Comparison of production and consumption profiles

Self-consumption has not been confused with self-sufficiency.
The electricity self-consumed reduces the ratio of energy injected into the network.

<u>Self-production</u>
Doing the self-production with renewables means installing renewables production plants, i.e. PV plant, Solar-thermal plant, cogeneration plant, etc…, that allow the company to self-producing a portion of the energy, which consumes herself.
Hence, the self-production of energy coming from renewables aims to decrease the costs of energy itself. Nevertheless, it does not allow to move towards the energy efficiency because the company could "waste" the energy self-produced. [13]

Usually only a portion of electricity produced by an industrial plant can be self-consumed.
The energy produced by Photovoltaic plant is compared to the maximum energy an industrial user can achieve. If the latter is smaller than the first one, self-consumption occurs whereas if the PV system produces more electricity than energy can be consumed, we have overproduction.
This excess of electricity is rejected into the grid at a price lower than the electricity purchase cost.

Month	Actual Consumption [kWh]	Maximum Energy Self consumed [kWh]	PV Productivity [kWh]	Self consumption/Over production	Energy self-consumed [kWh]	Energy not used [kWh]
January	593575	308659	24.979	Self consumption	24979	0
February	680039	353620	36.736	Self consumption	36736	0
March	691057	359349	60.865	Self consumption	60865	0
April	598302	311117	78.510	Self consumption	78510	0
May	724095	376529	99.116	Self consumption	99116	0
June	565319	293966	110.646	Self consumption	110646	0
July	744740	387265	118.941	Self consumption	118941	0
August	175336	91174	102.167	Over production	91174	10992
September	654856	340525	72.255	Self consumption	72255	0
October	573502	298221	46.675	Self consumption	46675	0
November	444454	231116	24.707	Self consumption	24707	0
December	287932	149724	21.017	Self consumption	21017	0
Total	**6733206**	**3501267**	**796.614**		**785622**	**10992**

Table 5.8: Comparison of Industry consumption, PV productivity and Energy self-consumed

For this scenario the **98,6** % of the energy generated by the Photovoltaic plant is self-consumed, the **1,4** % is injected into the network because overproduced.

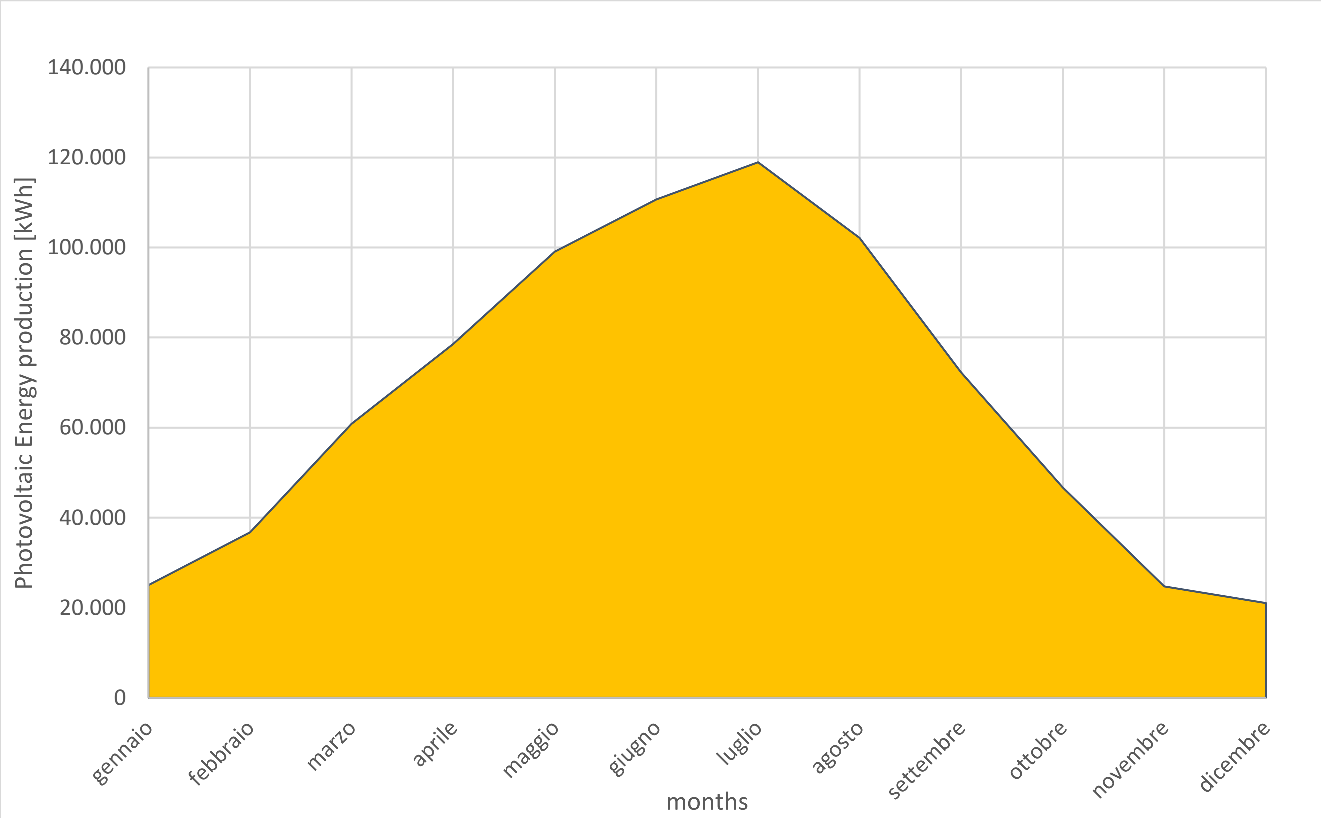


Figure 5.10: PV Energy production

This is the trend of the energy produced by the entire photovoltaic system.

As it can be noticed, the electricity produced by this renewable technology is very high during summer (the peak occurs in July with a production of roughly 120 MW) and it decreases considerably in the other months of the year.

This is mainly due to the fact the solar energy is an intermittent renewable source, which is more efficient in summer rather than in winter.

This is the energetic behaviour obtained by arranging all PV panels that follows the inclination of the roof, which is not an optimal configuration. In order to harvest more energy, a ballast system can be located on the top in order to tilt the PV arrays in a way they could capture more solar energy and, therefore, to produce more electricity for the industry.

Nevertheless, a ballast system is an expensive equipment which can affect the invested capital in the project and it will increase the payback time of the scenario.

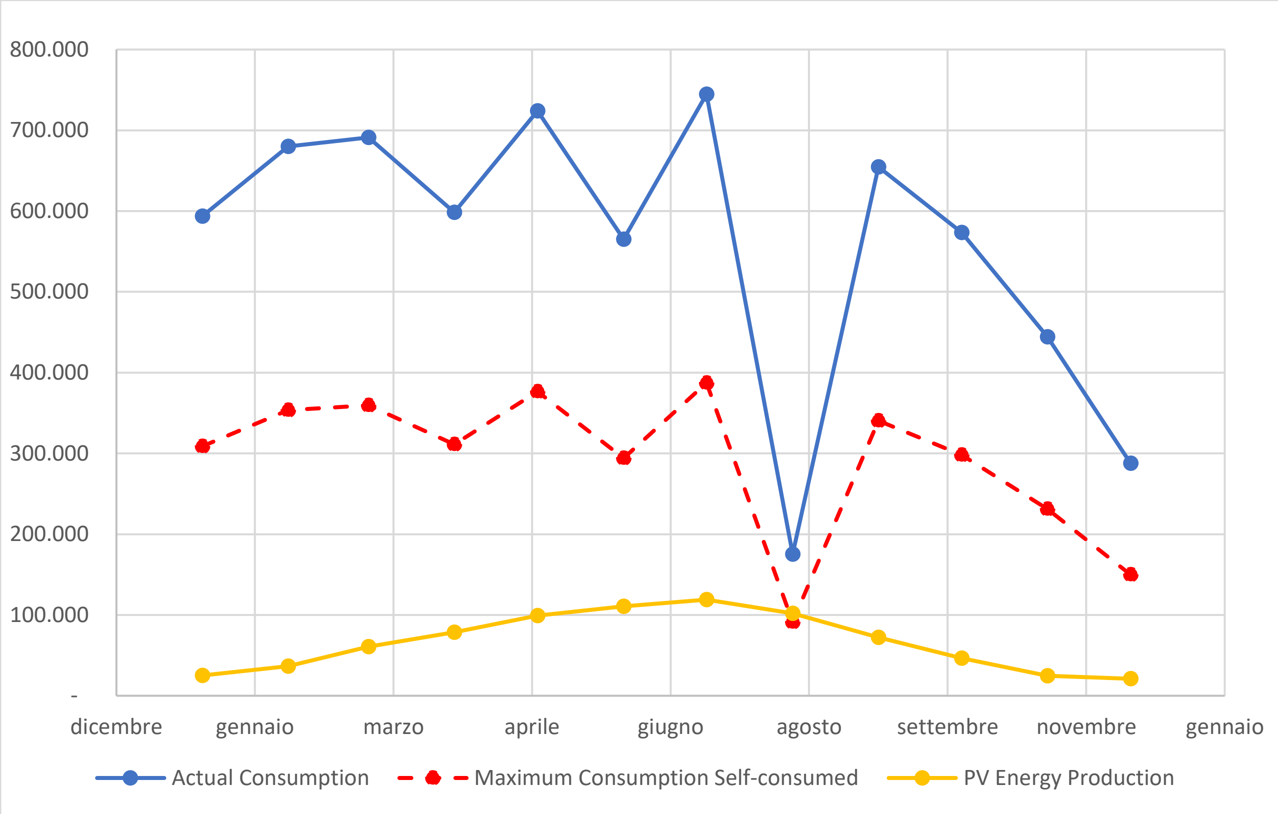


Figure 5.11: Electricity production compared to the actual and maximum energy needs of Tra.sma

