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Design and modelling of Renewable Energy Community: Analysis of the City of Parma

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Grazie a tutti :D

i. ABSTRACT

The main goal of this thesis is analysing the feasibility of implementing a Renewable Energy Community (**CER**, from the Italian words of 'Comunità Energetiche Rinnovabili') in the city of Parma, Italy. Only residential buildings were studied, evaluating their potential for the installation of photovoltaics panels and solar collectors. Several simulations of solar radiation and calculation of energy production were realized through QGIS software, whose results were compared with official data from PVGIS and ENEA to name just some checking sources.

The analysis was composed of different stages: initially, the useful roof areas were analysed separately for each type of technology (photovoltaic and thermal); later, its combined use was optimized. Also, an economic analysis was performed that allowed to determine the financial feasibility of the project in different case scenarios.

Finally, the results were compared with the initial forecasts, providing an integral vision of the energetic and economic benefits of the project. This investigation offers a replicable model for fostering the urban sustainability through the smart use of renewable sources and the creation of local energy communities.

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ii. INTRODUCTION

In recent years, the global energy panorama has gone through a profound transformation, driven by the urgent need to decarbonize economies, increase energy efficiency, and promote sustainability. The growing awareness of the environmental impacts associated with fossil fuels, combined with technological advances and evolving regulatory frameworks, has led to a significant change toward renewable energy sources. Within this context, **Renewable Energy Communities** (RECs or CERs in Italian) have emerged as an innovative and promising solution, fostering local actors to take control of their energy production and consumption in a more democratic, sustainable, and resilient way.

Energy communities allow groups of citizens, businesses, and institutions to collaborate in the production, management, and sharing of renewable energy, typically through decentralized installations such as photovoltaic panels or solar thermal collectors. These initiatives not only contribute to reducing greenhouse gas emissions but also reduce the pressure on the national electricity grid, promote energy self-sufficiency, and offer direct economic and social benefits at the local level.

This thesis aims to assess the feasibility of implementing a Renewable Energy Community in the city of Parma, Italy. The study focuses specifically on residential buildings, which represent a significant share of urban energy consumption. The technical analysis is conducted using geospatial tools such as QGIS to simulate solar irradiation and model the energy production potential of photovoltaic and solar thermal systems. A selection process based on factors like roof orientation, slope, surface area, and solar suitability is used to identify the most suitable buildings for renewable installations.

In addition to the technical dimension, the study includes an economic evaluation of various design scenarios, estimating costs, benefits, and payback periods. The legislative framework is also considered, particularly the recent Italian and European directives that support the creation and operation of energy communities.

By combining spatial data analysis, energy modelling, and economic feasibility studies, this research offers an integrated approach to understanding how cities like Parma can actively contribute to the energy transition. The final goal is to provide a scalable and replicable model for sustainable urban development, in line with national climate objectives and European energy policy.

1. CURRENT ENERGY AND GRID SITUATION

1.1. ENERGY SITUATION

1.1. ENERGETIC SITUATION

CURRENT GLOBAL ENERGY SITUATION

The rapid growth of clean electricity, changes in demand patterns, and decarbonization initiatives are all contributing to a significant transformation of the global energy landscape. In 2023, the world's demand for electricity increased by 2.2%, a moderate rate that reflected difficulties in developed nations where industrial activity shrank due to high energy and inflation costs. However, due to the economic recovery, the electrification of end-use sectors (such as transportation and residential heating), and the emergence of energy-intensive technologies like data centers, artificial intelligence (AI), and cryptocurrency mining, global demand is expected to grow at an annual rate of 3.4% through 2026. By 2026, it is anticipated that the demand for electricity from these technologies alone will have doubled to levels equal to Japan's overall electricity consumption [1] (IEA, 2024, p. 8).

Around the 85% of the additional demand for electricity through 2026 will come from emerging and developing economies, which are the primary drivers of this growth. The demand for electricity in China, which already contributes the most, increased by 6.4% in 2023 and is expected to surpass 1,400 TWh by 2026. As China's economy transitions from heavy industry to services, growth is predicted to slow somewhat, but the scale will still be unprecedent. Among the major economies, India is expected to grow at the fastest rate, with electricity demand expected to rise by more than 6% a year until 2026. India's overall electricity consumption will surpass that of the United Kingdom due to rapid electrification, economic growth, and increased demand for air conditioning [1] (IEA, 2024, pp. 9–10). While Africa lags behind due to structural issues like limited infrastructure and electricity access, Southeast Asia likewise exhibits robust annual growth of 5% [1] (IEA, 2024, p. 20).

Global developments revolve around the **shift to clean energy**, with renewables expected to supply all future demand growth by 2026. By early 2025, solar photovoltaic (PV) and wind power will likely overtake coal as the world's largest source of electricity generation due to declining costs and policy support. By 2026, the proportion of global generation that comes from renewable sources will rise from 30% in 2023 to 37%, thanks to large capacity expansions in China, the US, and Europe. Nuclear power is seeing a comeback alongside renewables, with new projects in China, India, and Korea as well as reactor restarts in France expected to boost generation to record highs by 2025 [1] (IEA, 2024, pp. 11–12).

As the proportion of fossil fuels used to generate electricity falls from 61% in 2023 to 54% by 2026, the CO_2 emissions from the global power sector are starting to structurally decline. This decrease is a result of the fast expansion of clean energy sources, which are replacing coal and gas-fired generation, especially in China, the US, and Europe. Through 2026, it is anticipated that the CO_2 intensity of electricity generation worldwide will decrease at a never-before-seen rate of 4% per year [1] (IEA, 2024, p. 13). But there are still issues, especially in Africa, where there is a lack of affordable electricity and a growing dependence on diesel generators [1] (IEA, 2024, p. 20). [2]

ENERGY SITUATION IN EUROPE

The energy sector in Europe faces a challenging environment characterized by growing renewable generation, industrial challenges, and decarbonization goals. After a similar decline in 2022, European electricity demand fell by 3.2% in 2023, marking the second consecutive year of declines following the energy crisis caused due to geopolitical tensions. With industrial electricity consumption experiencing the biggest drops, the contraction drove demand to levels not seen since the early 2000s. High energy costs and decreased competitiveness resulted in major production shutdowns and limitations in energy-intensive industries, especially chemicals, steel, and metals. Industrial output may suffer long-term losses as a result of this structural demand destruction [1] (IEA, 2024, pp. 20-22).

Renewable energy is still driving Europe's power sector transformation in spite of demand issues. Through 2026, it is anticipated that clean electricity sources (of which renewables will make up the largest share) will be able to meet all additional demand growth in Europe. Over the period, renewable generation (especially from wind and solar) is predicted to increase by 14% annually, reaching a combined 55% share of total electricity generation by 2026. The restart of French reactors and the construction of new nuclear capacity in several European nations are driving the recovery of nuclear generation at the same time [1] (IEA, 2024, p. 12).

Natural gas-fired generation is predicted to decline by 7% annually through 2026, while coal-fired generation fell by 26% in 2023 and is predicted to decline by 13% annually after that. This decline is made possible by improved nuclear output and the robust growth of renewable generation, which is causing emissions from the power sector to rapidly decline. Europe will see a significant reduction in CO_2 emissions from electricity generation by 2026, with the sector's CO_2 intensity declining at the fastest rate among major global regions, at an average annual rate of 13% [1] (IEA, 2024, p. 13).

Electricity costs in Europe are still higher than they were before the pandemic, which presents difficulties for small and medium-sized businesses (SMEs) and energy-intensive industries. Overall electricity prices are still twice as high as they were in 2019, even though they decreased by more than 50% in 2023 compared to 2022, especially in areas that rely significantly on imported natural gas. The disparity in prices has made European industries less competitive when compared to their American and Chinese counterparts. Energy-intensive industries, such as chemicals and metals, are especially susceptible to fluctuations in energy prices, which may worsen production drops and cause operations to relocate outside of Europe [1] (IEA, 2024, pp. 22-23).

In order to handle the increasing proportion of renewable energy sources, the European power industry is also making investments in grid infrastructure and system flexibility. In order to guarantee energy security and dependability, grid extensions, connections, and battery storage systems are necessary. Furthermore, in order to overcome the difficulties brought on by variable renewable generation, Europe is leading the way in the development of new market mechanisms. To stabilize power systems, nations like Germany, the United Kingdom, and Ireland are putting policies like fast frequency response markets into place [1] (IEA, 2024, p. 14).

To sum up, Europe is leading the global energy transition by implementing renewable energy initiatives while dealing with systemic issues with industrial demand and energy affordability. In the upcoming years, as the region navigates the effects of high energy costs, grid modernization, and changing industrial policies, its ability to strike a balance between decarbonization efforts and economic competitiveness will be crucial. [3] [4]

1.2. GRID SITUATION

PROBLEMS OF THE EUROPEAN ENERGY GRID

In the European context, the energy sector has continuously been fostered by the European Union to make a transition to alternative types of energies, greener ones, in order to pursue the proposed climate goals.

This has led to a lot of investments or creation of benefits in order to foster the adoption and competitivity of renewable energy technologies and it has worked quite well. However, to keep the pace of these developments is also necessary the evolution of the current electricity grid and this point has been forgotten and now the first consequences are starting to arise.

Basically, it could be said that in the current situation “electricity grids are the weak link in the clean energy transition” [5]. In the following the main problems that the grid is facing will be analysed.

To start, it is the problem of **lack and aging infrastructure**. In a world where electricity is becoming each time a more important part in modern life, the electrical grid is not keeping the peace with the development of technologies that depend on it.

In the way to a stronger grid, not only it would be necessary to modernize the current one, but also expand it to new areas. For instance, there a lot of new renewable energy projects in advance state but there is no granted that the grid would be ready before finishing the projects.

To achieve the climate goals accorded it would be necessary to invest strongly in the grid, since it has been prioritized the investment in all the new green energies, but the development of the grid has got a bit behind.

In addition, the **mismatch between the place of consumption and production**. This problem has got a lot worse with the introduction of large-scale project of renewable energy generation plans as photovoltaic or Eolic to name just a few. In general, in order to make viable these projects it is necessary to choose locations where the sources of renewable energies are optimal or greater than the average and the trouble with this is that usually these places are far away from the points of consumptions (cities and towns).

All this mismatch between the place of production and consumption generates the necessity of the creation or extension of new electrical grids, where they usually require a strong investment from part of governments.

Furthermore, it is the **underinvestment**. In the past years, it has been strongly fostered the transition to greener sources of energy due to the followed climate goals, focusing the investment on the development of new technologies or creating benefits for the adoption of them in order to make them competitive against the traditional ones.

In the electricity sector, this was mainly seen with the development of large-scale project of photovoltaic and eolic plants but also in local scales in the adoption of benefits for final consumers (i.e. reduction in taxes for incorporating solar panels). This has brought a promising advancement in renewable energy adoption; however, it was forgotten investing in the electric grid to make all this viable. So, now we are in situation where there a lot of renewables new power plants finished or almost finished waiting for the creation or adaptation of the grid in order to be able to connect them.

Moreover, the **barrier between regions** makes things harder. In order to facilitate the work between different regions or countries it would be a great advantage making compatible the different regulations of each local region, therefore making collaboration easier and breaking the legal barriers.

Also, a point to be improved in the current grid is its **flexibility** since the introduction of new sectors depending on the electricity as transportation and heating, and variable production of renewable energy sources as solar or wind energy requires a flexible and smart grid in order to manage these fluctuations.

Last but not least, if the goal is improving the current electricity grid, it is necessary to start **collaborating** between different countries of the European Union. This can be done harmonising regulations, searching for interdependencies between regions and focusing on common points to invest, this would accelerate progress and avoid wastes of time. To pursue the climate goals is compulsory working as a unity between the nations if a real change is the objective. [6]

SOLUTIONS

Even though the current electricity grid has several problems or is about to have them, the European Union is currently working in solutions and planning some others for the near future. In the following, the main solutions are going to be discussed and also some possible alternatives compatibles with the grid will be mentioned.

Firstly, it will be needed a big **infrastructure investment** to modernize and strengthen the current grid. Also, this improvement can come as investment in benefits for local consumers that decide to adopt renewable energy options for producing their own energy and in this way lowering the pressure in the global grid.

Then, the introduction of **smart grids** is great option in order to improve the efficiency of the existent grid, allowing the optimization of electricity flows, reduce outages and allow consumer to adapt their consumption according to offer of energy. [7]

Another problem brought due to the introduction of the renewable energy production plants are the fluctuations in production (due to the nature of energy sources as the sun and wind). Due to this some solutions have been analysed. One of them is **energy storage systems**, such as batteries, anyways improvements are necessary yet to make them viable in large scale. Another option taken into consideration, it is **demand-response mechanisms** that basically allows to consumers change their energy consumption based on the current state of the grid at each moment avoiding in this way overloads and adding flexibility to the grid.

Additionally, working in the creation of **connection between the grid of state member**s would improve its resilience and would facilitate the integration with renewables at European scale.

Another possible card to play is the encouragement of **energy communities** and renewable energy projects at local scale where the main players are the same consumers that decide to join forces to achieve the auto-consumption or some degree of it. They are an optimal option since reduce the pression of the existent grid, are more independently and allow to communities to manage their energy needs more efficiently.

The main argument of this thesis is the feasibility analysis of an energy community, so in the next sections this topic will be studied in greater depth.

Also, some **standards** have been introduced to follow similar regulations and frameworks between countries in the introduction of modern technologies, such as "Digitalization of Energy Action Plan".

Finally, the investment in **research** is continuously fostered as it has the potential of opening new solutions for existent problems. For instance, one of them is "Horizon Europe Research" program. Nowadays, grid optimization tools and new materials for energy storage are the hot-topics related to this area.

2. ENERGY COMMUNITIES

2.1. Basic concept of energy community and what they bring

In short words, an energy community is a group of different actors, such as normal citizens, associations, business, institutions, and others, that join together with the goal of producing, consuming and managing energy. Frequently they focus on renewable energy sources. In this way, they achieve some sort of independency while improve local benefits and align with global goals related to climate change fight, in other words, it is a win-win situation for all the actors.

<u>How Energy Communities can help:</u>

Energy communities are born as a way of solving several problems that the electricity grid is currently having while it improves the local situation (economic, sustainability and environment) of communities. It is a win-win situation from all the players.

Hereunder, the possible advantages that they can bring to the grid and to the local communities will be discussed.

Firstly, it can be mentioned that they help to **decentralize the energy production and consumption** since by producing energy locally using renewable resources like biomass, wind, or solar, they reduce the dependence on national grids and centralized power plants, which are more susceptible to interruptions. In this way, the strain in the grid is reduced and also the transmission losses and congestion as well.