Month	Actual Consumption [kWh]	Energy Self consumed by PV [kWh]	Electricity withdrawn from the grid [kWh]	Coverage of Energy Needs	Energy reinjected into the grid [kWh]
January	593575	24979	568596	4%	-
February	680039	36736	643302	5%	-
March	691057	60865	630192	9%	-
April	598302	78510	519792	13%	-
May	724095	99116	624979	14%	-
June	565319	110.646	454673	20%	-
July	744740	118941	625799	16%	-
August	175336	91174	84161	52%	**10992**
September	654856	72.255	582601	11%	-
October	573502	46.675	526827	8%	-
November	444454	24.707	419747	6%	-
December	287932	21017	266915	7%	-
Total	**6733206**	**785622**	**5947584**	**12%**	**10992**

Table 5.9: Numerical results of scenario 1

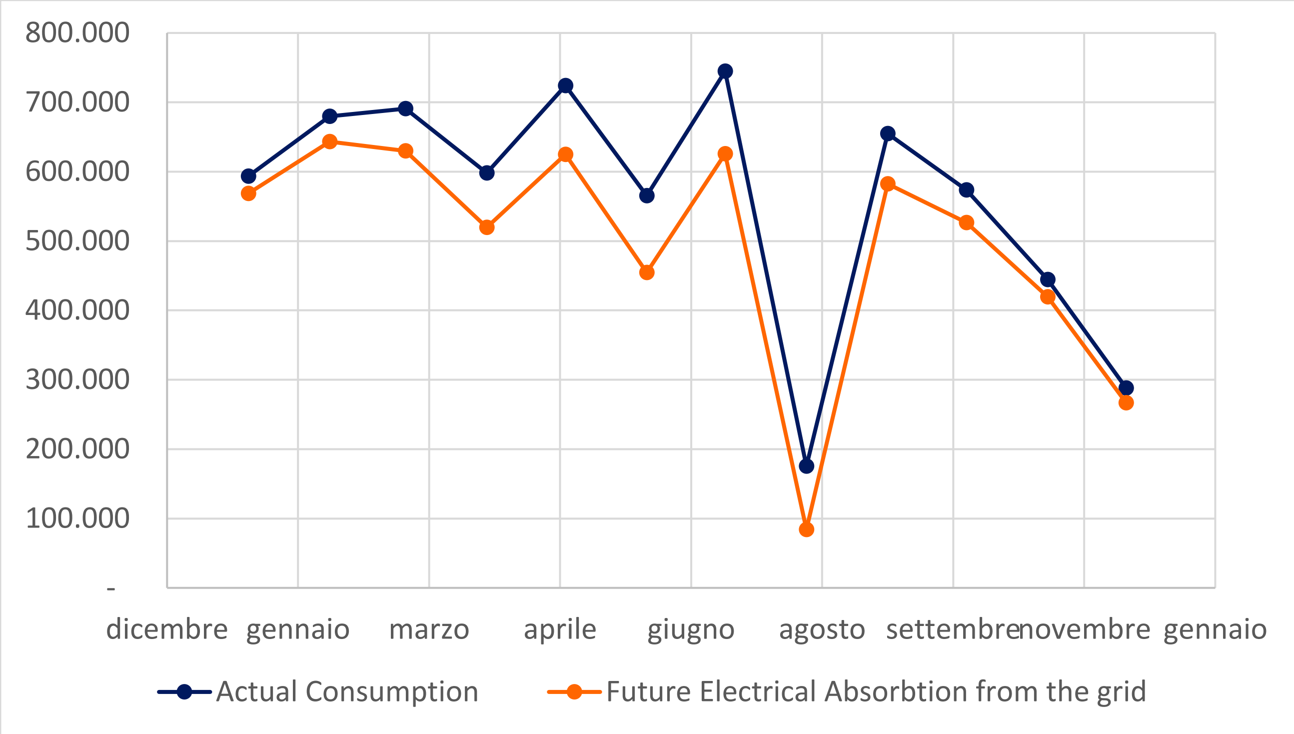


Figure 5.12: Behaviour of Electrical withdrawal from the network

By looking the graph above, we can observe we have reduced the electricity withdrawn from the grid even if in a low quantity compared to the total energy consumed by the user.
The major energy reduction occurs in August whereas the minor one occurs in January.
Particularly, the 88% of electricity employed for the MV user is still purchased from the network.

As a final consideration, the installation of a renewable plant for an industrial structure can be a reasonable solution to decrease the amount of energy withdrawn from the electrical network even if not entirely. In addition, it contributes to reduce the greenhouse gases emissions and the cost of electric bills.

6. Scenario 2: Coupling of a PV system with CHP technology

6.1. The Project's purpose

We want now to consider the case in which a Photovoltaic plant is "coupled" with a CHP technology. As it was said in previous chapters, the industrial user meets its energy needs by employing a Cogeneration unit which is fuelled by natural gas. In this second scenario the installation of Photovoltaic plant is added to CHP system.
The intention is to increase, compared to the scenario 1, the share of self-consumed electrical energy and, therefore, make the company more independent from the electrical grid.
For dimensioning of PV system, we adopt the same procedure employed for the project of case 1.
Then we conclude the study with an economic analysis in order to understand the cost and the convenience of this scenario, compared with the first one.
The technical characteristics of cogeneration used currently by Tra.sma are resumed below.

	Moncalieri	Trofarello	Unit of measure
Type of Plant	Cogeneration with ICE	Cogeneration with ICE	
Brand	Jenbacher	Jenbacher	
Model	JMS 420 GS N.LC	JMS 616 GS N.LC	
Engine Characteristics			
Electrical nominal Power	1416	2188	[kW_e]
Thermal nominal Power	1532	2301	[kW_{th}]
Rated gas quantity	363	547	[Nm^3/h]
Electrical efficiency	41,1	42,1	[%]
Thermal Efficiency	44,5	44,3	[%]
Total efficiency	85,6	86,4	[%]

Table 6.1: Technical data of CHP plant

Let's suppose to couple the PV sized in the first scenario with the cogenerator currently installed in the industry.
If the self-consumed energy from the PV system of scenario 1 is added to the self-consumed energy from the CHP, mostly of this overall energy exceeds the electrical consumption required by the company. It means that the electricity overproduced is wasted on the grid, and also the economic convenience of scenario 2 is reduced because the payback time will increase.
Therefore, combine the two technologies, as they are, is not convenient from the point of view of energy efficiency.
To solve this issue, the currently scenario can be modified in the following way:

1. The size of photovoltaic plant dimensioned in the scenario 1 must be changed, in particular its size can be reduced to avoid energy in excess.
2. The cogeneration unit already installed in Moncalieri must be replaced with an efficient one, mainly because it is at the end of its life, but also because it tends to generate a very high amount of energy if coupled with PV system.

Firstly, we analyse individually the energy contribution of each technology and, then, we will examine the two systems coupled.

6.2. Dimensioning and Productivity of a new PV system

By employing the same tool of scenario 1, the modules will be rearranged on the roof of building.
In this case, since the plant will be smaller than the previous one, it was thought to install most of panels on the field oriented in southern direction, that have a greater irradiance such as to maximize the energy produced.
Furthermore, for simplicity it is preferred to adopt the same type of module of case 1.
The configuration of the new system is the following.

Figure 6.1: New PV plant configuration

		Unit of measure
n° of modules	**798**	-
Total Power installed by PV plant	**430,9**	[kW_p]

Table 6.2: Size of new PV system

Figure 6.2: New PV plant configuration – Side view

Month	Irradiation on the module surface [kWh/m²] Field n°1	Performance Ratio [%]	Total Productivity of PV plant [kWh]
January	45,35	77%	15048
February	66,24	76%	21694
March	107,23	76%	35118
April	137,31	75%	44377
May	171,01	75%	55269
June	189,77	75%	61332
July	207,41	74%	66139
August	177,96	75%	57515
September	128,22	75%	41439
October	84,65	75%	27358
November	44,96	76%	14724
December	38,93	76%	12750
TOTAL	**1399,04**		**452762**

Table 6.3: New Energy production

Self-consumption

Month	Actual Consumption [kWh]	Maximum Energy Self consumed [kWh]	PV Productivity [kWh]	Self consumption/Over production	Energy self-consumed [kWh]	Energy not used [kWh]
January	593575	308659	15048	Self consumption	15048	
February	680039	353620	21694	Self consumption	21694	
March	691057	359349	35118	Self consumption	35118	
April	598302	311117	44377	Self consumption	44377	
May	724095	376529	55269	Self consumption	55269	
June	565319	293966	61332	Self consumption	61332	
July	744740	387265	66139	Self consumption	66139	
August	175336	91174	57515	Self consumption	57515	
September	654856	340525	41439	Self consumption	41439	
October	573502	298221	27358	Self consumption	27358	
November	444454	231116	14724	Self consumption	14724	
December	287932	149724	12750	Self consumption	12750	
Total	**6733206**	**3501267**	**452762**		**452762**	0

Table 6.4: Outcomes for PV production

For this new configuration, the whole Photovoltaic plant is able to self-consumed the entire energy that it has produced. Hence the electricity obtained is totally consumed for the industry without being rejected into the grid.