Another aspect to consider, it is that the **grid flexibility** and **overall resilience** are improved. These communities frequently use smart technologies and energy storage, which improves the grid's capacity to manage variable renewable energy inputs. Energy storage systems, such as batteries, improve resilience by storing excess energy that can be used during outages or periods of high demand, ensuring a consistent power source. Furthermore, energy communities frequently develop microgrids that can operate independently from the main grid—a feature known as islanding—to maintain energy access during emergencies or grid failures. This localized, decentralized approach strengthens energy systems and improves their ability to deal with unexpected disruptions like natural disasters or energy market volatility. By diversifying energy sources and fostering strong community cooperation, energy communities create systems that are resilient, flexible, and ready to withstand both immediate disruptions and long-term changes, such as those caused by climate change.

Besides, **faster deployment of clean energy solutions** is made possible by local ownership of renewable projects, which can avoid administrative grid connection bottlenecks.

Moreover, the **demand response and load management** is enhanced. By enabling members to modify their energy consumption habits to match supply, energy communities can even out peak loads and reduce the need for costly grid reinforcements.

In addition, energy communities play an important role in **attracting investment** by encouraging collaboration among individuals, businesses, and local governments. By allowing collective ownership of renewable energy projects such as solar panels, wind turbines, and energy storage systems, energy communities reduce individual financial burdens while creating opportunities to develop infrastructure that benefits everyone. This shared ownership model reduces risk and increases investor confidence, making it easier to secure funding for ambitious projects. Furthermore, energy communities frequently have access to government subsidies, grants, and financial incentives designed specifically to promote renewable energy initiatives. Furthermore, by selling excess energy back to the grid or to community members, energy communities generate revenue that can be reinvested in new projects or used to upgrade existing infrastructure.

In conclusion, by adopting these types of systems Europe could address key grid challenges while promoting energy equity and sustainability. What is more, this solution supports the larger European and IEA objectives for a decentralized, more robust energy system. [8]

2.2. Energy community in Europe

"Energy communities are legal entities that empower citizens, small businesses and local authorities to **produce, manage and consume their own energy**. They can cover various parts of the energy value chain, including production, distribution, supply, consumption, and aggregation. Energy communities may vary depending on their location, involved actors and provided energy services." [9] [10] [11]

Frequently, the energy communities follow one of the next models:

- **Generation and supply**
- **Collective investments in production installations**
- **Collective self-consumption**

It is possible to combine the mentioned models.

It is always necessary to consider the regulatory context and the financial incentives that exist in each country and/or region where the energy community is planned to be done. These local conditions will be affected drastically the feasibility of the project.

Some new information about energy communities was added by the European Commission in the *"Clean energy for all Europeans"* package, in 2019. Sometime later, deeper and more specific information related to renewables energy communities was included in the "*Renewable Energy Directive*" and in the "*Internal Electricity Market Directive*".

These types of communities are allowed to operate in the electricity and heating sector, as long as it is proved that the energy comes from renewable sources. Also, one important condition for the creation of a community is that it must be autonomous, since the idea is keeping a democratic behaviour for taking decisions between the members.

According to EU legislation, they can be formed as one following typologies:

- Association
- Cooperative
- Partnership
- Non-profit organization
- Limited liability company
- Other

2.3. Renewable Energy Community in Italy

"A **CER** is a group of citizens, small and medium-sized enterprises and local authorities, including municipal administrations, cooperatives, research institutions, religious bodies, third sector and environmental protection institutions, that have decided to share the renewable electricity produced by facilities in the availability of one or more entities associated with the community.

In a CER, renewable electricity can be shared between the different producers and consumers, located within the same geographical perimeter, thanks to the use of the national electricity distribution network, that makes virtual sharing of such energy possible" [12].

The creation of a CER brings environmental, social and economic advantages for its members and for the nearby local areas.

In order to constitute this type of community, firstly it is necessary to define the area where it will be located and then define which the user will be. Besides, the CER needs to be constituted legally in some of the possible kind of associations, in order to obtain juridic autonomy. Therefore, each CER will be characterized by a constitution and a statute.

The individual members of the community keep the originals rights of final clients, as for instance the decision of the energy supplier's right.

It is possible to participate in a CER as one of the following kind of members:

- **Renewable energy producer:** person/actor who carries out a photovoltaic installation (or another typology, i.e. hydroelectric, eolic, biogas, biomass, etc).
- **Auto-consumer of renewable energy:** person/actor who has a renewable energy installation and it also consumes its own produced energy and shares the remaining to the other members.
- **Consumer of electrical energy:** person/actor who does not have any energy installation, however it has the necessity of consuming electricity. This consumption can partially be covered by the renewable energy produced of the other member of the community.

Regarding to the benefits or incentives provided by the government in order to foster the creation of these communities, the legislative decree n. 199 of 2021 (**Decreto legislativo n. 199 del 2021**) provides all the related information. The decree gives two major types of incentives:

- **Rates incentives:** valid for the national territory (Italy), from the small town to the metropolitan city. It allows to save money in the energy consumption of the community members due to the reduction in the energy rates (incentives).
- **Contribution due to initial investment (PNRR):** Only valid for small towns (under 5000 inhabitants). Return up to 40% of the investment of the creation of an Energy Community. It is allowed to use it in combination with the incentive rates.

The decree was approved the last 23 February of 2024, with a delay of 1 year and 7 months.

With respect to the current situation, up to 2024 there were 154 facilities related to sharing of energy between members in Italy, varying between renewables energy communities and configurations of collective auto-consume. Even though the numbers were good, they could have been a lot better without all the delay produced. It is estimated that at least 400 more renewables energy communities would have been created in absence of the problems mentioned.

Anyways, it is expected that the approval of the decree will impulse the creation of this kind of communities and, therefore, the future forecast seems to be good even if there are yet some problems related to the decree to solve, as for instance the no inclusion of the geothermal energy. [13] [14] [15] [16]

3. CASE STUDY: Parma

3.1. Location

General description of Parma's Location and Context

Located in the northern part of Italy, a nation renowned for its natural, historical, and cultural diversity, Parma is a mid-sized city with about 200,000 residents.

Parma is specifically located in the Emilia-Romagna region, which is renowned for its thriving economy, gastronomic traditions, and historical contributions to art and science. It is the second most populated city in the region behind Bologna and followed by Modena. Additionally, Emilia-Romagna offers a combination of hilly and fertile plains, stretching between the Po River to the north and the Apennine Mountains to the south. However, considering the global picture, it can be noticed that also the Alps are located in the North. All these geographical conditions make a natural barrier and avoid the arrival of sea air and make difficult the air renewal. This relative isolation, make it susceptible to the **urban heat island** phenomenon. [17]

The Province of Parma, one of Emilia-Romagna's administrative divisions, has Parma as its capital. The terrain of the province is varied and includes rolling hills, agricultural plains, and portions of the foothills of the Apennines. Producing some of Italy's most recognizable culinary items, including Parma ham and Parmigiano Reggiano cheese, the area is thriving due to its agricultural and food sector.

The city center and the surrounding rural and suburban areas make up Parma, which is a comune, the smallest administrative unit in Italy. Parma is ideally situated on the Via Emilia, an old Roman route that links many of the important cities of Emilia-Romagna, about midway between Milan and Bologna. Parma is a significant hub for trade, culture, and transportation because of its location.

Detailed Description of Parma's Location in each sub-region

In the following, it will be described the main characteristics related to the ubication of Parma from a geographical perspective. Starting from the general overview and increasingly entering into the local scope of the subregions where the city is located.

Europe

Parma is located in southern Europe, a region distinguished by the diversity of its languages, cultures, and historical influences. It is well-known as a center of culture and cuisine since it is a part of Italy, which benefits from the larger European context of interconnected nations, shared traditions, and modern infrastructure.

Figure 1- Location of Italy [18]

Italy

The city is ubicated in northern Italy, a region known for its historical significance, fertile plains, and hardworking cities. Because of its location, Parma plays a significant part in Italy's agricultural and culinary traditions, reflecting both the Mediterranean climate and the thriving economy that characterizes northern Italy.

Figure 2 – Emilia-Romagna region [19]

Emilia-Romagna

Northern Italy's Emilia-Romagna region is bounded to the north by the Po River and to the south by the Apennine Mountains. It extends from the Ligurian and Tuscan borders in the west to the Adriatic Sea in the east. Parma serves as a gateway between the mountainous Apennine regions and the lush agricultural plains of the Po Valley due to its location in the western Emilia-Romagna.

Due to its geographical position, Emilia-Romagna is a vital region for trade, transportation, and culture. Bologna, Modena, Reggio Emilia, and Parma are among the major cities that are connected by the Via Emilia, an old Roman road. The connection of the area is still impacted by this road.

Respect to the topography, their varied landscapes are advantageous to Parma. The agriculturally rich plains of the Po River provide the area with the raw materials needed to make its well-known culinary delicacies. The Apennine Mountains to the south offer outdoor recreation options and a source of scenic splendour.

Moreover, the region is renowned for its thriving economy, rich cultural heritage, and excellent standard of living. Standing out the food production, the automobile industry (including Ferrari and Lamborghini), and its education always focusing on innovative topics.

Emilia-Romagna in general stands out from other Italian areas due to its harmonious blend of cultural preservation and economic growth. This harmony is seen in Parma, where contemporary industries and infrastructure coexist peacefully with the city's medieval center.

Figure 1 - Physic- politic map of Emilia-Romagna [20]

Figure 2 - Provinces of Emilia-Romagna [21]

Province of Parma

Parma serves as the capital of the province that bears its name in the Emilia-Romagna region. The province is vast, spanning from the rolling foothills of the Apennines to the low-lying plains of the Po River. A variety of agricultural pursuits, including as the manufacture of Parmigiano Reggiano cheese, Parma ham, and exquisite wines, are supported by this geographic diversity. Parma's location in this exuberant environment emphasizes its function as a center for both the city and the countryside.

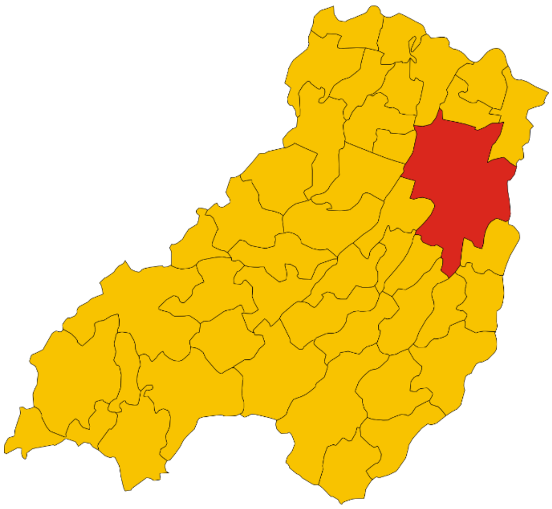

Figure 3 – Comunes from Parma province [22]

Comune of Parma

The city and its surrounding suburbs make up the Comune di Parma, which serves as the main administrative region. It serves as an essential connection between important Italian cities like Milan, Florence, and Bologna due to its placement along the Via Emilia and in close proximity to the A1 motorway. The city's strategic and attractive location is further highlighted by its easy access to the mountains and rural areas.

In the following picture the neighbourhoods of the city can be seen.

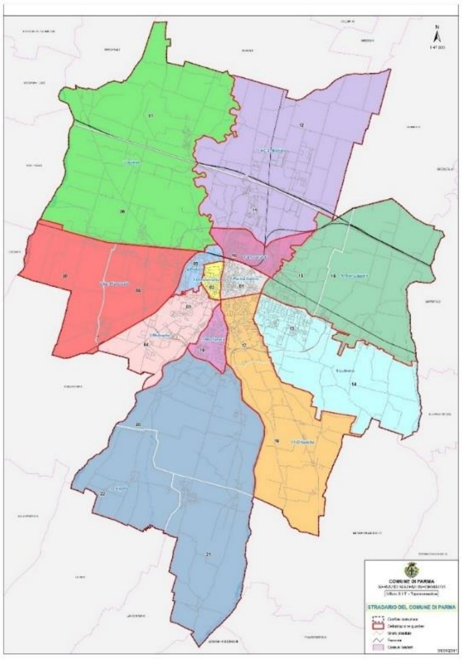

Figure 4 – Neighbourhoods of Parma city [23]

In conclusion, Parma has a special combination of benefits due to its location in the Emilia-Romagna area. Its location along ancient and contemporary trade routes, in the center of northern Italy's fertile plains, further solidifies its standing as a city of cultural, economic, and geographic significance.

3.2. Description of the city

Parma is a medium-sized city with a mix between historical, economic, cultural and educational environments. Also, it is known as the birthplace of Parmigiano Reggiano cheese and Parma ham (prosciutto), making it a gastronomic hub that draws food enthusiasts from around the world.

It is a city with Roman origins where over time has suffered the pass of other movements as for instance the medieval age, Renaissance and Baroque period, resulting in an important cultural wealth. It is well known for its magnificent architecture, which includes the lovely Teatro Regio, a representation of its operatic traditions, the Baptistery of Parma with its pink Verona marble facade, and the Romanesque Parma Cathedral.

Even though, it is not an industrial giant, it keeps having a strong participation in the economy of Emilia-Romagna region. With a vast presence of small and medium companies.

Also, it has an important educational background with the presence of the University of Parma since the 11th century, one of the oldest universities in the world. Making Parma an educational and research center. This brings each year a vibrant student population and allows the development of several fields like engineering, food science, sustainability and others.

Something important to highlight is that Parma is recognized for its sustainability efforts since it has been part of several European initiatives to reduce emissions and improve the liveability.

The city is also home of several galleries and museums, including the Galleria Nazionale, which features pieces by artists like Parmigianino and Correggio. Parma is a delightful fusion of history, art, and natural beauty, with its charming streets lined with pastel-colored buildings and green areas like the Ducal Park (Parco Ducale).

Regarding to the information about the **social characteristics** of the city, it has been used the data extracted from **ISTAT** (Istituto Nazionale di Statistica), particularly from the ***census realized in 2021*** [24] about the permanent population in Parma.