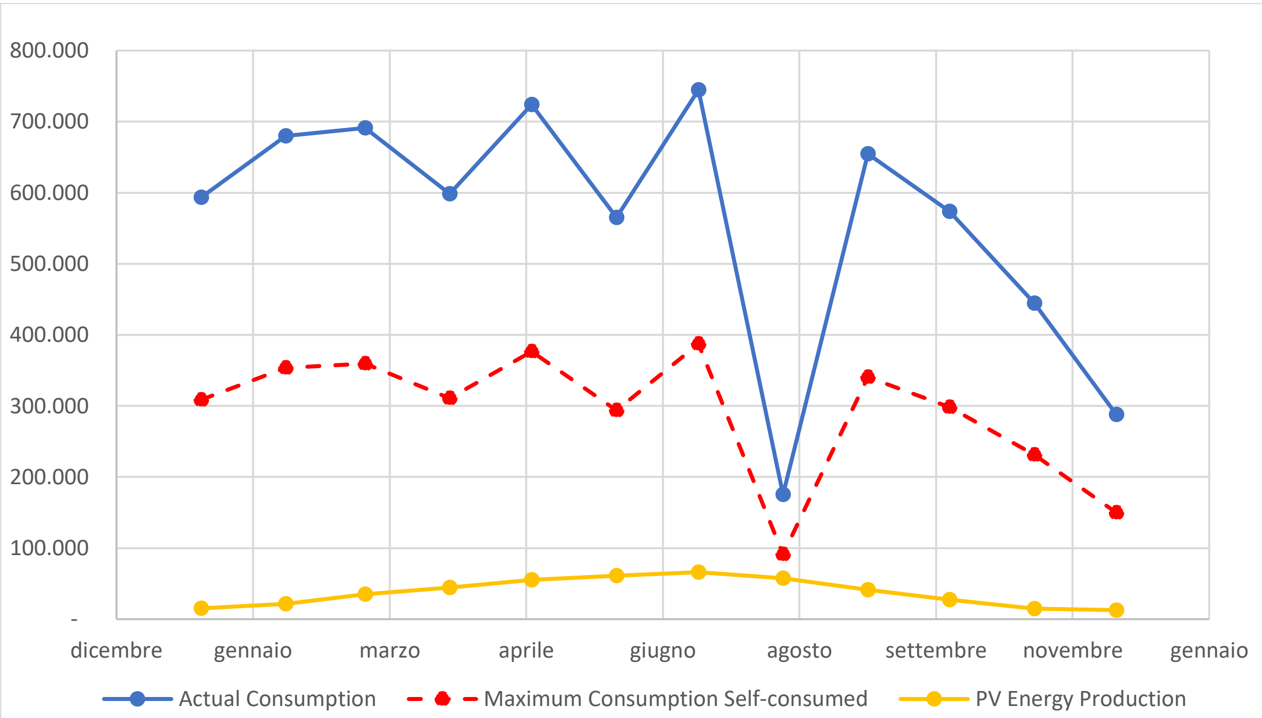


Figure 6.3: PV Electricity production compared to the actual and maximum energy needs of Tra.sma

6.3. Estimation of consumption of a new CHP

Let's assume to change the current cogenerator into a smaller one, with the following new values of rated powers and efficiencies. The new cogeneration unit will be installed in the same place of the previous one, therefore outside the building.

2G AVUS 1000b [15]		Unit of measure
Typology	Natural Gas Cogenerator	
Electrical Power	**1248**	[kW_e]
Thermal Power	**1306**	[kW_{th}]
Rated Gas quantity	**281,8**	[Nm^3/h]
LHV of Natural Gas	**10,25**	[kWh/m^3]
Electrical efficiency	**43,2**	[%]
Thermal efficiency	**45,3**	[%]
Overall efficiency	**88,5**	[%]

Table 6.5: New CHP features

To come up with the energy produced by the new cogenerator, the electrical and thermal power of the machine must be assessed, by considering that the unit works for the same number of hours of the pre-existent CHP and almost full load, like the existing one.
Hence, we enable to obtain the following outcomes.

Combined Heat Production Simulation					
Month	**Working hours [h]**	**Methane consumption [Sm^3]**	**Primary Energy [kWh_{th}]**	**Electricity produced [kWh_{el}]**	**Thermal Energy produced [kWh_{th}]**
January	467	123400	1264847	535377	572976
February	471	123745	1268388	538683	574580
March	545	14288	1448204	616060	656036
April	437	111873	1146699	489584	519455
May	429	109284	1120162	480892	507433
June	388	105808	1084528	472552	491291
July	477	131608	1348986	581515	611091
August	120	32868	336898	145529	152615
September	458	125886	1290333	558365	584521
October	450	122655	1257216	544970	569519
November	474	119333	1223167	526252	554095
December	231	85110	872378	87121	395187
Total	**4947**	**1332859**	**13661804**	**5576900**	**6188797**

Table 6.6: Main numerical results for CHP

In percentage, the total energy produced by CHP is:

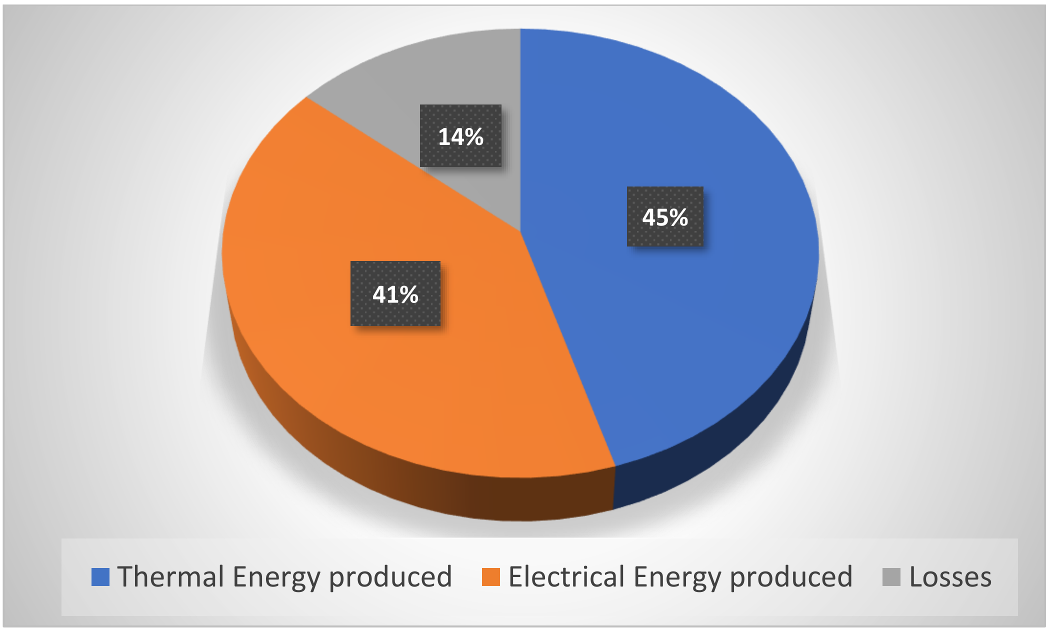


Figure 6.4: Partition in [%] of CHP contribution

High Efficiency Cogeneration and White Certificates

A Cogeneration unit is defined at high efficiency if the following conditions are satisfied:

- The Global Efficiency of the machine must be higher than 75 %
  This value is defined as the ratio between the sum of electrical energy E_{el} and thermal energy E_{th} produced and the primary thermal energy injected into the cogenerator E_{fuel}.

$$\eta_{tot} = \frac{E_{el} + E_{th}}{E_{fuel}} = 86{,}1\ \%$$

- The Primary Energy Saving (PES) of CHP must overcome 10 %
  It's the conventional evaluation of the energy saving for a cogenerator producing the same quantities of useful energy (electricity W and heat Q) by employing the fuel F, with respect to the separate production (SP) requiring F^{SP} [14]

$$PES = \frac{F^{SP} - F}{F^{SP}} = 1 - \frac{F}{\frac{W}{\eta_{el}^{SP}} + \frac{Q}{\eta_{th}^{SP}}} = 25\ \%$$

Since the two requirements are completely satisfied, the cogenerator used can be classified as HEC (High Efficiency Cogenerator) and therefore it can access to the white certificates mechanism.
White certificates are negotiable securities that certify the achievement of savings in the final uses of energy through projects to increase the energy efficiency.
One certificate is equivalent to saving one Ton of Oil Equivalent (TOE) [16]

In order to estimate the monetary value of these energy certifications, the following parameters must be evaluated:

- The Primary energy savings realized by CHP measured into MWh/y.

$$PES = \frac{E_{el,CHP}}{\eta_{el}^{RIF}} + \frac{E_{th,CHP}}{\eta_{th}^{RIF}} - F_{CHP} = 6217 \;\; [MWh/y]$$

Where:

- η_{el}^{RIF} is the conventional average efficiency of the Italian electricity production park, assumed to be 0,46, corrected according to the connection voltage, the amount of self-consumed energy and the amount of energy fed into the grid, according to the calculation methods reported in Annex 7 of the decree of 4/08/2011.

$$\eta_{el}^{RIF} = (46\ \% + 0{,}369\%) * 0{,}925 = \ 42{,}9\ \%$$

- η_{th}^{RIF} is the conventional average efficiency of the Italian thermal production park, supposed to be 0.82 in case of direct use of the exhaust gases and equal to 0.90 in case of steam / hot water production.

- The quantity of white certificates which the plant can acquire.

$$CB = \ PES * 0.086 * k = 695 \quad [CB/y]$$

Where:

- K is a harmonization coefficient which depends on size of Cogeneration plant
  It is 1,3 for an electric power among 1 MW_e and 10 MW_e [17]

Currently the value of a white certificate is 258,4 €/y [18]

Finally, the total annual economic value of White certificates is **179605 €/y**

Self-consumption of CHP

Month	Electricity produced [kWh_e]	Energy self-consumed with old CHP [%]	Actual Energy self-consumed by new CHP [kWh_e]	Energy not used [kWh_e]
January	535377	88%	470379	64999
February	538683	92%	495813	42870
March	616060	90%	552243	63817
April	489584	96%	470397	19187
May	480892	92%	442741	38150
June	472552	85%	401630	70923
July	581515	98%	571744	9772
August	145529	83%	120682	24847
September	558365	91%	510197	48168
October	544970	87%	475986	68983
November	526252	63%	331749	194503

December	87121	75%	65159	21962
Total	**5576900**		**4908718**	**668182**

Table 6.7: Self-consumption – new CHP

The only contribution of cogeneration unit gives an energy self-consumed of 88 %.
The remaining 12 % is, as usual, reinjected into the network.

6.4. Self-consumption of two technologies

The last step to follow is to evaluate which the self-consumption is, obtained with both technologies analysed so far.
So the share of electricity self-consumed by the renewable system is added to the self-consumption obtained with the cogenerator.

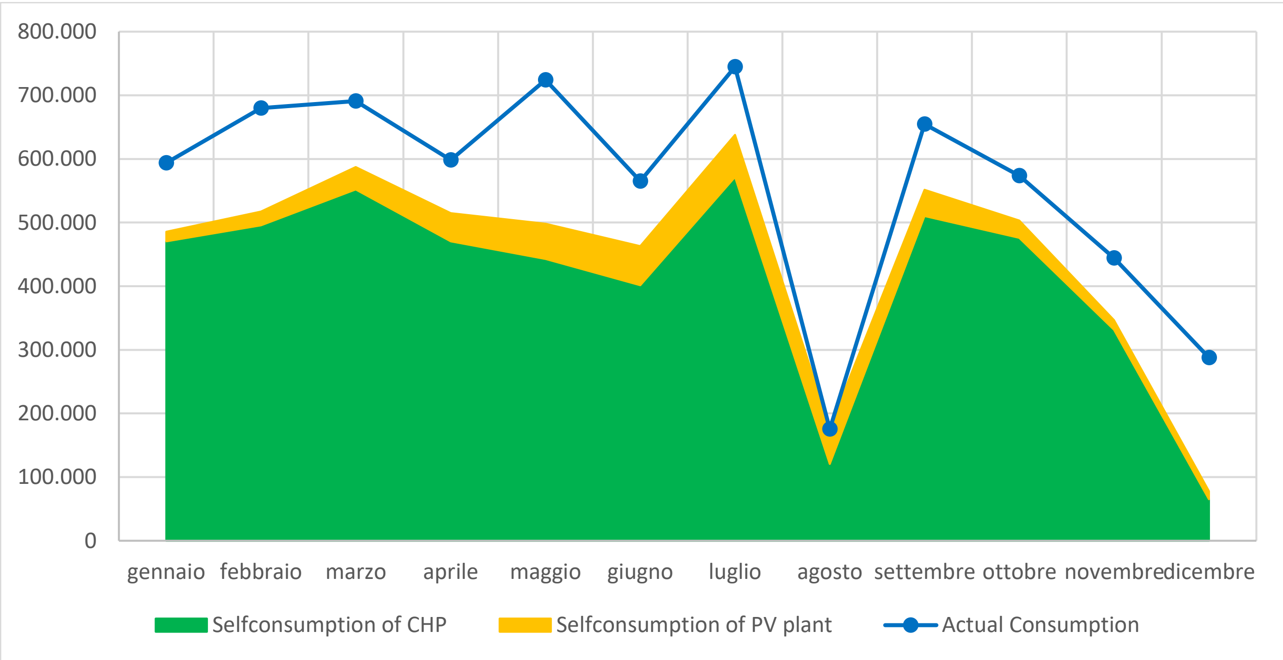


Figure 6.5: Overall energy self-consumed

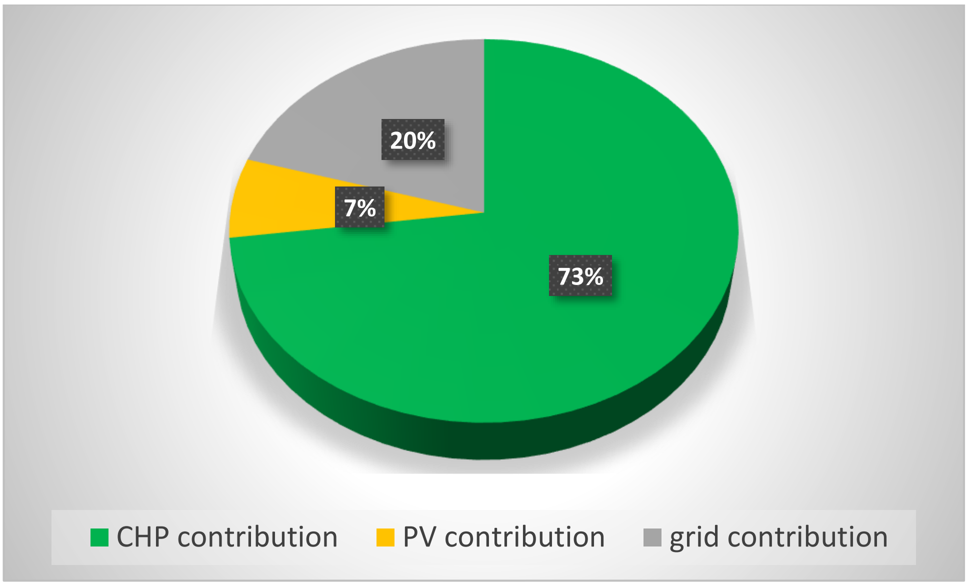


Figure 6.6: Share of Total Self-consumption

In this second scenario, the entire energy which can be self-consumed by the industry is 80 %.

Month	Electrical consumption with only PV [kWh]	Self-consumption with new CHP [kWh]	Future withdrawl from grid [kWh]	Energy needs covered [%]	Energy into the grid [kWh]
January	578527	470379	108149	81%	64999
February	658345	495813	162532	75%	42870
March	655939	552243	103696	84%	63817
April	553924	470397	83527	85%	19187
May	668826	442741	226085	66%	38150
June	503987	401630	102357	80%	70923
July	678601	571744	106858	84%	9772
August	117821	120682	0	102%	24847
September	613417	510197	103220	83%	48168
October	546144	475986	70158	87%	68983
November	429730	331749	97981	77%	194503
December	275182	65159	210023	24%	21962
En. elettrica	**6280444**	**4908718**	**1374587**		**668182**

Table 6.8: Final outcomes of PV and CHP systems

The combination of the photovoltaic technology with the cogeneration unit allows to reduce significantly the electricity withdrawn by the network, thanks to the high energy self-consumed.

7. Economic Study

After having studied in detail the dimensioning, the energy productivity and the self-consumption, we conclude the master thesis with an economic evaluation of the two scenarios.
The main cost items will be assessed, which are the invested capital and the maintenance and operating costs.
By analysing the cash flows and estimating the discount rate we will evaluate the economic convenience of the projects by means of net present value calculation.
Moreover, a sensitivity analysis will be assessed in order to understand the parameters that affect the net present value.
Then it will be important to determine and compare the pay back time of two technologies.

7.1. Capital Expenditure

It represents the investment costs that must be considered for the realization of the plant.
They include

- Purchasing and installation costs for equipment
- Engineering costs
- General costs for plant management and security

In the analysis of two scenario, the renewable plants are considered build in only one night (in fact the costs referred to this solution are called "*Overnight costs*"). [18]

Scenario 1

Photovoltaic Modules		
Type	**Suntech**	
Power [W]	540	
Numbers of Modules	1442	
Price per unit [€/Wp]	0,34	
Transport [€]	29589	
Total Price [€]	**294341**	
Inverter DC/AC		
Type	**Solaregde SE 90K**	**Solaredge SE 82,8 K**
Quantity	1	7
Price [€/cad]	2197	3828
Total Price [€]	**1358**	**16612**
Power Optimizers		
Type	**P800p**	**P1100**
Quantity	1244	99
Price per unit [€/Wp]	72	78
Total price [€]	**55532**	**4802**
Smart Meter		

Type	**Solaredge**	
Quantity	1	
Price per unit [€/Wp]	840	
Total price [€]	**840**	
3 Phase Current Sensor		
Type		
Quantity	3	
Price per unit [€/Wp]	60	
Total price [€]	**180**	
Installation costs		
Type	**Quantity**	**Price [€]**
Cables, pipes, electrical connections	778,7	15574
Switchboards AC/DC	778,7	38934
Meter PV	1	1500
Electrical substation Adjustment	1	12000
Labor	778,7	54508
Total Price [€]		**122515**
Type		
Electrical Design		
Meter calibration		
Authorization from the municipality	1	
General Practices		
On-site exchange activation		
Total Price [€]		**14350**
Plant Management		
Type		
Check + Meter calibration	3	1950
Check Interface protection	2	1000
General	1	10.000
Total Price [€]		**12950**
Security		
Type	**Quantity**	**Price [€]**
Opere provvisionali	400	10000
Platform rental	8	8000
Castelletto	1	800
Total Price [€]		**18800**
Total CAPEX [€]		**542280**