TOTAL INHABITANTS
195.436

TOTAL NUMBER OF FAMILIES (PARMA)
92.324

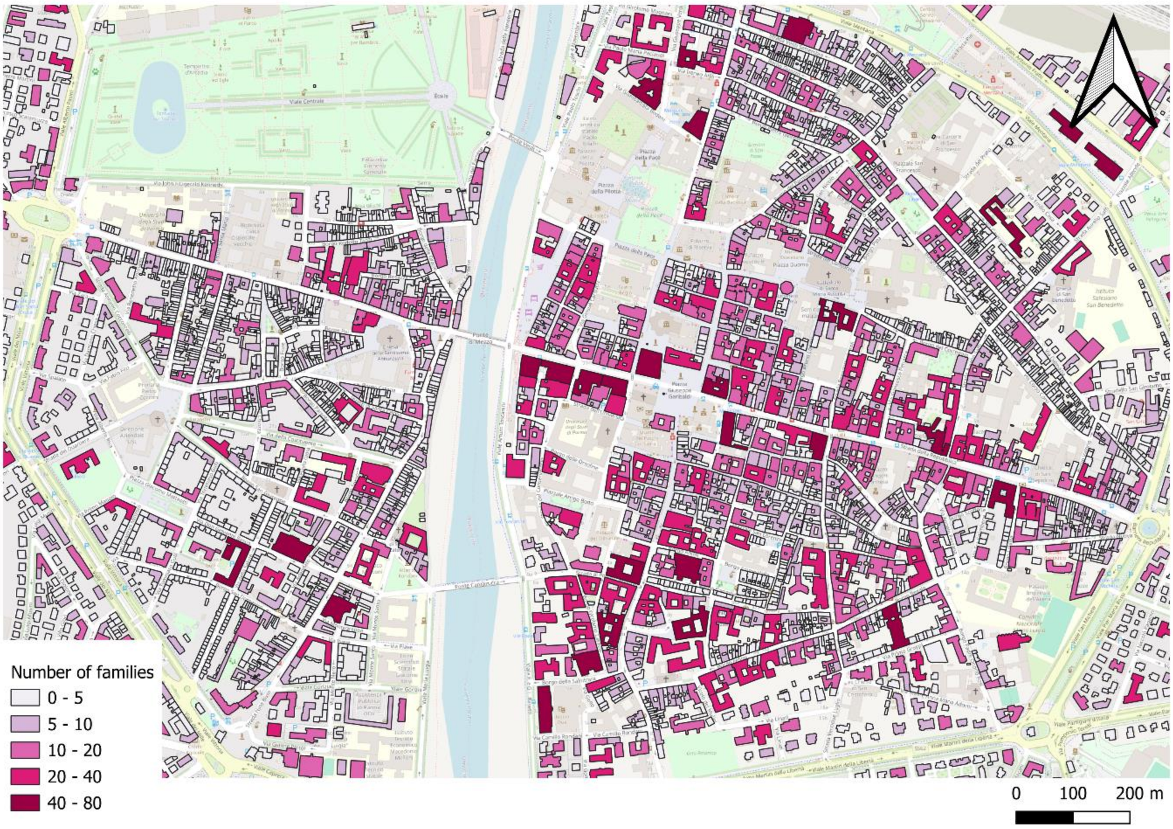

Figure 3 - Number of families

Additionally, using QGIS to get the information about the total volume of the residential buildings of Parma and ISTAT to obtain the number of inhabitants and families, it is possible to calculate some extra parameters of the city. For instance, the inhabitants and families per cubic meter have been calculated in this way.

Volume of residential buildings	
57.063.814	m3
Inhabitants per cubic meter	
0.00342	inhabitants/m3
Families per cubic meter	
0.00162	families/m3

3.3. Possible potential

Parma can be an interesting city for renewable energy studies due to its geographic and climatic characteristics, especially for solar energy. Due to its location in the north of Italy, it faces challenges regarding to the solar energy potential since the sunlight hours are reduced in comparison to southern regions. Nevertheless, with the help of government incentives and correct urban planning strategies these problems can be successfully addressed.

Before doing an analysis in depth, it can be forecasted that Parma' **solar potential** is **moderate**. Anyways, positioning strategically the solar panels and taking advantages of the local incentives, it keeps being a worthy option to study.

Hereunder, some useful graphs and information are showed from where can be seen implicitly the solar radiation potential roughly speaking.

For instance, the *viewshed calculation* is an illustration of the whole sky that is either visible or obscured when viewed from a specific point in time. A viewshed is determined by calculating the maximum angle of sky obstruction, also known as the **horizon angle**, around the area of interest in a predetermined number of directions.
Horizon angles are calculated by interpolating for all other unexplored directions. A cartesian diagram (Fig. 4) can be used to illustrate the results where the x-axis represents the azimuth angles of the searched directions, while the y-axis measures the sun height with horizon angles. Moreover, this can also be shown on a polar diagram (Fig. 2 and 3), where the radius of the circle indicates the sun direction (azimuth angle) and concentric circles indicate the solar height.

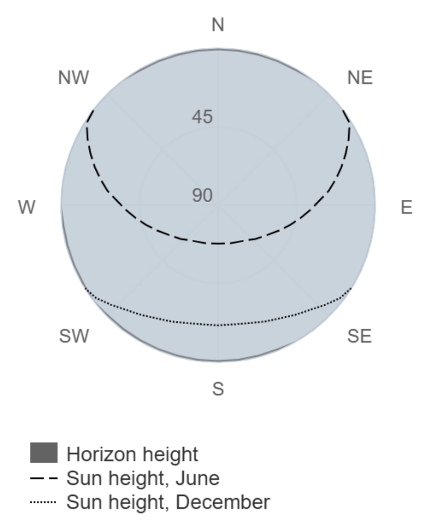

Figure 4 - Parma's Outline of Horizon [25]

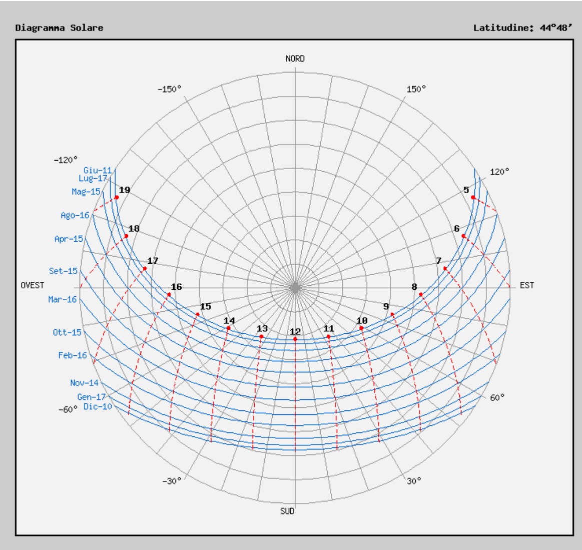

Figure 5 - Parma Polar Diagram [26]

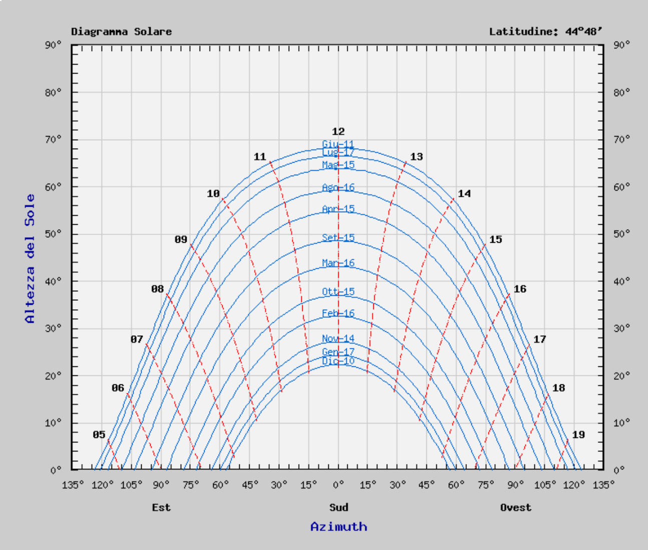

Figure 6 - Parma Cartesian Diagram [26]

Then, the viewshed is combined with other types of maps, as the SunMap and the SkyMap, in order to make the calculation of the solar irradiation.

In addition, sunrise and sunset times of representative days are showed since they bring useful information to the project and will be used in the calculations.

Day	**Sunrise (CET)**	**Sunset (CET)**	**Duration of the day**	**Equation of time**
17 January	7h 57'	16h 59'	9h 02'	-9'20"
16 February	7h 24'	17h 42'	10h 17'	-14'14"
16 March	6h 36'	18h 20'	11h 44'	-9'21"
15 April	5h 41'	18h 57'	13h 16'	-0'14"
15 May	4h 56'	19h 33'	14h 37'	3'56"
11 June	4h 38'	19h 58'	15h 20'	0'48"
17 July	4h 53'	19h 56'	15h 03'	-6'01"
16 August	5h 26'	19h 21'	13h 55'	-4'41"
15 September	6h 01'	18h 27'	12h 27'	4'39"

15 October	6h 37'	17h 31'	10h 54'	14'25"
14 November	7h 19'	16h 48'	9h 29'	15'20"
10 December	7h 50'	16h 33'	8h 42'	7'08"

Figure 7 - Sunrise and Sunset times of Parma (Lat=44°48' Long=10°2) [27]

3.4. Primary Transformation Substation (Cabina Primaria)

One of the most important requirements for creating a Renewable Energy Community (CER) according to the Italian regulations is that all the participants (prosumers, consumers or consumers) have to be connected to the **same primary transformation substation ("cabina primaria")** of the electricity distribution network.

This substation has the function of connecting point between the national transmission grid (high voltage) and the local distribution network (medium voltage). Also, from this point, the lines reach secondary substations, which transmit energy to the final users at low voltage.

In a CER, the sharing of energy is allowed only among the users that fall under the same primary substation, since only in this area is technically and legally permitted. The goal of this requirement is to allow the energy sharing at local level, since in this way is achieved a reduction in grid losses and improves the collective self-consumption.

Other aspect to consider is that a primary substation does not necessarily correspond to well-defined municipal or territorial boundaries. It is common to find buildings located in the same neighbourhood or municipality; however, they belong to different primary substations. Consequently, a preliminary assessment of the current electrical infrastructure is essential during the design phase of a CER.

Therefore, all this means that before establishing a CER, it is necessary to verify that all the buildings and users are connected to the same primary substation. In the case of the **city of Parma**, all the buildings are into the influence of the same primary substation ('medesima cabina primaria'), allowing to design the CER without taking extra precautions regarding this topic.

In order to support this verification process, the GSE (Gestore dei Servizi Energetici) gives an accessible interactive map of Italy's primary substations, available on its official website (https://www.gse.it/servizi-per-te/autoconsumo/mappa-interattiva-delle-cabine-primarie). In the following are shown two images, firstly the complete national map of primary substations and then a detailed view of the primary substations serving the city of Parma (main focus of the case study).

Figure 8 - Complete national map of primary substations

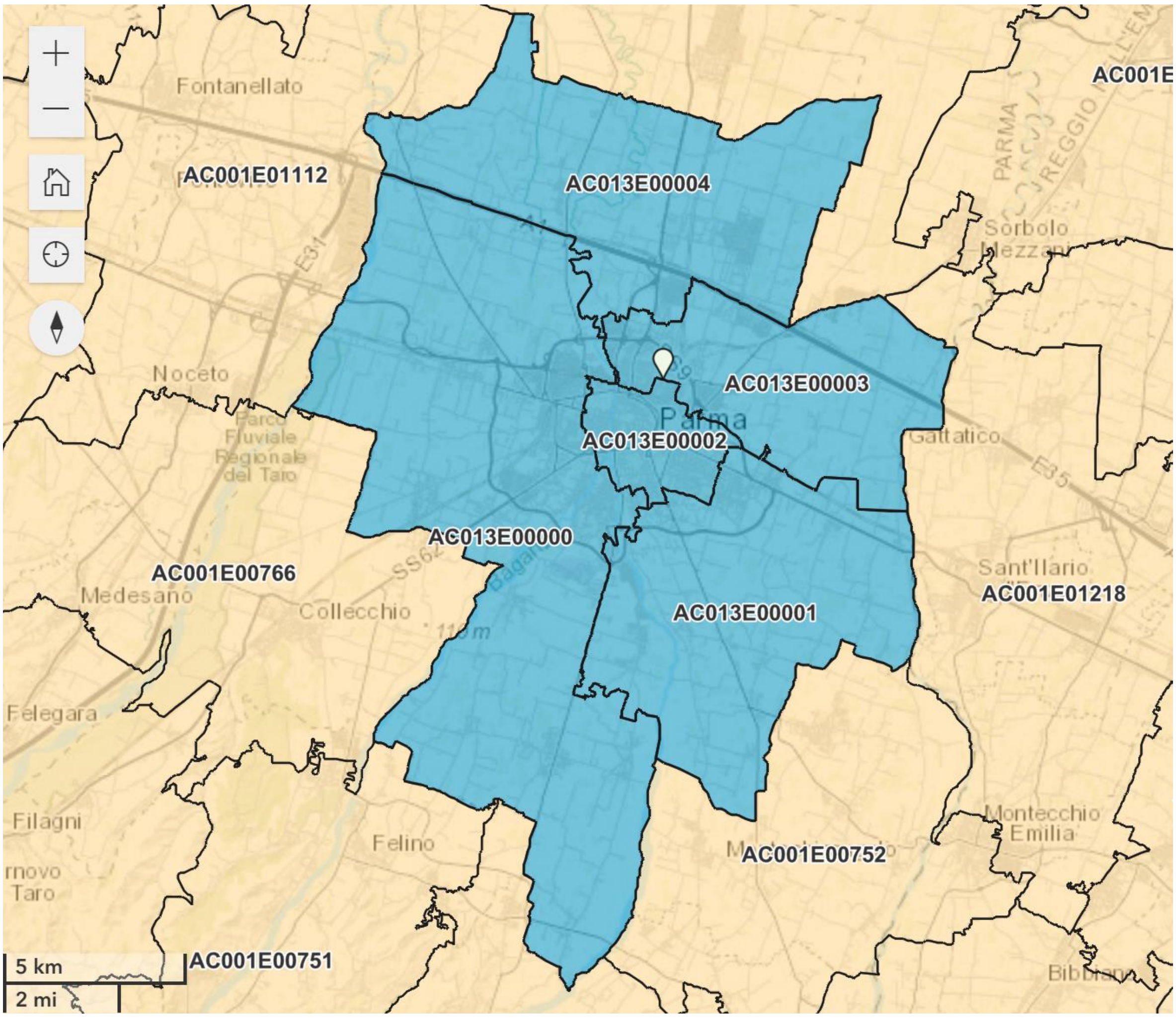

Figure 9- Detailed view of the primary substation serving the city of Parma

3.5. Energy Performance Certificates (EPCs)

What is an ETC and How to get it?

An **Energy Performance Certificate EPC** (in Italy, Attestato di Prestazione Energetica APE) is a mandatory certificate in Italy that represents the energy performance of an entire building or an individual unit. It assigns an energy class to the property in scale that goes from **A4** (maximum efficiency) to **G** (minimum efficiency) giving also pieces of advice to improve the energy consumption.

It is useful to owners, buyers and tenants to know the level of consumption of the property. Besides, it helps to professional (engineers, architects, etc) to assess possible energy interventions.

It is only possible to get the certification by a certified energy assessor (engineer, architect or qualified technician) and it is valid for 10 years unless significant modifications occur.

When is mandatory?

In Italy the EPCs are required in the following cases:

- Sale of a property:
  To sell a new or existing building, it is required that the seller provides an EPC to the buyer, otherwise the sale cannot be done. Also, the energy classes (A4, A3, B, C, etc) must be stated in the advertisements.
- Rental contracts:
  To rent an entire building or an individual unit is required the EPC and also it has to be specified in the contract.
- Major renovations:
  In the case that an intervention affects more than the 25% of the building envelope, the released of a new EPC is required. This applies to thermal insulation, window replacements, HVAC (Heating, Ventilation and Air Conditioning) upgrades, etc.
- New buildings:
  All the new buildings are required to have an EPC issued before use. Moreover, they have to meet nZEB (Nearly Zero Energy Building) standards since 2021.
- Public buildings:
  In the case a building owned by a public authority is over 250 m^2, the EPC must be display.

Then, there are some exceptions where it is possible not to do it.

Finally, in the case the EPC is missing in a required building, different penalties are applied. The most common ones are monetary sanctions or fines.

Benefits of getting an EPC

Not only because it is mandatory in a lot of situations to have the certificate issued, also it is possible to get financial incentives and tax benefits for improving the energy performance of a building and achieving a higher EPC classification. This is a way to promote the energy efficiency and decarbonization in the construction sector by the national government.

Some of the main incentives for improving the EPC classification are:

- Superbonus 70% (previously 110%)
  In the case of improving the EPC classification by at least two classes it is possible to get a major tax deduction for the energy efficiency upgrades (thermal insulation, heating system upgrades, photovoltaic systems, etc).
- Ecobonus 50% - 65%
  Again, a tax deduction for energy efficiency upgrades, but this time independent of the two-class improvement rule.
- Conto Termico 2.0
  A direct cash contribution for energy efficiency and renewable energy installations.
- Sismabonus + Ecobonus (combined bonus)
  To encourage deep renovations that improve both EPC and earthquake resistance, it was introduced a combined tax incentive (up to 85% deduction) related to these improvements.

Besides, it can be said that making these types of improvements will increase the property value, lower energy bills and get a higher rental demand since attract more tenants due to the low cost of living.

Analysis in the Province of Parma

In the following section it will be discussed briefly the current building situation of the **province of Parma** from the energy performance point of view.

The data for the analysis was extracted from the "**Sistema Informativo sugli Attestati di Prestazione Energetica (SIAPE)"** (https://siape.enea.it/) that is the national instrument for collecting the EPCs (Attestati di Prestazione Energetica APE in Italy) of buildings and individual properties. The SIAPE was made and it is managed by ENEA with the primary aim of giving a detailed picture of the state-of-the-art of energy upgrading of the national building stock.

It was not possible to get the data related only to the city of Parma, neither the data linked to each building, therefore the quantitative analysis is out of reach. However, it is possible to use this information to analyse the current situation of the buildings in a **qualitative way**.

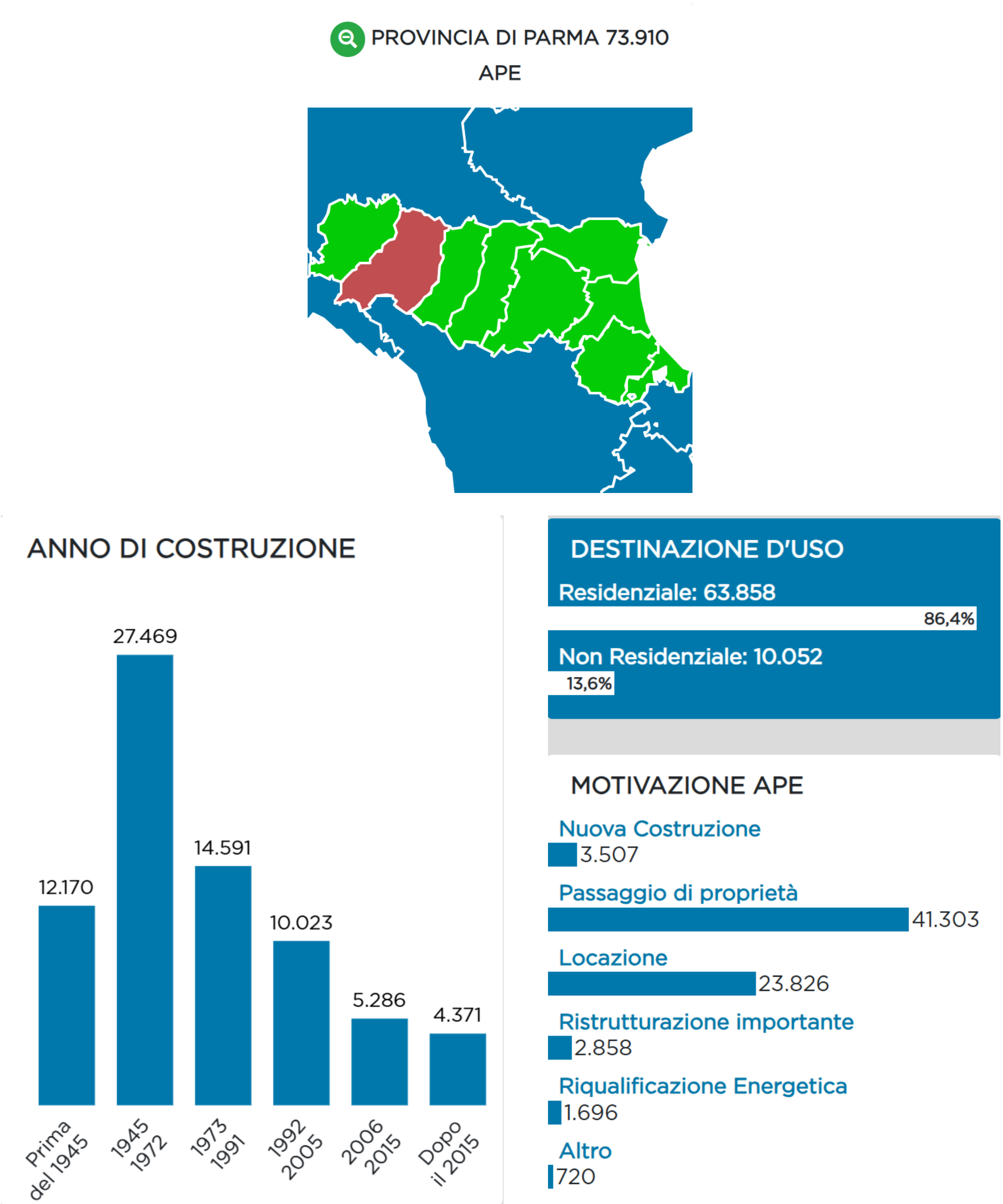

Figure 10 - Data related to the EPCs from the Province of Parma

It is easy to notice that the vast majority of buildings were done before 1991 with the peak in construction during the 1945 and 1972 period (after the Second World War), due to this the energy classification of them is quite low since the building rules and energy conscientization were totally different to modern ones.

Also, the two most common reasons to get the EPC are due to the sale of a property or the need to do a rental contract. Therefore, the EPC will represent the current energy performance of the building and since almost all of them were constructed a long time ago and usually without improvements done, the classification will be low in almost all the cases.

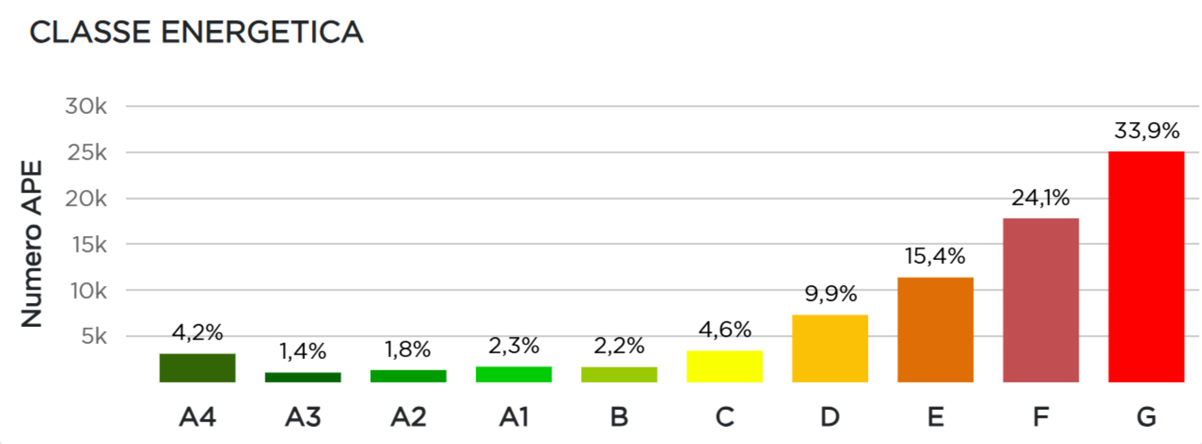

Figure 11 - Current energetic classification of buildings in the Province of Parma

Having so many buildings with a low energy classification lead to a higher energy consumption to achieve comfortable conditions for living in them. This greater consumption profile difficulties to achieve a good level of self-sufficiency in our energy community since the production can be incremented up to certain threshold.

Anyways, it is fair to think that in a near future a lot of existing buildings will be requalified/improved since all the current incentives have been created in order to produce this trend. Therefore, possibly in the future the consumption profile gets reduced, making even more feasible the adoption of CERs.

4. CALCULATION METHODOLOGY

4.1. QGIS methodology

The main tool utilized for the calculation of the solar irradiation and renewable energy production was **QGIS software**. Moreover, it was used for several auxiliary calculation made in combination with Excel sheets.

<u>What is QGIS?</u>

QGIS (Quantum Geographic Information System) is a free and open-source Geographic Information System (GIS) software that enables users to create, edit, visualize, analyze, and publish geospatial data. It supports both raster and vector data formats and is widely used for spatial data management and geographic analysis.

One of the core strengths of QGIS lies in its versatility and extensibility. It is compatible with a broad range of data formats including shapefiles, GeoTIFF, PostGIS, SpatiaLite, and GeoPackage. Users can perform complex spatial analyses, such as buffering, overlay operations, spatial joins, and terrain modeling. Additionally, QGIS supports the use of Python-based plugins, which allow users to enhance its functionality to suit specific project needs.

QGIS also includes a powerful cartographic interface that allows for the design and production of professional-quality maps, complete with legends, scale bars, labels, and various annotation tools. It is commonly used in fields such as urban planning, environmental management, natural resource monitoring, disaster risk assessment, and academic research.

As an open-source platform, QGIS is community-driven and continuously evolving, offering users regular updates and a wide range of documentation. It is available on multiple operating systems including Windows, macOS, and Linux, making it accessible to a broad user base without licensing restrictions.

<u>Calculation methodology</u>

All values obtained from QGIS were subsequently cross-verified with additional sources such as the PVGIS website, ENEA, and others. Furthermore, several key input parameters for the QGIS tools were derived from specialized software, for example, the Linke Turbidity Factors (TL) were obtained using Meteonorm.

This initial section of Chapter 4 aims to provide a broad overview of the methodology employed to obtain the final results. Each component of the process will be discussed in greater detail in the following chapters.

To begin, Figure 12 explains in detail the QGIS simulation with the buildings as territorial units. The DSM serves to show the evaluation of slope and aspect of each surface of the urban environment, a crucial step for solar analysis.

In order to evaluate the solar irradiation, the characteristics of sun and sky should also be defined. They can be explained by two monthly variables: diffuse-to-global irradiation (D/G) and Linke Turbidity factor (TL) or transmissivity. The data for these values were taken from the PVGIS website and Meteonorm software. A constant albedo of 0,25 was used according to the average for urban environments.

After that, the daily solar irradiation was calculated with the tool "*r.sun.insoltime*" for all points every 1 m in the city, especially on the roofs of the buildings. The results of these analyses are raster images, which were processed to have numerical values for solar irradiation.

Then, the raster images were converted to vector files (points in this case), and in this format were made several database calculations to make possible deeper analysis. Finally, these points were associated to the residential buildings.

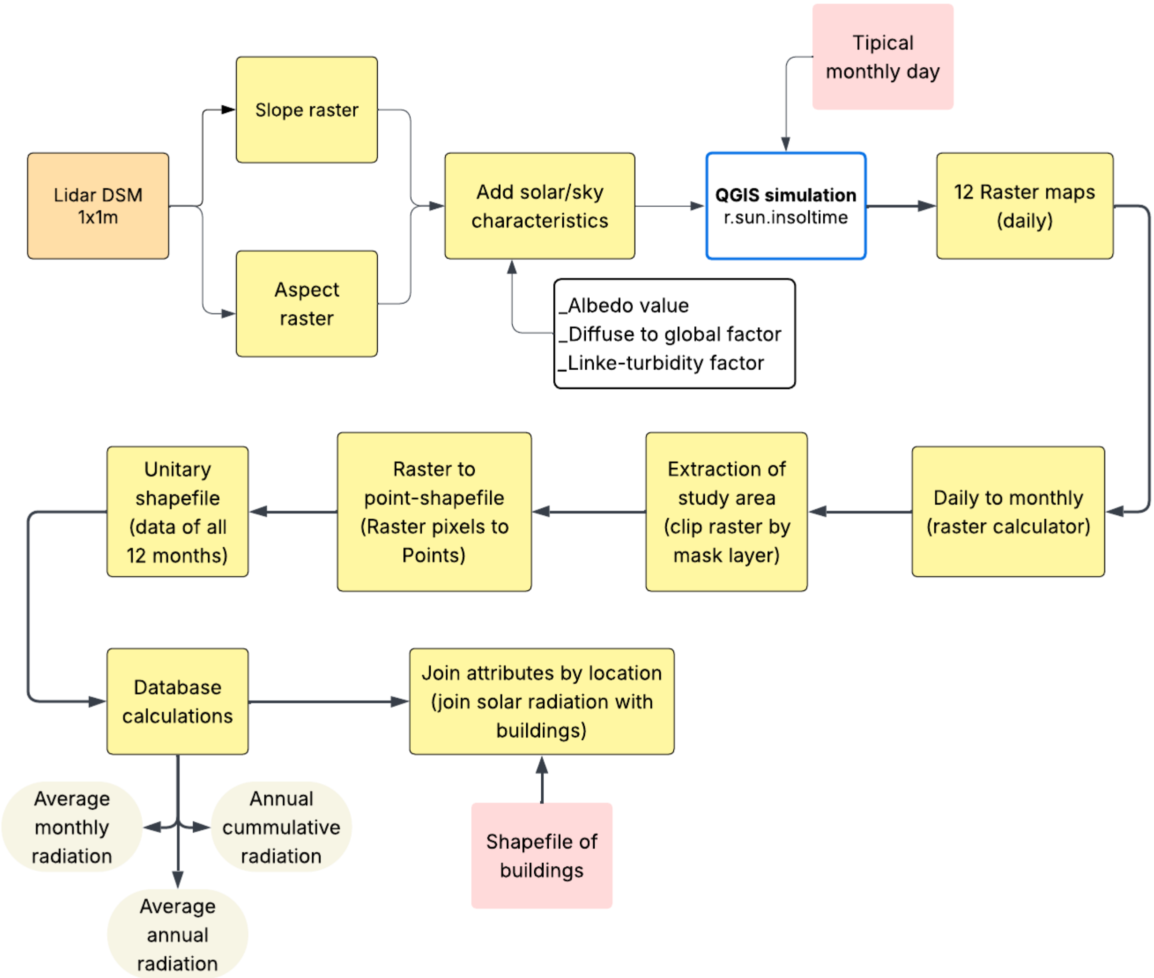

Figure 12 - Description of DSM realization and solar irradiation calculation

Below is shown the procedure from the selection of the optimal buildings where to install the PV and thermal systems to the final calculation of energy productions. These last values are of vital importance to make the economic analysis of the different case scenarios.