Table 7.1: Overall Purchasing costs

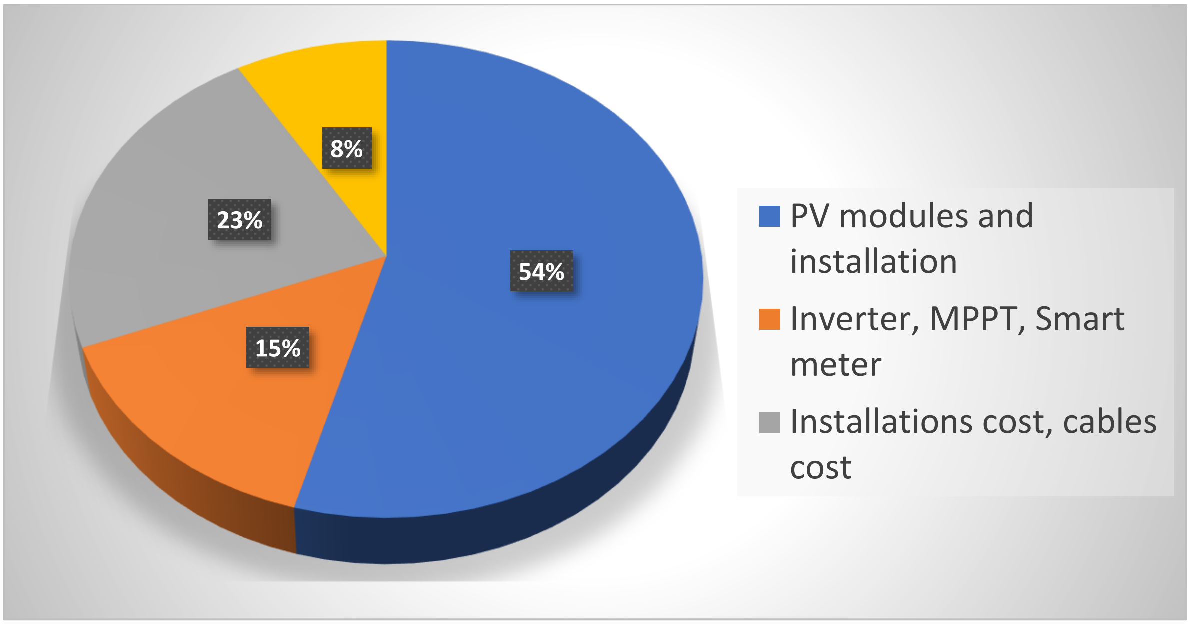


Figure 7.1: Percentage of Cost items

Scenario 2

CAPEX of Photovoltaic plant

Photovoltaic Modules		
Type	**Suntech**	
Power [W]	540	
Numbers of Panels	798	
Price per unit [€/Wp]	0,34	
Transport		
Total Price [€]	**162888**	
Inverter DC/AC		
Type	**Solaregde SE 90K**	**Solaredge SE 100 K**
Quantity	4	7
Price [€/cad]	2197	4286
Total Price [€]	**5431**	**18601**
Power Optimizers		
Type	**P1100**	
Quantity	411	
Price per unit [€/Wp]	78	
Total price [€]	**19935**	
Smart Meter		
Type	**Solaredge**	
Quantity	1	
Price per unit [€/Wp]	840	
Total price [€]	**840**	

3 Phase Current sensor		
Type		
Quantity	3	
Price per unit [€/Wp]	60	
Total price [€]	**180**	
Installation costs		
Type	**Quantity**	**Price [€]**
Cables, pipes, electrical connections	430,9	8618
Switchboards AC/DC	430,9	21546
Meter PV	1	1500
Electrical substation Adjustment	1	12000
Labor	430,9	30164
Total Price [€]		**73829**
Type		
Electrical Design	1	
Meter Calibration		
Authorization from the municipality		
General Practices		
On-site exchange activation		
Total Price [€]		**14350**
Plant Management		
Type		
Check + Meter calibration	3	1950
Check Interface protection	2	1000
General	1	10.000
Total Price [€]		**12950**
Security		
Type		
Opere provvisionali	400	10000
Platform rental	8	8000
Total Price [€]		**18800**
Total CAPEX [€]		**327804**

Table 7.2: Total Invested Capital

CAPEX of CHP

Cogeneration Unit	
Type	**2G avus 1000b**

Power [kW_e]	1248
Quantity	1
Unit cost [€/kW_e]	800
Total price [€]	**998400**
General costs	
Electrical installation	
Hydraulic installation	
Practices	
Total price [€]	**200000**
Total CAPEX [€]	**1198400**

Table 7.3: Investment costs of CHP

The overall capital expenditure for the scenario 2 is **1526204 €**

<u>Observation</u>

The estimation of the investment costs for the two scenarios did not consider the business profit, since it is linked significantly to the choice of the company that has to build the plant.

7.2. Operating Expenditure

It is defined as the ordinary and not ordinary operating and maintenance costs of the plant at which the plant is subjected.
Let's assume these costs for a Photovoltaic project involve the replacement of a module, inverter or the cleaning of panel surface.
In the project, for the PV system, the OPEX is assumed 1% of Capital expenditure. [10]

	Scenario 1	Scenario 2
CAPEX [€]	542280	1526204
Percentage [%]	1	5
OPEX [€]	**5422,8**	**76310,2**

Table 7.4: Estimation of OPEX

7.3. Weighted Average Cost of Capital

In the Discounted Cash flow methods, the discount rate has a key role in the assessment of an investment to compare cash flows.
The evaluation of this parameter should include:

- The real, risk-free discount rate referring to other possible and alternative investments.

- Inflation during the whole lifetime of the project that reflects the loss of purchasing power of the capital invested in the same period.
- A premium to assign to its own equity capital as a metric of the expected rate of return from a risky investment.

The WACC is estimated basing on the financial structure of the investment
Hence, the formula to calculate the discount rate is the following:

$$WACC = k_E \left(\frac{E}{E+D}\right) + k_D \left(\frac{D}{D+E}\right)$$

As it can be noticed, it depends on

- E and D which are the percentage of equity and debt of the investment project.

They are assumed equal to 50 %

- Cost of equity kE

$$k_E = R_f + premium$$

It accounts two components, which are

- the systemic risk of a certain investment *Rf*. It is 1,65.
- the premium expected by the investors
  Premium = Rs + β*(Rm – Rf)
  It is equal to 6,42

The result is: **k_E = 8,07 %**

- Cost of debt k_D

$$k_D = IRS + spread$$

where:
IRS: Interest Rate swap. It is equal to 0,76
Spread: Increase of the interest rate depending on the capability of the investor to return the capital. It is equal to 1,72

The final value is **k_D = 2,48 %**
Therefore, the final value of WACC is **5,27 %** [19]

7.4. Net Present Value

The Net Present Value is a parameter which establishes the profitability of a project or an investment. It is given by the algebraic sum of the investment cost I, with the net cash flows B_k over the whole lifetime of the project that are discounted by considering the weighted average cost of capital estimated in the chapter 6.3.
The net discounted cash flow is the difference between Incomes R and O&M costs.

$$NPV = -I + \sum_{k=1}^{N} \frac{R_{,k} - C_{O\&M,k}}{(1+WACC)^k}$$

An investment is considered profitable when NPV >=0, whereas it is not accepted if NPV is negative. Let's assume for both scenarios the overall investment cost is given at the first year.
Consequently, revenues and O&M costs are null in that year and they begin at the further year. [19]

Scenario 1

As it was said before, in this analysis, the renewable plant is considered built in one night.
The useful life of the PV plant is assumed to be 25 years.

	Percentage [%]	[kWh]	€/kWh$_e$	Revenues [€]
Energy self-consumed	98,6	785622	0,146	114701
Energy rejected into grid	1,4	10922	0,054	594
Total				**115294**

Table 7.5: Energy savings – PV plant

Years [k]	$R_{PV}/(1+WACC)^k$ [€]	$C_{O\&M}/(1+WACC)^k$ [€]	R_{PV} - $C_{O\&M}$ [€]	NPV [€]
0	0,0	0,0	0,0	-542280,0
1	115294,0	5422,8	109871,2	-437909,1
2	109522,2	5151,3	104370,9	-338763,3
3	104039,3	4893,4	99145,9	-244580,8
4	98830,9	4648,5	94182,5	-155113,3
5	93883,3	4415,8	89467,5	-70124,7
6	89183,3	4194,7	84988,6	10609,2
7	84718,6	3984,7	80733,9	87301,5
8	80477,5	3785,2	76692,3	160154,4
9	76448,6	3595,7	72852,9	229360,2
10	72621,5	3415,7	69205,8	295101,4
11	68985,9	3244,7	65741,2	357551,5
12	65532,4	3082,3	62450,1	416875,2
13	62251,7	2928,0	59323,7	473229,0
14	59135,3	2781,4	56353,9	526761,7
15	56174,9	2642,2	53532,7	577614,5
16	53362,6	2509,9	50852,8	625921,5
17	50691,2	2384,2	48307,0	671810,1
18	48153,5	2264,9	45888,6	715401,5
19	45742,9	2151,5	43591,4	756810,6