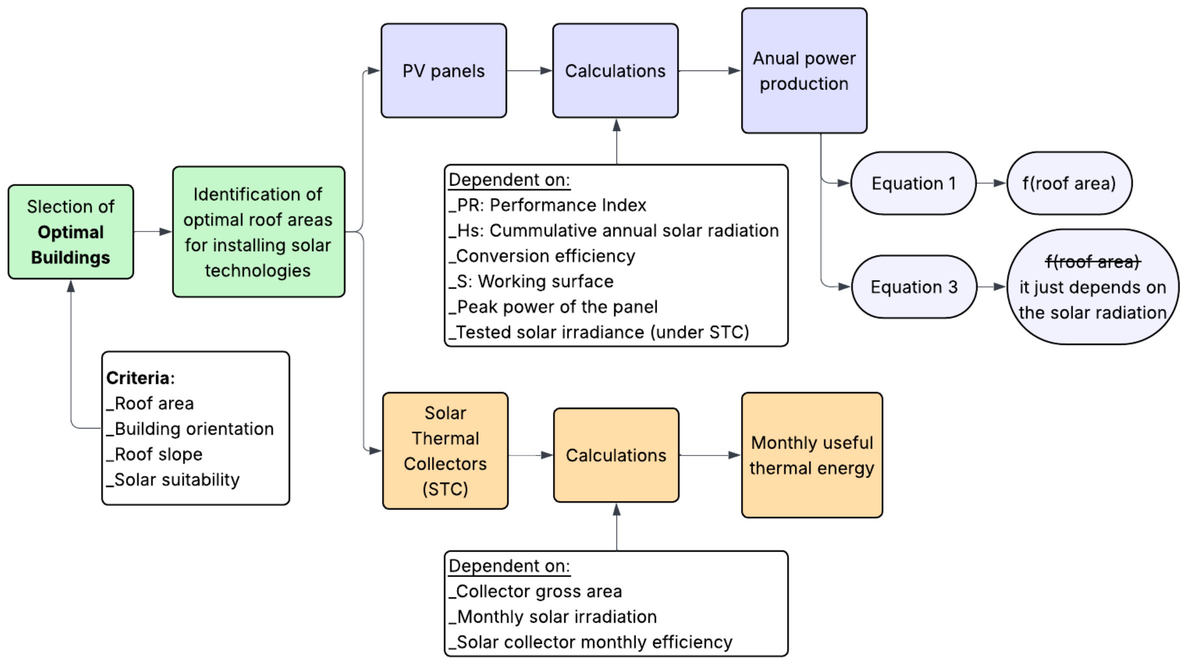

Figure 13 - Description of PV and Thermal production calculations

Next, a brief overview of the main costs considered for doing the economic analysis.

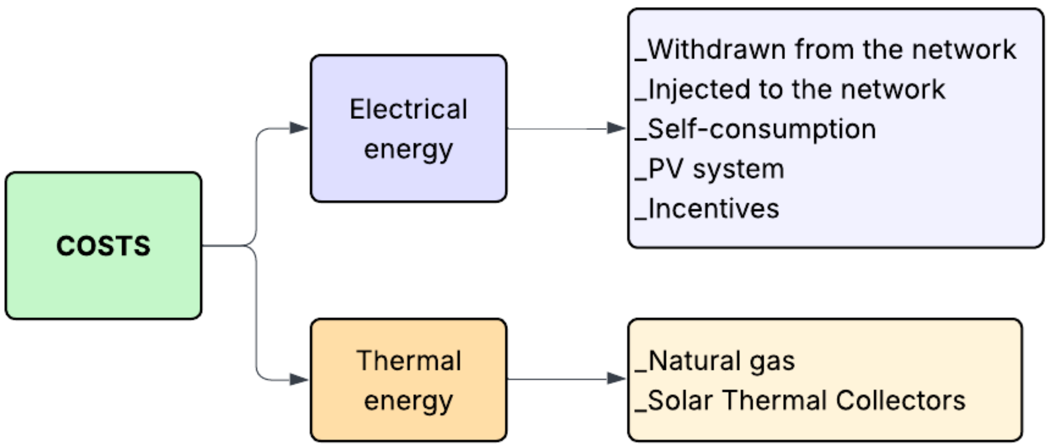

Figure 14 - Overview of costs

Also, it is shown a image explaining the variables to take into account to calculate the energy consumption (electricity and thermal energy).

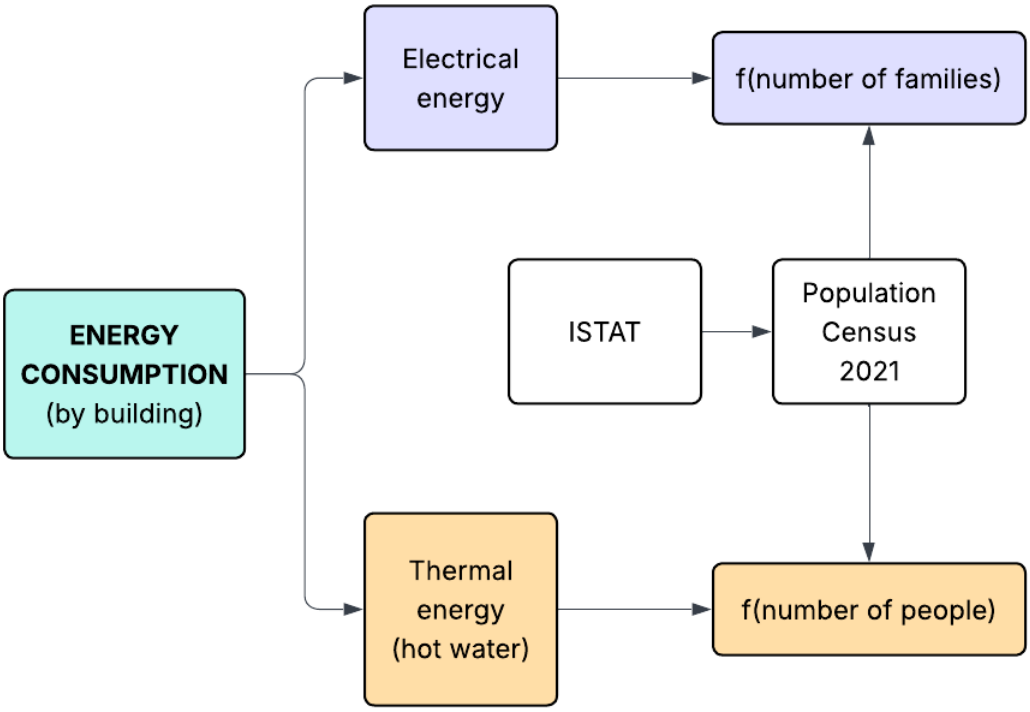

Figure 15 - Overview of the Energy consumption

4.2. Input Data

Data needed for the simulation:

- Digital Surface Model (DSM)
- Aspect raster
- Slope raster
- Albedo value
- Linke turbidity coefficient
- Diffuse-to-global factor
- Average monthly day

<u>DSM</u>

A **Digital Surface Model (DSM)** is a three-dimensional representation of the Earth's surface that includes the elevation of the terrain as well as all objects situated on it, such as buildings, trees, vegetation, and other man-made or natural structures. Unlike a Digital Elevation Model (DEM), which depicts only the bare-earth terrain without any overlying features, a DSM reflects the 'first return' elevations captured by remote sensing technologies such as LiDAR, photogrammetry, or radar. It gives us the elevation data of each rectangular grid (raster file) and it can be used or manipulated by computer.

In our case the data was extracted from LIDAR technology provided by the "Ministero dell'Ambiente e della Sicurezza Energetica" [28]. The cell size is of 1x1 meter, a good level of detail for the analysis that was done.

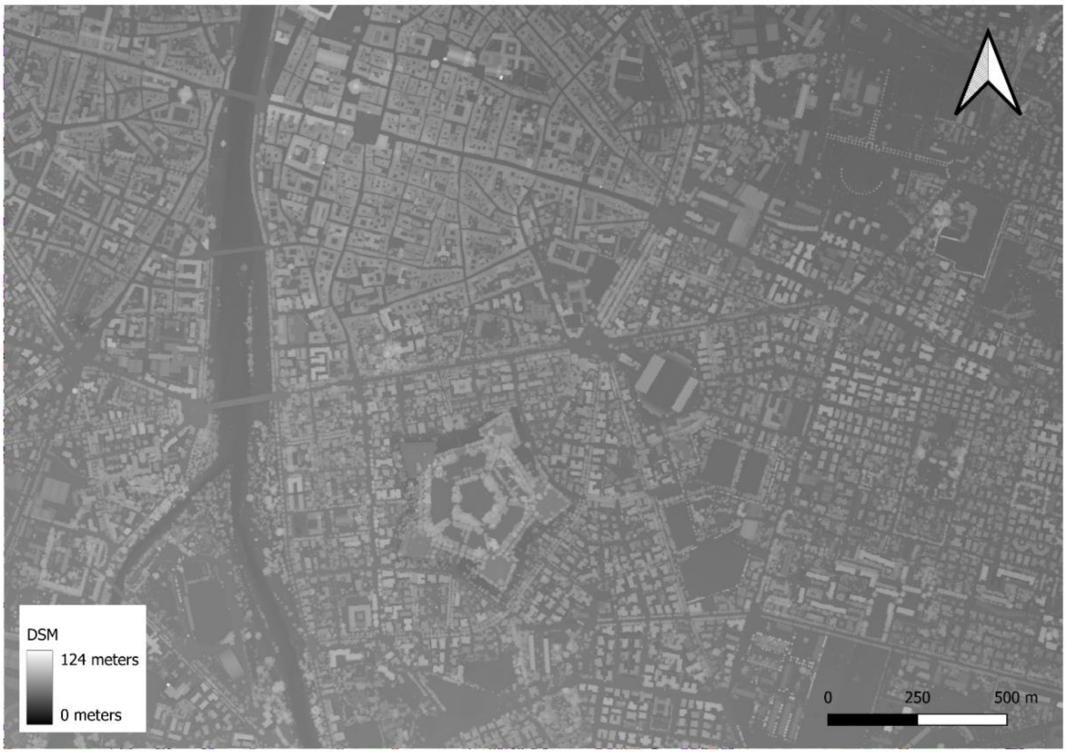

Figure 16 - DSM of Parma

<u>Aspect raster</u>

It expresses the slope direction of the input DSM. It goes from 0 (North) to 360, in clockwise direction.

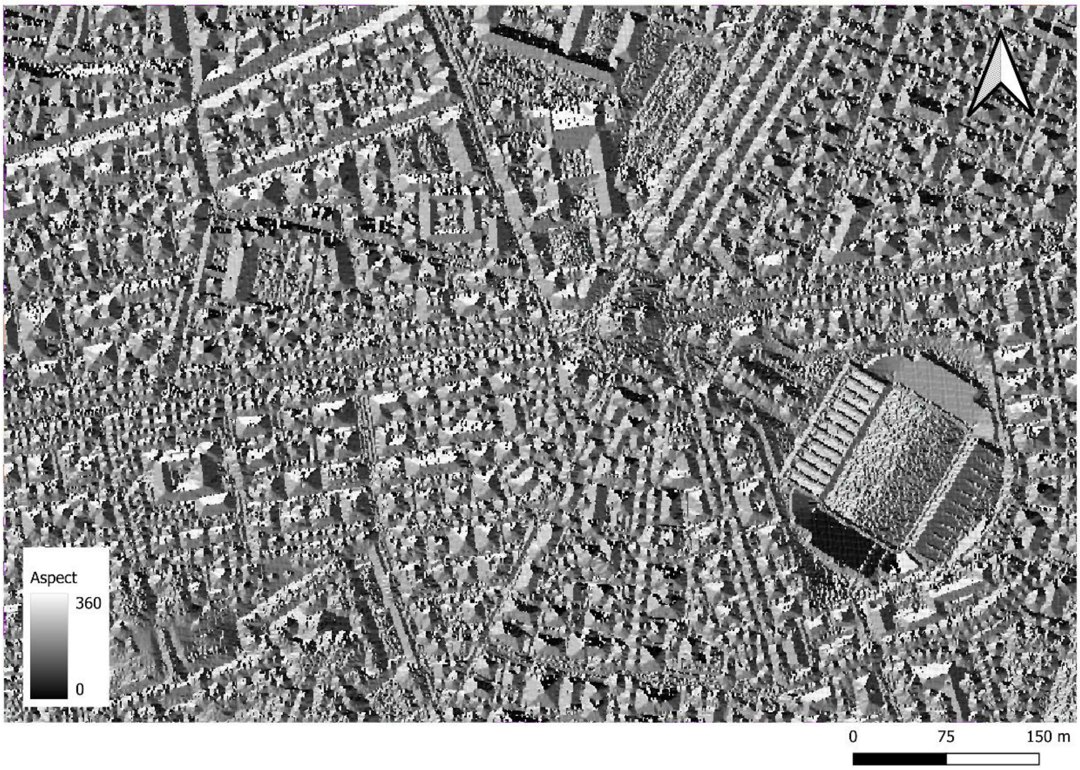

Figure 17 - Aspect raster

Slope raster

It is obtained the angle of inclination of the terrain. It is expressed in degrees.