20	43452,9	2043,8	41409,1	796146,8
21	41277,6	1941,5	39336,1	833513,6
22	39211,2	1844,3	37366,9	869009,9
23	37248,2	1752,0	35496,2	902729,1
24	35383,5	1664,2	33719,2	934760,3
25	33612,1	1580,9	32031,2	965187,9

Table 7.6: Cash flow and NPV costs – Photovoltaic plant

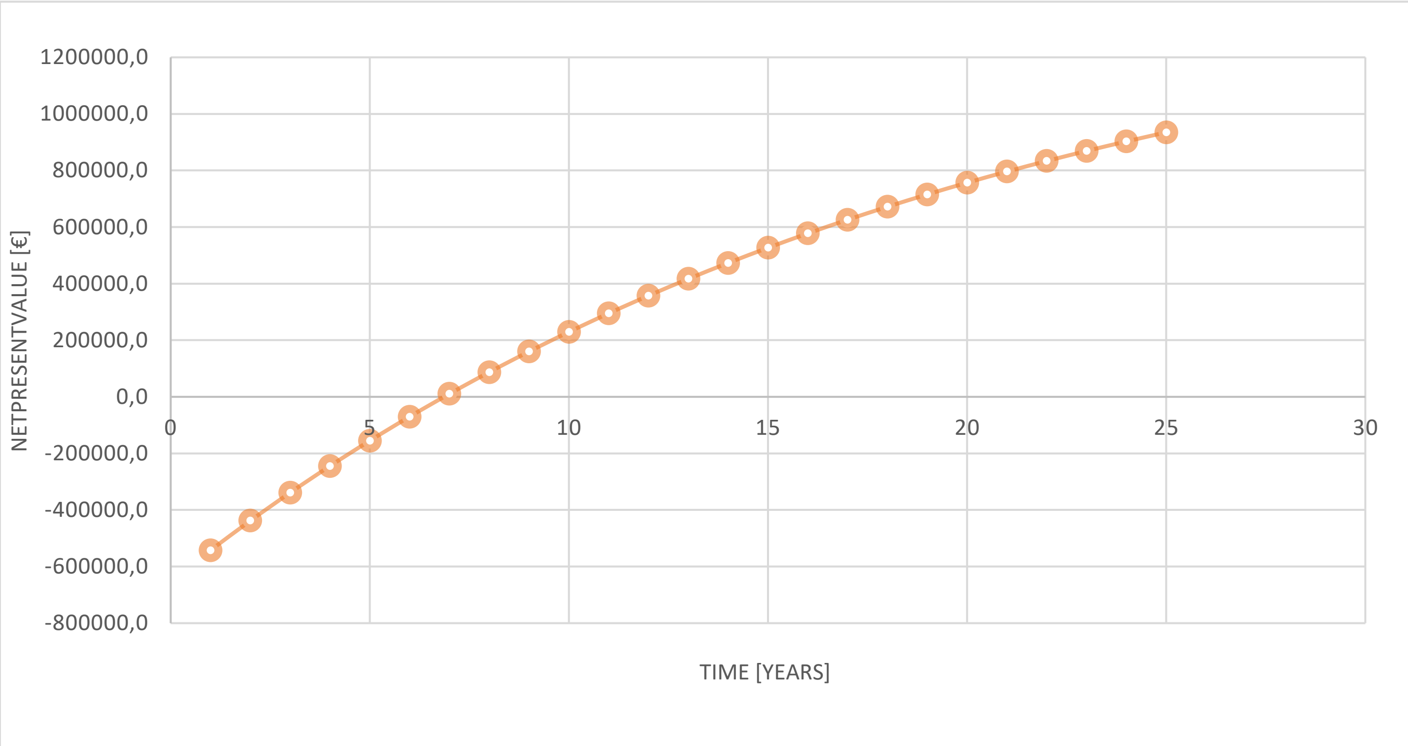


Figure 7.2: NPV curve - PV system

By analysing the graph above it is possible to recognize the Net Present value after 25 years of operation of PV plant: **965187,9 €**

Scenario 2

PV system	Percentage [%]	[kWh]	€/kWh$_e$	Revenues [€]
Energy self-consumed	100	452762	0,146	66103
Energy rejected into grid	-	-	0,054	-
Total				**66103**

Table 7.7: Incomes

CHP	Revenues [€]
Methane Consumption	362538

Electrical Savings	752755
Thermal Savings	208666
Total	**598883**

Table 7.8: Net energy savings of CHP

Years [k]	$R_{PV} - C_{O\&M}/(1+ WACC)^k$ [€]	NPV [€]
0	-1526203,6	-1526203,6
1	559206,0	-966997,6
2	531211,2	-435786,4
3	504617,8	68831,4
4	479355,8	548187,2
5	455358,4	1003545,5
6	432562,3	1436107,9
7	410907,5	1847015,4
8	390336,8	2237352,1
9	370795,8	2608148,0
10	352233,1	2960381,1
11	334599,7	3294980,8
12	317849,1	3612829,9
13	301937,0	3914766,9
14	286821,5	4201588,4
15	272462,7	4474051,2
16	258822,8	4732873,9
17	245865,6	4978739,6
18	233557,2	5212296,8
19	221864,9	5434161,7
20	210758,0	5644919,6
21	200207,0	5845126,7
22	190184,3	6035311,0
23	180663,4	6215974,4
24	171619,0	6387593,4
25	163027,5	6550620,9

Table 7.9: Cashflow discounted and NPV – Photovoltaic plant and CHP

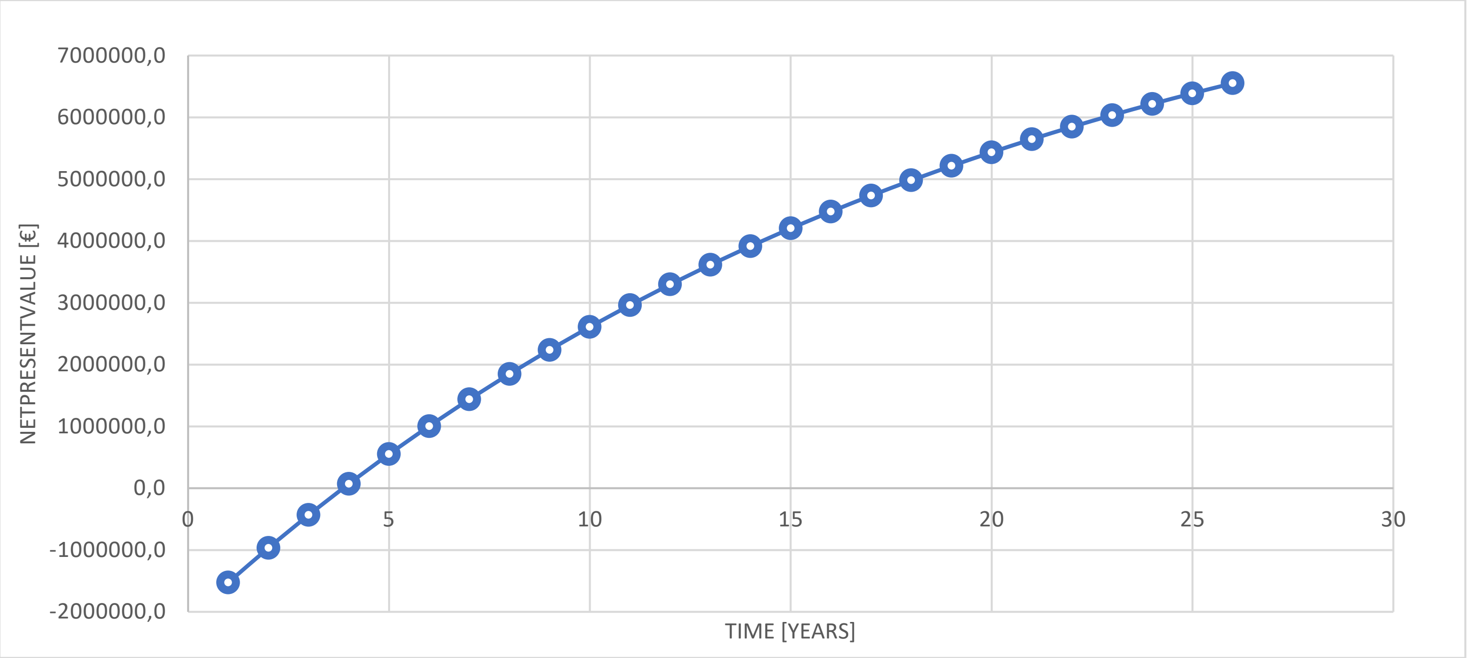


Figure 7.3: NPV behaviour – PV with CHP

The Net Present value after 25 years of operation of Cogeneration unit coupled with a PV system is **6550620,9 €**

Comparison of 2 Scenarios

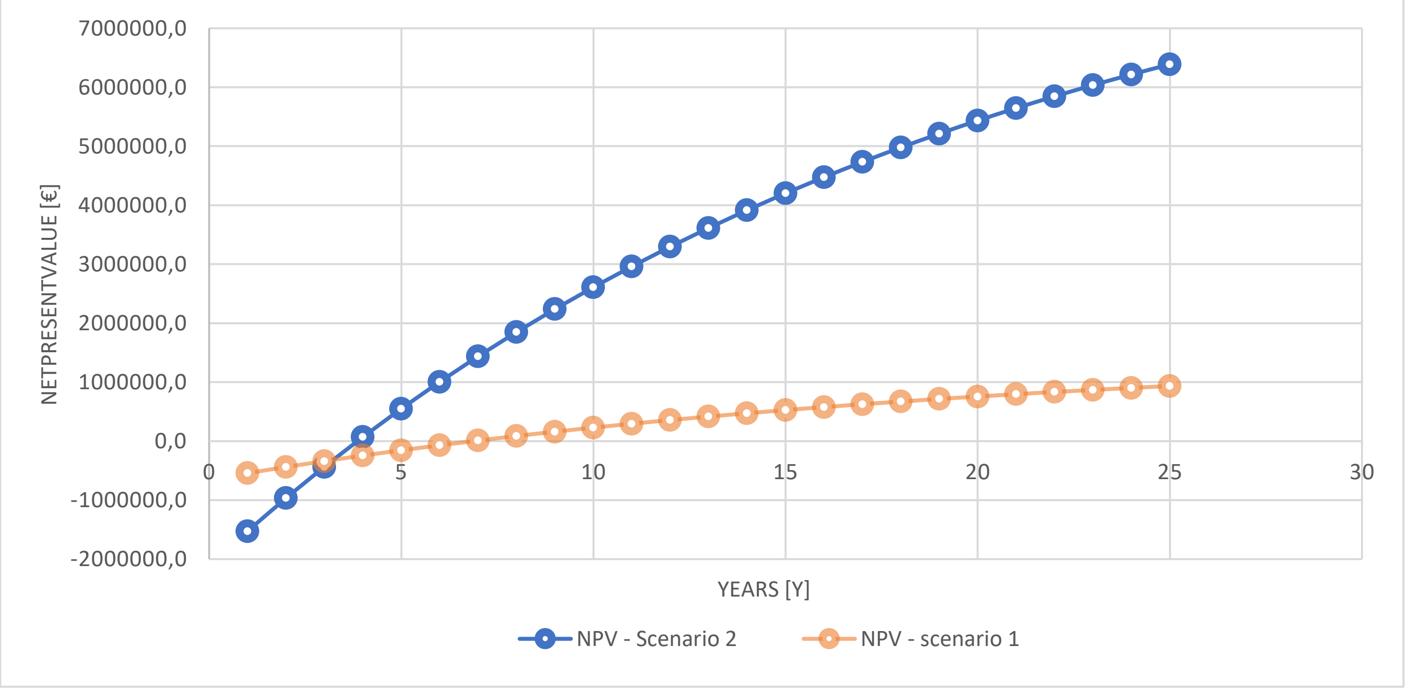


Figure 7.4: NPV slopes for the 2 scenarios

It should be noted that both scenarios, after a 25-year life span of the plants, have a very positive number of the net present value.
Particularly for scenario 1 the economic investment begins to be profitable after 6 years whereas, for the second one, after 3 years.
Indeed, the scenario which combines renewable plant and cogeneration records a NPV higher than the case in which only a single PV plant is employed.
This benefit is mainly due to the fact that the savings obtained in scenario 2, thanks to the self-consumed energy, are higher since the contribution of the cogenerator is added to the photovoltaic one.

7.4.1. Sensitivity Analysis

The formula of Net Present Value does not include explicitly the uncertainty which can affect the estimation of independent variables (i.e., Production, Revenues, CAPEX, OPEX).
Actually, they are considered to be constant over the whole project lifetime.
Therefore, a Sensitity analysis is often carried out on these variables to obtain a "spider diagram".[19]
By considering one independent variable at a time, it was decided to modify its value in an interval ranging from -20% to + 20% of the "nominal" value (i.e. the NPV calculated in paragraph 6.4.) keeping the other values of the formula constant.
In this way, it will be possible to understand which variable will affect the most the behaviour of the net present value.

For the scenario 1, the energy produced by the PV plant is the quantity that displays a wider fluctuation on the net present value, compared to the trends shown by Investment costs and OPEX Particularly, the variation of productivity tends to increase the nominal NPV, while the one of the other parameters leads to a slight decrease of it.

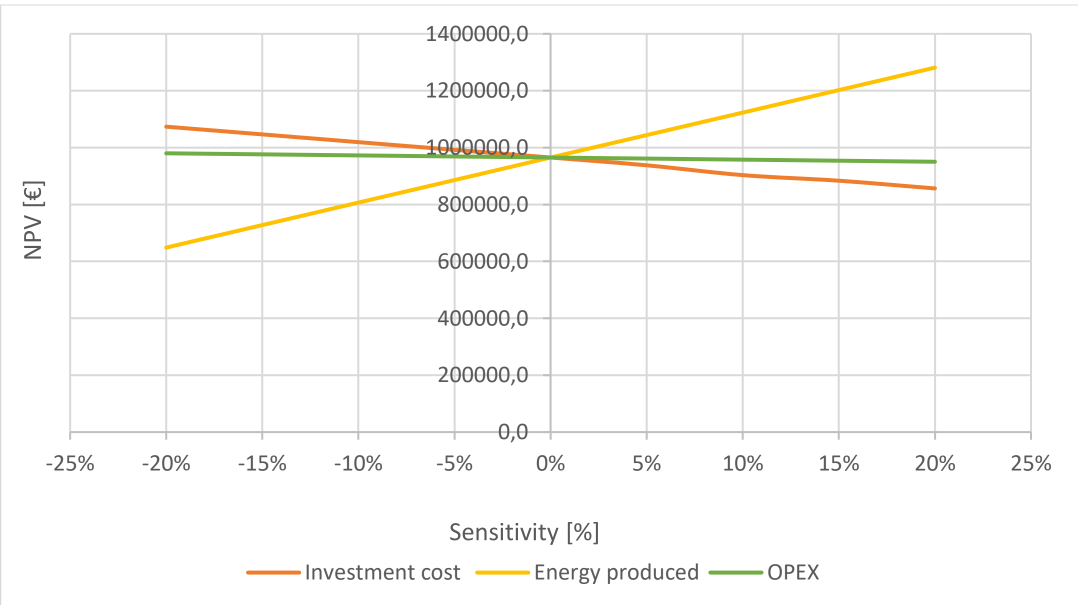


Figure 7.5: Spider diagram – scenario 1

In the scenario 2, the trend of C0 and OPEX is almost constant, whereas a variation of revenues, which depends on energy production, contributes to change the NPV by ± 28 %

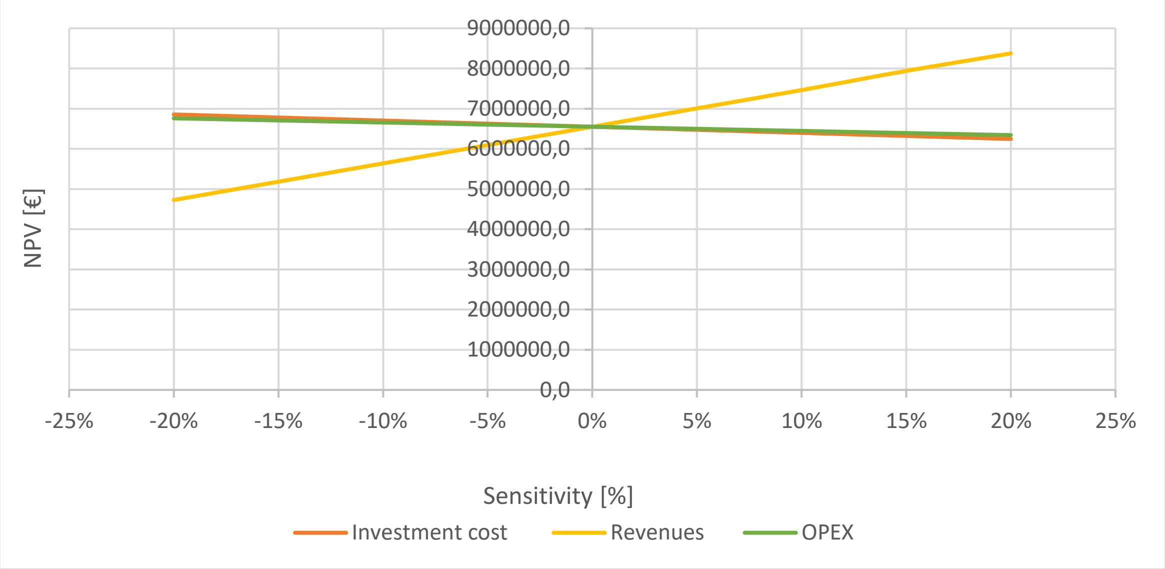


Figure 7.6: Spider diagram - scenario 2

7.5. Benefit Cost Ratio

The benefit cost ratio describes the average profitability of an investment per unit of invested capital.

$$BCR = \frac{Benefits}{Costs} = \frac{\sum_{k=1}^{N} \frac{B_k}{(1+WACC)^k}}{I}$$

The evaluation of this parameter is not affected by the size of the project.