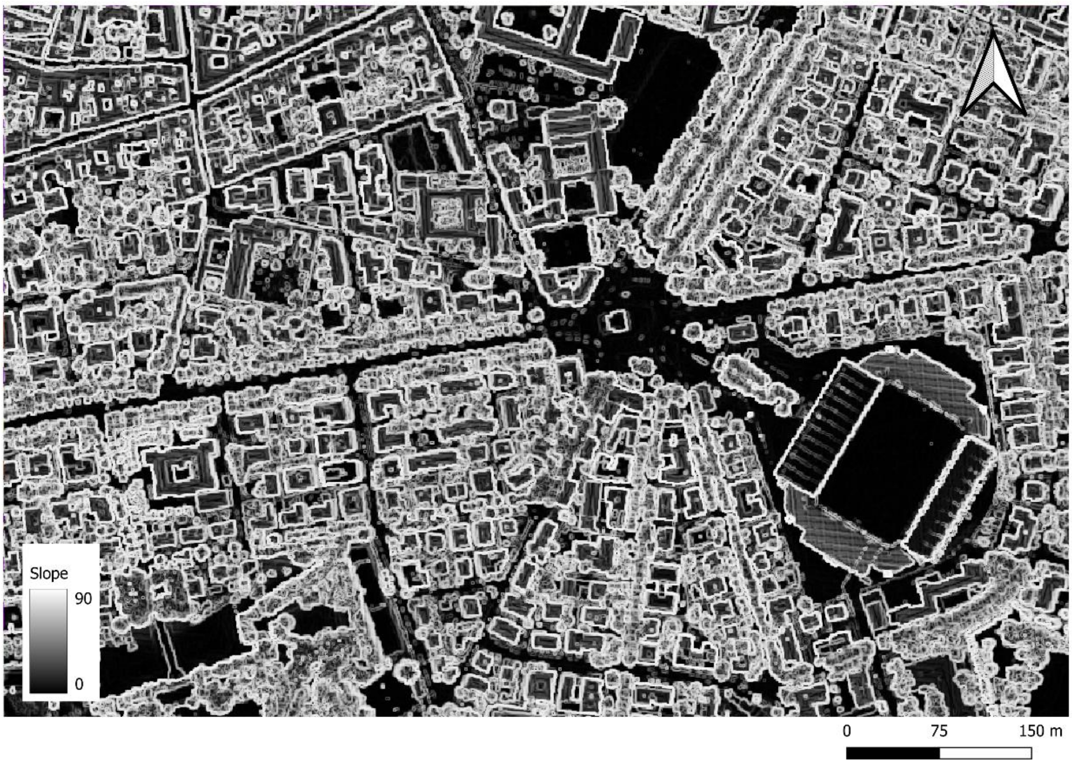

Figure 18 - Slope raster

Albedo value

The albedo value gives an idea of the reflectivity of a surface. It is the fraction of solar radiation that is reflected back into space; thus, it is value goes from 0 to 1.

Thus, low albedo value (close to 0) is when the surface absorbs almost all the radiation and reflects almost nothing (e.i. asphalt). On the other hand, high albedo (close to 1) value means that most of the sunlight is reflected back with almost no absorption (e.x. snow).

In the case analysed was taken the following value:

0.25 → TYPICAL VALUE IN HIGH DENSITY CITIES

Linke turbidity coefficient

Coefficient that refers to the smog quantity in the atmosphere throughout a certain period of time.

In order to have an understanding of the meaning of each value, it could be said that 1 represents a perfectly transparent atmosphere and 3 is a typical value for rural and urban areas.

The values for the case were obtained with the help of **Meteonorm software** (https://meteonorm.com/en/).

	Interpolated
January	3.12
February	3.38
March	3.91
April	4.34
May	4.33
June	4.31
July	4.11
August	3.96
September	3.84
October	3.79
November	3.46
December	3.12
Year	3.81

Figure 19 - Data of Linke Turbidity factor in Parma

Diffuse-to-global factor

It represents the fraction of global solar radiation that is diffuse instead of direct. Frequently, it is used for describing the proportion of sunlight that reaches the Earth surface **after** being modified by the presence of molecules and particles in the atmosphere.

$$\text{Diffuse to global factor} = \frac{D}{G} = \frac{\text{Diffuse radiation}}{\text{Global radiation}}$$

Where: Global radiation "G" = Direct radiation + Diffuse radiation

It was used the **web tool PVGIS** to get the monthly values:

	Kd
January	0.5
February	0.39
March	0.36
April	0.36
May	0.41
June	0.37
July	0.32
August	0.33
September	0.36
October	0.42
November	0.43
December	0.48

Figure 20 - Diffuse-to-global radiation factor in Parma

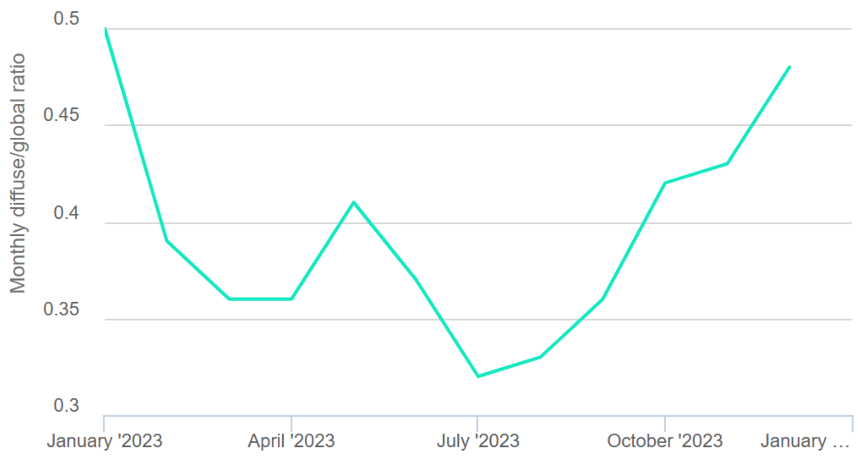

Figure 21 - Monthly average diffuse to global ratio

<u>Average monthly day</u>

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ave Day	17	16	16	15	15	11	17	16	15	15	14	10
i^{th} Day	i	31+i	59+i	90+i	120+i	151+i	181+i	212+i	243+i	273+i	304+i	334+i
Day No	17	47	75	105	135	162	198	228	258	288	318	344

Source: Klein, 1977 as cited in Duffie and Beckman(2013)

Figure 22 - Average day (Duffie, Beckman)

4.3. SOLAR IRRADIATION: QGIS simulation

The tool used to compute the global irradiation is "**r.sun.insoltime**". This tool allows to get the following irradiation maps for a **given day** and location under specified conditions:

- Direct (beam) solar radiation
- Diffuse solar radiation
- Reflected solar radiation

It was run 12 times, once for each typical day of each month of the year. Then, these values were transformed into monthly values multiplying the 12 average daily values for their corresponding number of days per month.

After that, it was possible to calculate the **annual cumulative radiation** as the sum of the 12 monthly values. Also, it was obtained the **average annual radiation** as the last value divided by the 365 days of the year.

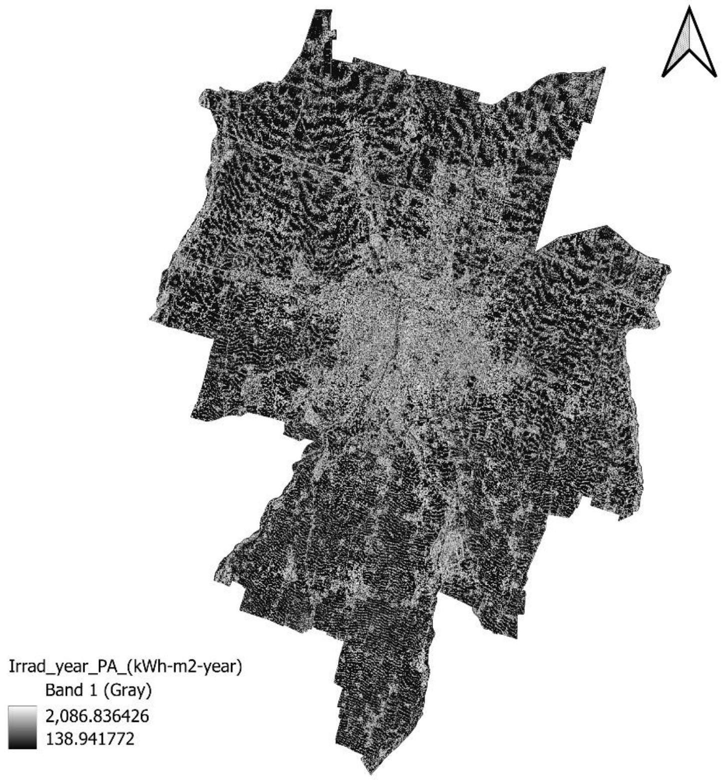

Figure 23 – Annual Solar Irradiation in Parma [kWh/m2/year]

After realizing a statistical analysis of the solar irradiation per m2 in all the area in analysis, the following results were obtained:

	QGIS MONTH			
	mean [kWh/m2/month]	median [kWh/m2/month]	ENEA [kWh/m2/month]	PVGIS [kWh/m2/month]
January	39.8	41.7	38.4	43.5
February	56.3	59.3	57.8	76.8
March	92.6	96.8	105.9	130.4
April	118.6	123.1	138.7	167.1
May	157.5	161.8	176.8	171.2
June	157.7	161.8	196.2	201.3
July	162.2	166.6	207.5	221.6
August	141.5	146.2	178.0	186.3
September	102.0	106.3	126.9	142.9
October	71.9	75.4	78.2	88.5
November	42.7	44.9	41.4	58.3
December	32.7	34.3	33.6	39.9

Figure 24 - Comparison of calculated solar irradiation against ENEA and PVGIS

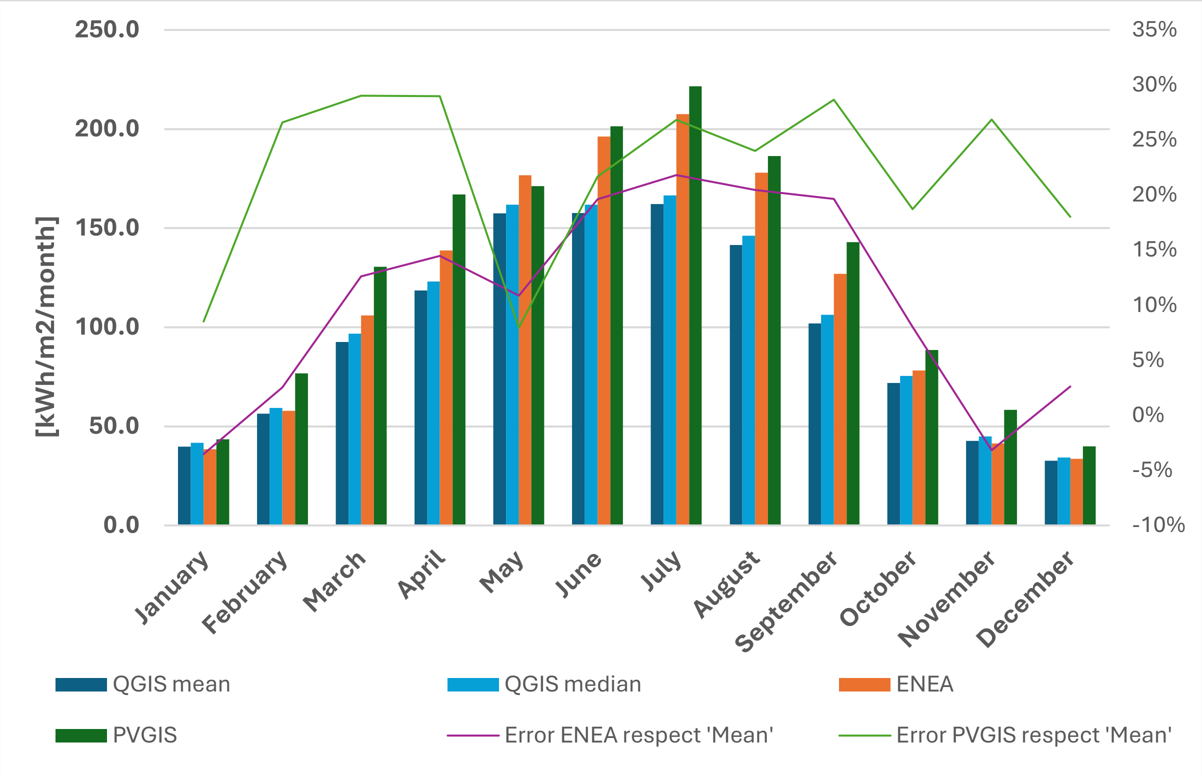

Figure 25 - Solar irradiation graph

	ERROR			
	respect MEAN		respect MEDIAN	
	ENEA	PVGIS	ENEA	PVGIS
January	-4%	9%	-9%	4%
February	3%	27%	-3%	23%
March	13%	29%	9%	26%
April	14%	29%	11%	26%
May	11%	8%	8%	5%
June	20%	22%	18%	20%
July	22%	27%	20%	25%
August	20%	24%	18%	22%
September	20%	29%	16%	26%
October	8%	19%	4%	15%
November	-3%	27%	-9%	23%
December	3%	18%	-2%	14%
MAPE	**11%**	**22%**	**7%**	**19%**

Figure 26 - Relative errors regarding solar irradiation

The result obtained from QGIS were compared against values from another sources. The other data was extracted from **ENEA** (Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile) and **PVGIS**[1] (Photovoltaic Geographical Information System) websites, the first one is from an Italian agency and the second from the European Union. It can be noted that there are some relative errors, especially summer months, since in QGIS is analysed all the geographical area of the city meanwhile in ENEA and PVGIS the values obtained are from a specific coordinate or location. [29] [30]

Finally, MAPE values are presented. It is possible to observe that MAPE values are lower against the median since these values allow not to take into account extreme outliers (better at reflecting the "typical" conditions). Therefore, median is more robust to anomalies and skewed distributions.

	MAPE	
Respect to...	ENEA	PVGIS
Mean values	11%	22%
Median values	7%	19%

Figure 27 - MAPE values

4.4. Building characteristics and Associated incident solar irradiation

First of all, it was obtained the data about the location and characteristic of the existent buildings in Parma. In this way, it was possible to categorize the city according to the building uses, dividing mainly in residential, industrial, public and other types. The data

[1] Data from 2023 – Solar radiation dataset PVGIS-ERA5

was obtained from the **Geoportale of Emilia-Romagna** [31] that is the channel for sharing geographical information of the Emilia-Romagna region and also manages, documents and makes available data, products and services of a cartographic nature.

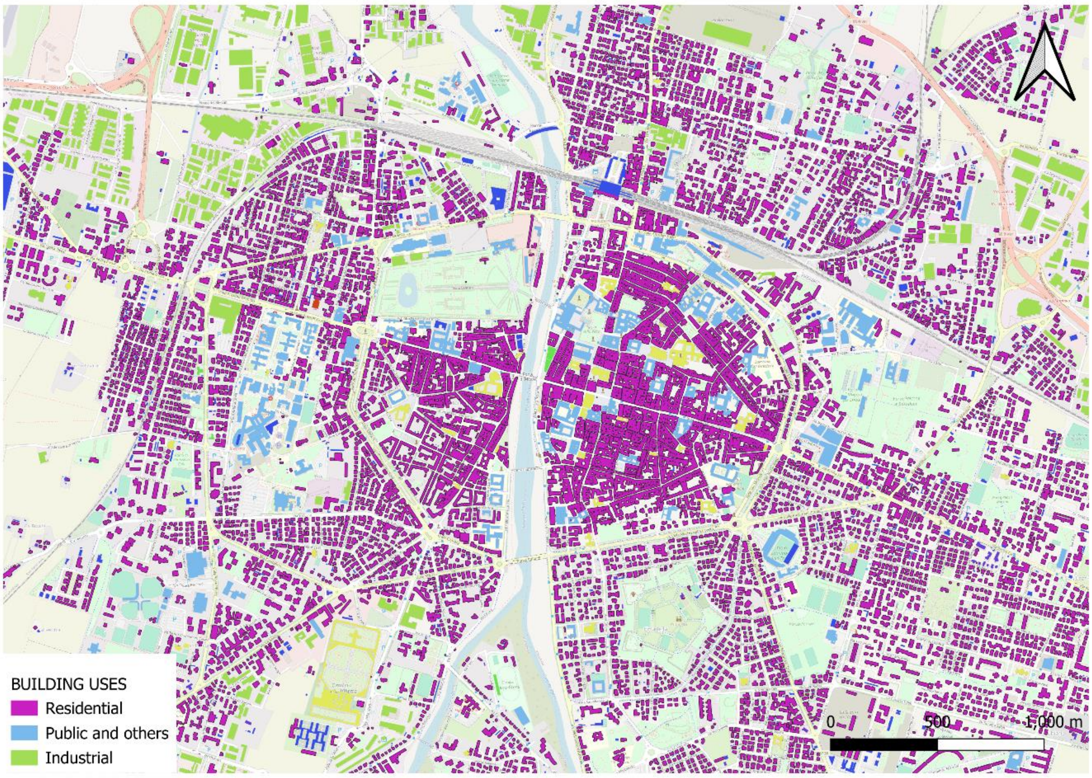

Figure 28 – Building uses

After this, the buildings were linked to their corresponding solar irradiations. The results are in kWh per m2, without multiplying for the useful roof area of the buildings. Next it is showed the map of monthly solar radiation for January.