	Scenario 1	Scenario 2
Discounted Cash flow [€]	1507467,9	8076824,5
Investment costs [€]	542280	1526204
BCR [-]	2,72	5,29

Table 7.10: Profitability index

The project with the higher BCR value should be chosen. [19]

7.6. Payback Time

In an economic analysis, it measures the time within which the invested capital is recovered from the positive cash flows of the investment. [19]

$$-I + \sum_{k=1}^{\tau} \frac{B_k}{(1 + WACC)^k} = 0$$

Scenario 1

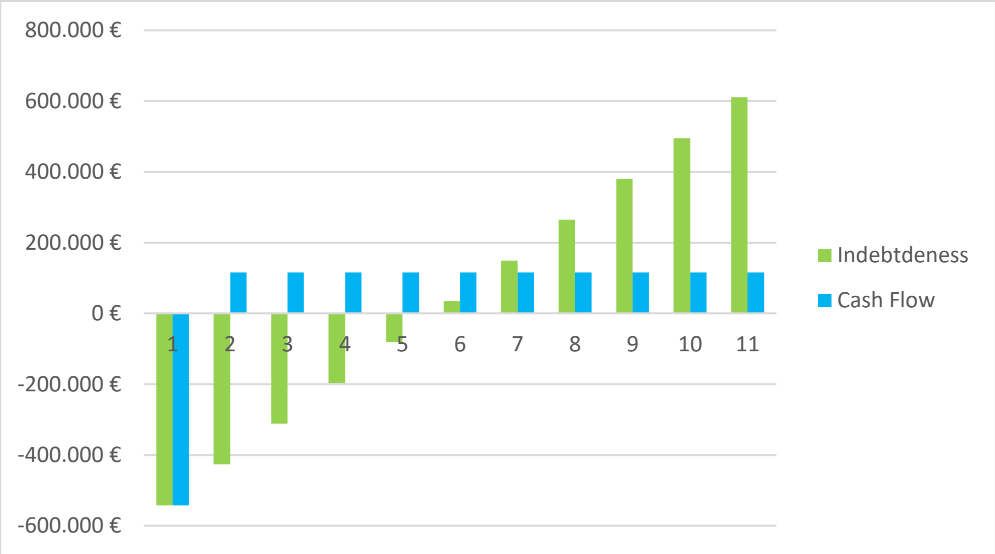


Figure 7.7: Monetary cash flow of scenario 1

The Payback time, if the only PV plant is installed, is **4,7** years.
It means, starting from that time, we will have only positive cash flow .

Scenario 2

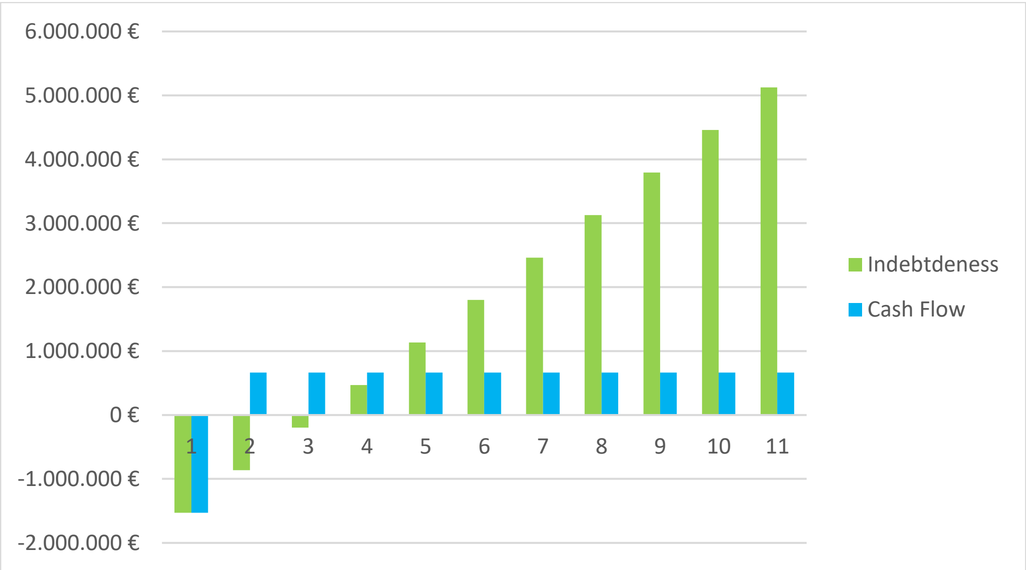


Figure 7.8: Monetary cash flow of scenario 2

The Payback time, if we consider the combination of the two technologies , is 2,3 years.

Conclusions

The thesis work aimed to focus attention on an industrial plant located in the south of Turin.
Starting from the analysis of the energy consumption required by the company in 2019, we wanted to study the feasibility of two types of scenarios. The goal of the first one was to examine the application of a grid-connected photovoltaic system.
Since it was decided to place it on the roof of the building, a three-dimensional model of the industry was built to understand how much solar energy the surface can capture. After having chosen a panel that was as performing as possible, the entire renewable plant was sized in terms of installed power. At this point the total energy produced by the system was calculated.
It was observed how a portion of the latter was actually self-consumed and, therefore, how the electricity withdrawal from the grid was reduced.
The second scenario, on the other hand, focused on the coupling of two technologies, such as the photovoltaic and the methane cogenerator. The thermal and electrical energy of the cogenerator was estimated on the basis of the consumption of the existing cogenerator.
This time the total self-consumed energy obtained by both plants is 80% and this allowed users to withdraw only more than 20% of electricity.
The last chapter of the thesis compared the two scenarios from the economic point of view.
First, the investment and operation costs were assessed. Secondly, the net present value was obtained for both cases and scenario 2 highlighted a greater profitability of the investment.
Last but not least, the calculation of the payback time was important because it proved that the coupling of chp and photovoltaic allows to return to the investment costs in 2 years and 3 months instead of in 4 years and 7 months as in the case of the only PV plant.

Appendix

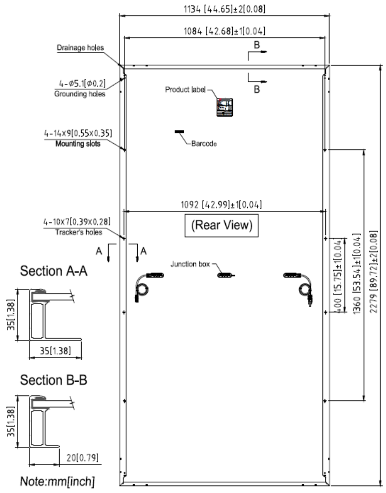
Electrical Characteristics

STC	STPXXXS-C72/Vmh				
Maximum Power at STC (Pmax)	550W	545W	540W	535W	530W
Optimum Operating Voltage (Vmp)	42.05V	41.87V	41.75V	41.57V	41.39V
Optimum Operating Current (Imp)	13.08A	13.02A	12.94A	12.87A	12.81A
Open Circuit Voltage (Voc)	49.88V	49.69V	49.54V	49.39V	49.24V
Short Circuit Current (Isc)	14.01A	13.96A	13.89A	13.83A	13.76A
Module Efficiency	21.3%	21.1%	20.9%	20.7%	20.5%
Operating Module Temperature	-40 °C to +85 °C				
Maximum System Voltage	1500 V DC (IEC)				
Maximum Series Fuse Rating	25 A				
Power Tolerance	0/+5 W				

STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5;
Tolerance of Pmax is within +/- 3%;
For tracker installation, please turn to Suntech for mechanical load information.

NMOT	STPXXXS-C72/Vmh				
Maximum Power at NMOT (Pmax)	415.0W	411.5W	408.0W	404.3W	400.6W
Optimum Operating Voltage (Vmp)	38.9V	38.7V	38.6V	38.4V	38.2V
Optimum Operating Current (Imp)	10.67A	10.63A	10.58A	10.53A	10.47A
Open Circuit Voltage (Voc)	46.9V	46.7V	46.5V	46.4V	46.3V
Short Circuit Current (Isc)	11.22A	11.18A	11.13A	11.08A	11.02A

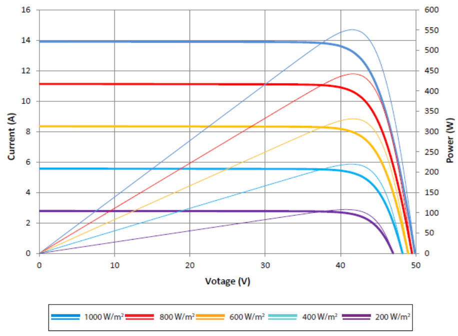
NMOT: Irradiance 800 W/m², ambient temperature 20 °C, AM=1.5, wind speed 1 m/s.



Temperature Characteristics

Nominal Module Operating Temperature (**NMOT**)	42 ± 2 °C
Temperature Coefficient of Pmax	-0.36%/°C
Temperature Coefficient of Voc	-0.304%/°C
Temperature Coefficient of Isc	0.050%/°C

Current-Voltage & Power-Voltage Curve (550S)



Mechanical Characteristics

Solar Cell	Monocrystalline silicon 182 mm
No. of Cells	144 (6 × 24)
Dimensions	2279 × 1134 × 35 mm (89.7 × 44.6 × 1.4 inches)
Weight	29.1 kgs (64.2 lbs.)
Front Glass	3.2 mm (0.126 inches) fully tempered glass
Frame	Anodized aluminium alloy
Junction Box	IP68 rated (3 bypass diodes)
Output Cables	4.0 mm², Portrait: (-) 350 mm and (+) 160 mm in length or customized length

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Acknowledgments

My career has come to the end of a path that has been long, sometimes complicated, but always very interesting.
I would like to thank my supervisor, Professor Pierluigi Leone, for his availability during the writing of my thesis.
I want to express my gratitude to the Light Wire company (Turin), which offered me the opportunity to join their engineering team and helped me in the project.
A special thanks goes to all my friends and to my colleagues that I shared this university experience with.
Finally, particular acknowledgments are dedicated to my parents, Saveria and Antonio and my sister Elisa: their deep support and affection were an essential element of this journey.