Figure 29 - Daily Irradiation of January – [kWh/m2/month]

Now, the same but focusing on the downtown.

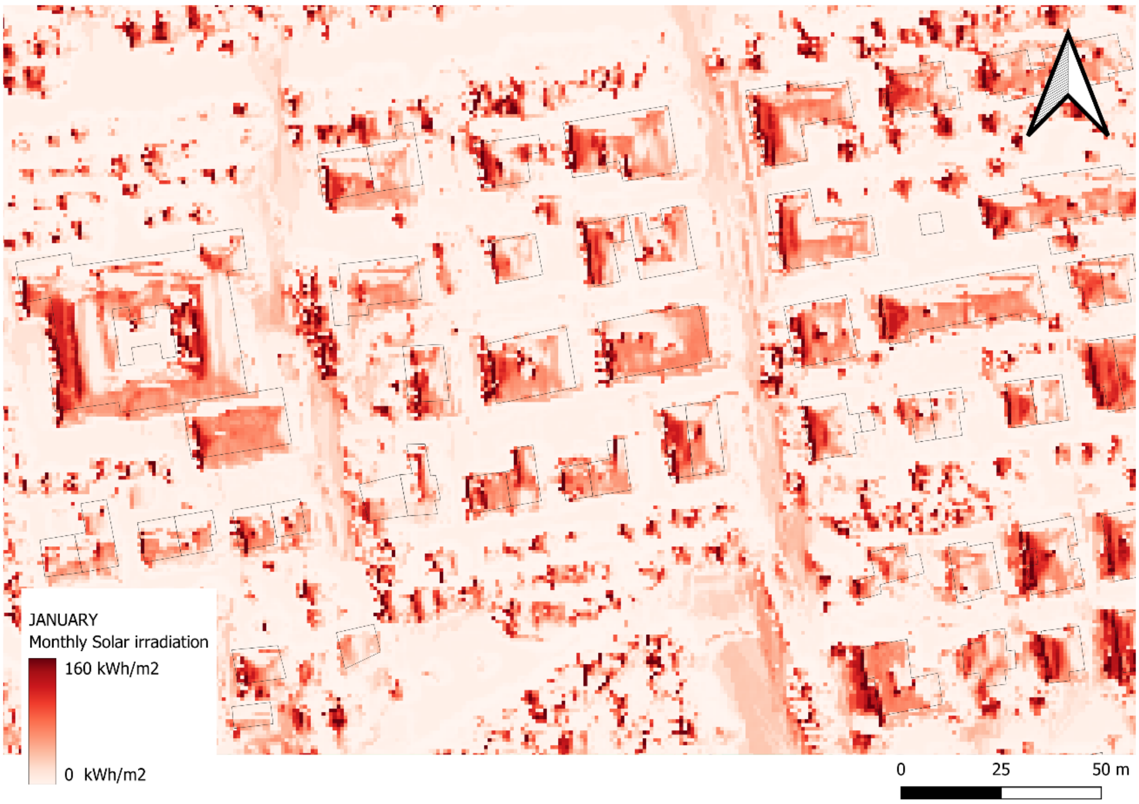

Figure 30 - Daily Irradiation of January – Zoom in [kWh/m2/month]

This was done for each month and with this information was calculated also the yearly solar radiation in a map with similar characteristics.

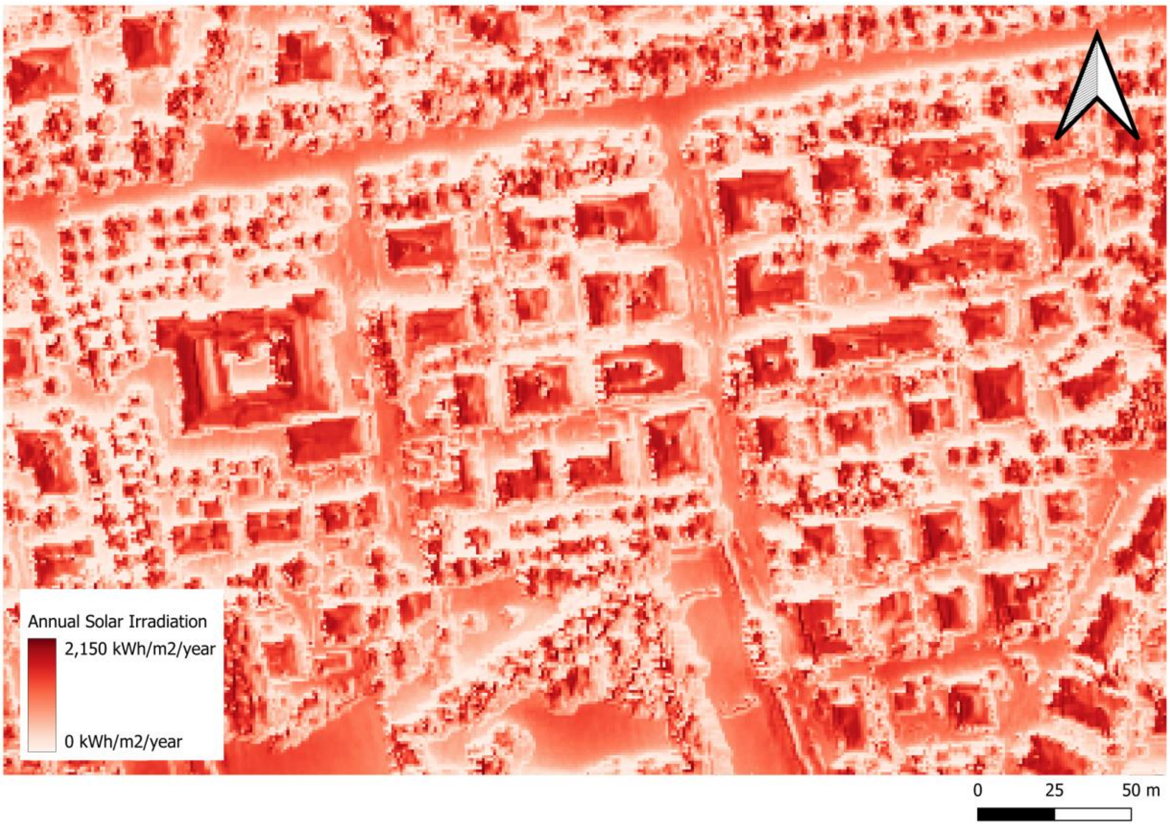

Figure 31 - Annual Solar Irradiation raster map

4.5. Study Area

The data to work with was extracted from the "**Ministero dell'Ambiente e della Sicurezza Energetica"**. In particular, the raster utilized came from a LIDAR device with a precision of 1mX1m [28].

Even though the initial idea was to analyse all the city of Parma, it was only possible to work with the most populated area of the city since the data of the remaining area was missing. Luckly, this constraint was not very limiting since the vast majority of residential buildings were located in this available zone and the remaining zone was mainly composed by industrial buildings or few residential houses in the countryside, not affecting greatly the final result.

Below, it is appreciated the data available regarding the city of Parma:

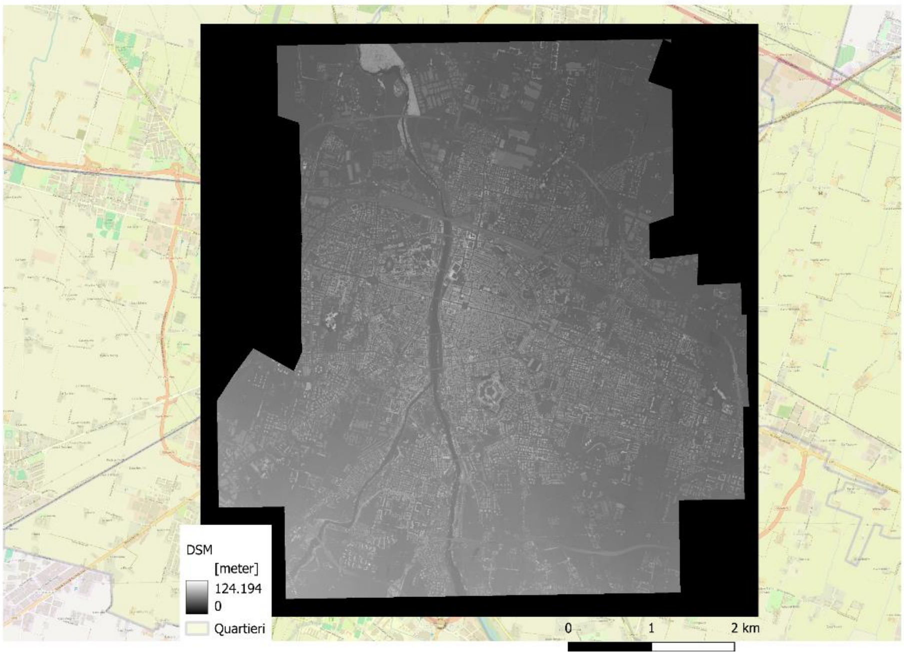

Figure 32 - Data available

And following, the study area selected taking as criteria for the choice: to take the most densely populated zones, to use as borders clear limits (ex: motorways, principal streets, etc).

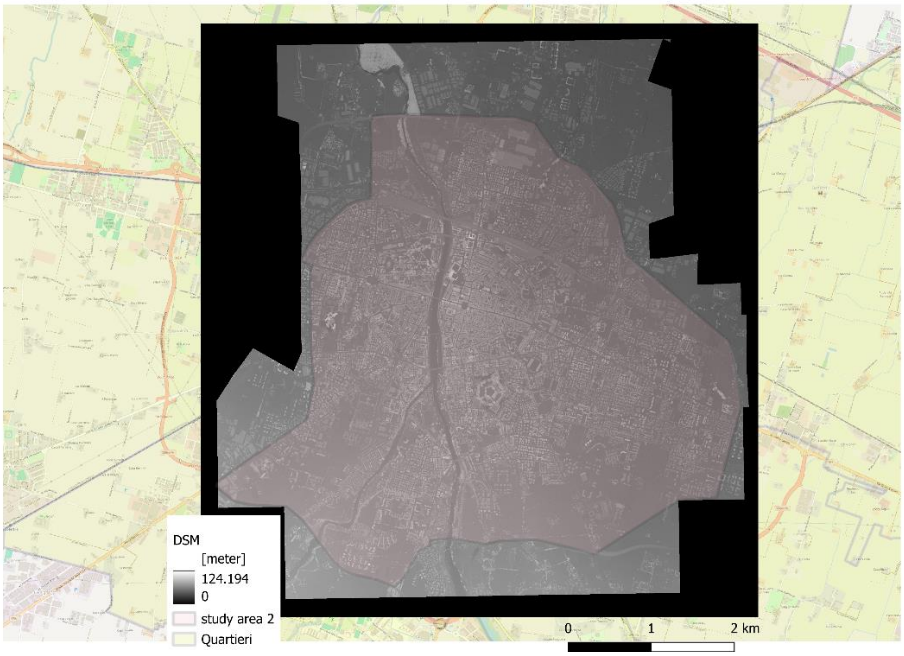

Figure 33 - Selection of study area considering the available data

Afterward, it is shown a comparison between the official borders of Parma and the study area selected.

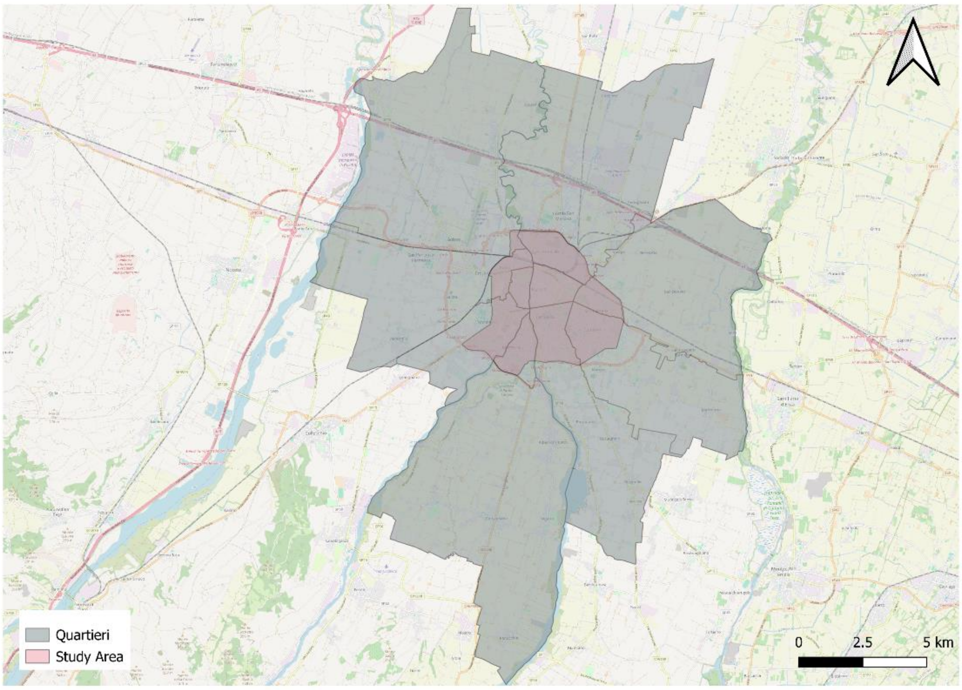

Figure 34 - Study Area

It may look like that the study area is too small, however the other areas are mainly countryside with very low density of residential buildings or zones dedicated to industrial structures. This can be clearly seen in the following two images:

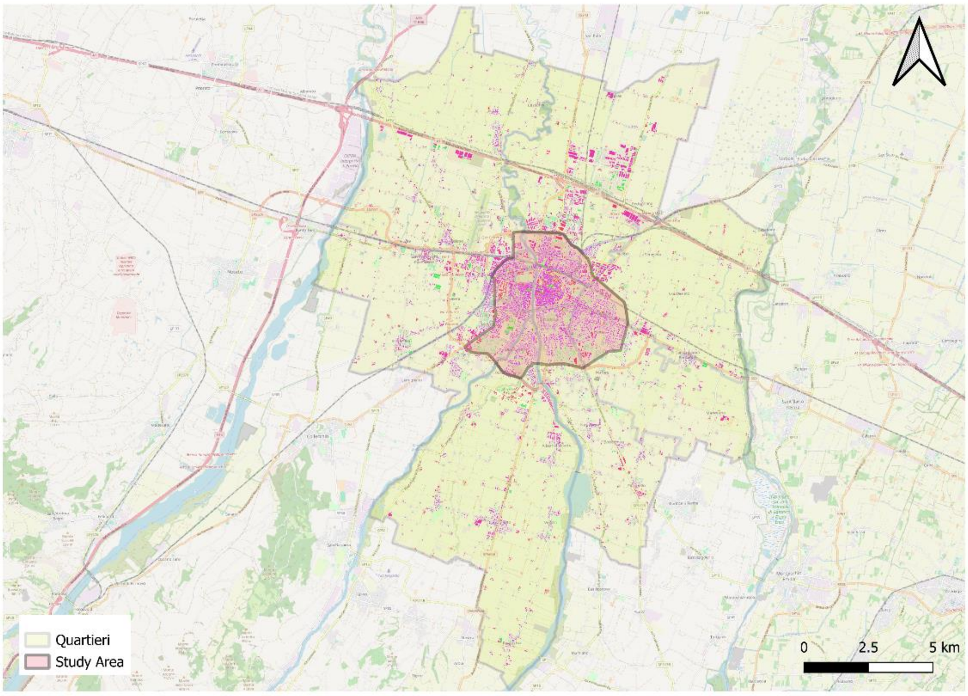

Figure 35 - Study Area and Buildings

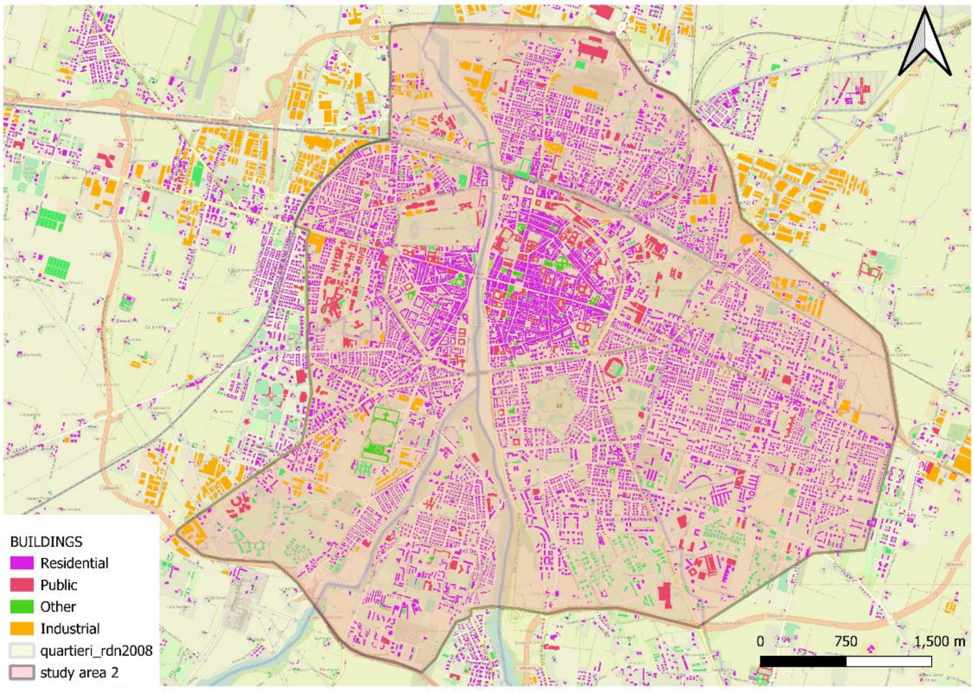

Figure 36 - Study Area and Building uses – Zoom in

On the other hand, the population of the CER is the following:

CER Parma -Study Area	
CER population =	113.846
Number of families =	53.781

4.6. Selection Criteria for Optimal Buildings

Even though in almost all the structures would be possible to install PV panels and thermal collectors, not all buildings have the same potential. With this in mind, it is fundamental to consider the factors that influence directly the energy efficiency and feasibility of the intervention.

4 criteria were considered to select the optimal residential buildings for the analysis of installing PV panels and thermal collectors:

- Main orientation
- Solar Suitability
- Roof slope
- Roof area

Below, it is provided an analysis of each factor and the criteria to choose the optimal range of values in each situation. Also, it is described their impact on the feasibility of the project.

Orientation

The main orientation of the buildings is a crucial factor for the productivity of solar panels.

Generally, the south orientation in the Northern Hemisphere is the most favourable since it allows the maximum solar exposition through all day. Moreover, the Southeast and Southwest can offer a good performance even though there will be a small reduction in the efficiency regard the South orientation.

On the other hand, the buildings with roofs oriented towards the North are excluded since the solar irradiation received is not enough to justify the investment.

The orientation not only influences the performance of solar panels, but also a good orientation reduces significantly the need for inclined support systems. Therefore, with this criterion it is possible to reduce the installation costs and maximize the useful roof area.

Orientation Class	Count
East-West	4535
North-South	4281
Northwest-Southeast	1472
Northeast-Southwest	1416

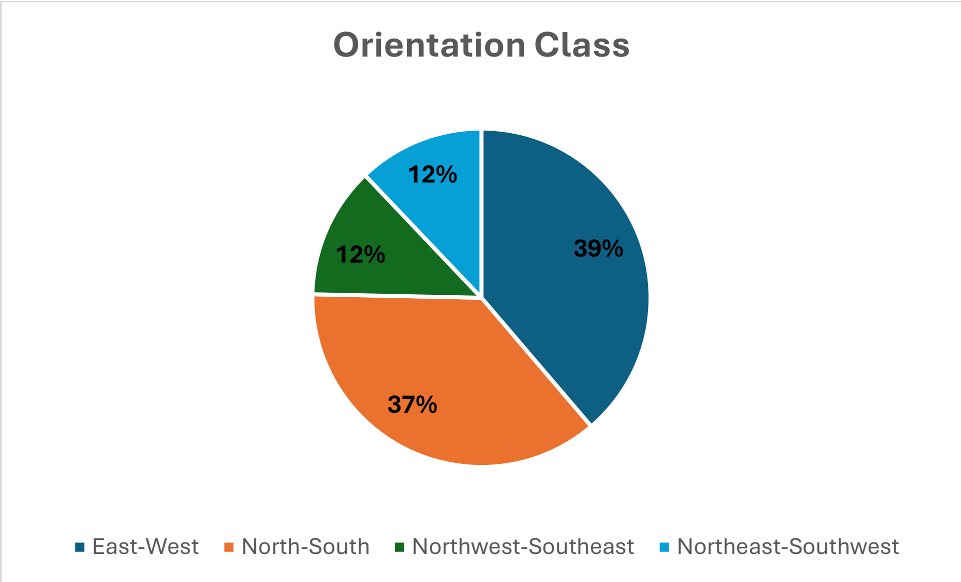

Figure 37 - % of each orientation class

Analysis of adding North-West orientation

An additional consideration was considered, the fact of installing or not panels facing the North-West orientation. Even though, the typical orientation for increasing the absolute values of PV production is the South facing one, adding in the North-West face the PV system brings an important advantage and is that the PV production curve is translated to the later hours of the afternoon for places in the Norther hemisphere (like Parma), therefore the peak of production is closer to the second peak of the consumption profile. This increases the percentage of energy that is auto-consumed, improving the overall functionality of the CER and increasing the economic benefits.

In order to assess this topic, several daily curves were analysed to see whether the addition was worthy it or not. The curves were extracted from PVGIS portal for the different orientations. The image can be seen below:

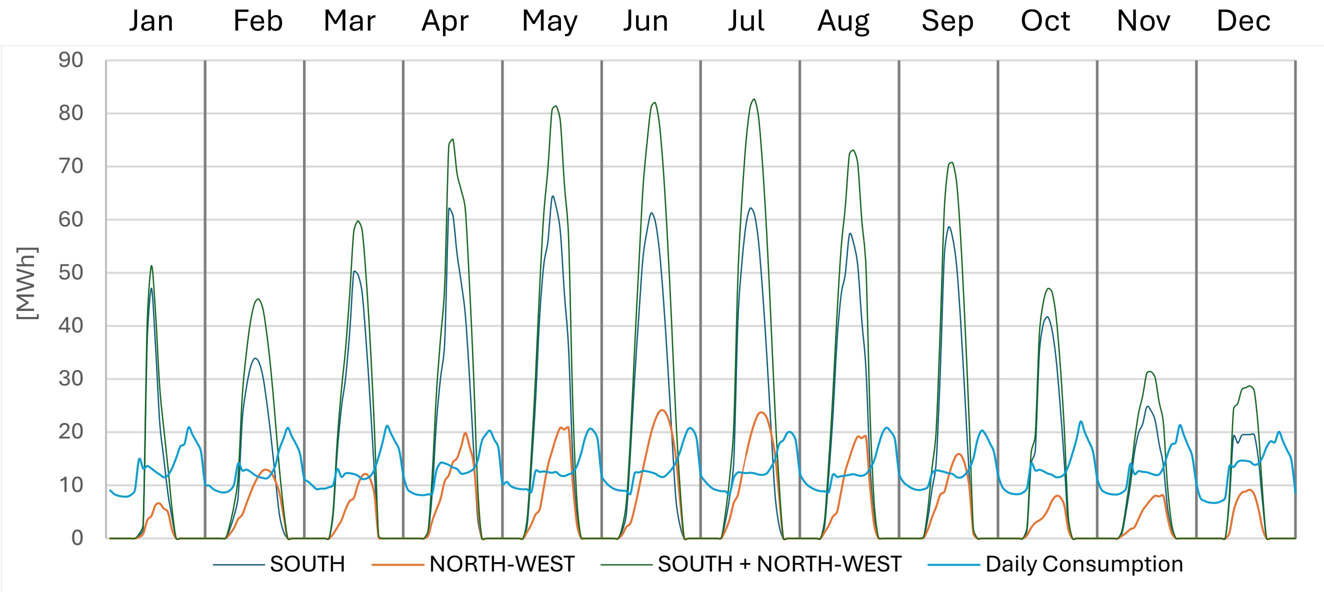

Figure 38 – Daily analysis of PV production considering diverse orientations

From the graph it can be appreciated that the North-West orientation brings a considerable displacement of the overall production curve to the second consumption peak and also flattens the production curve, covering in this way a more extended time period. Therefore, it was considered worthy adding this effect to the project.

Thus, the final layer for the installation of the PV system is the following:

PANELS FACING...	INSTALLED OR NOT
North	NO
North-East	NO
East	NO
South-East	**YES**
South	**YES**
South-West	**YES**
West	NO
North-West	**YES**

Solar Suitability

The solar irradiation is a measure of how much solar energy arrives to a surface in a period of time, generally expressed in kWh/m^2/year. This criterion is directly related to energy production potential of the solar panels.

This value will be dependent on several factors as:

- Near obstacles (other buildings, trees, structures, etc) that can produce shadows and reduce the effective solar irradiation.
- Geographical characteristics. **Latitude** and local meteorological conditions can deeply affect the mean solar irradiation availability.

In order to select the optimum buildings, those who had a mean value greater than 1200 kWh/m^2/year were chosen in the preselection. This threshold was considered a value enough to guarantee a significative energy production.

Later in the calculation, for those buildings selected will be done a detailed analysis to identify the areas in each roof where the solar irradiation is greater than 1400 kWh/m^2/year in order to use only these spaces to install the panels.

Solar Suitability	Yearly Irradiation [kWh/m2/year]	Count
Not Suitable	< 800	761
Limited	800 - 1000	1146
Good	1000 - 1200	3492
Very Good	1200 - 1400	5103
Excellent	> 1400	1202

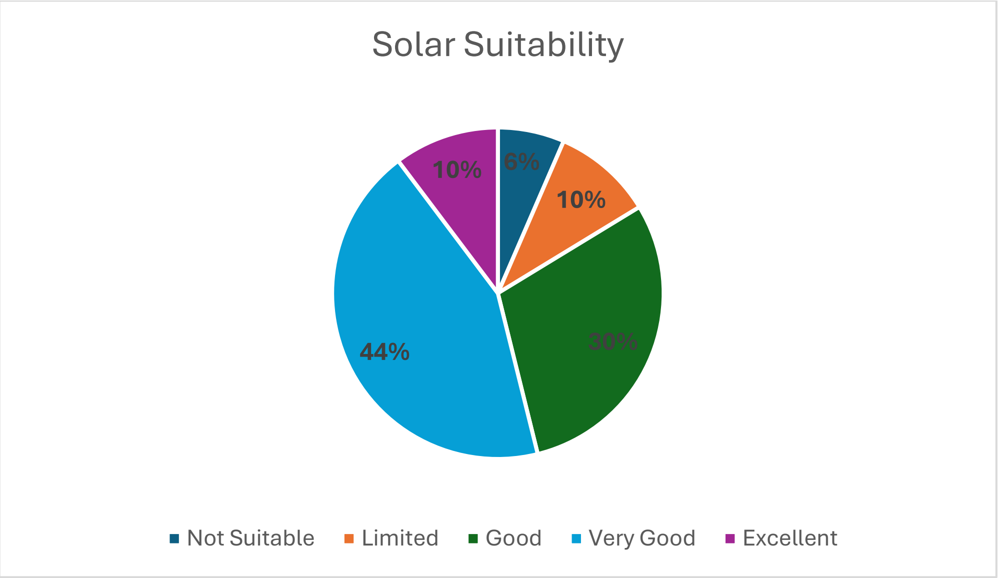

Figure 39 - % of solar suitability classes

Roof Tilt

The roof inclination (or tilt) is also an important factor to improve the efficiency of solar panels. The optimum angle varies from place to place, relying mainly on the latitude.

- In Italy, the ideal inclination of PV panels varies from **30° to 35°** since this allows to capture the maximum quantity of annual solar irradiation.
- Inclination too small **(<10°)**. They could also be used, however, it will be necessary to install support structures to incline the panels increasing the cost and possibly creating shadows in the nearby PV panels rows.
- Inclination too elevated **(>45°)**. Efficiency starts to decrease in summer when the sun is higher un the sky and the installation and maintenance become harder, increasing the cost.

Due to this, the selection of the optimal buildings takes into account this aspect, favouring those who are nearer to the ideal angle range.

Roof Slope(mean)	Count
Flat (0°–5°)	18
(5°–15°) - Good for PV	147
(15°–30°) - Ideal for PV	3744
(30°–45°) - Ideal for Thermal	7055
(>45°) - Less Suitable	740

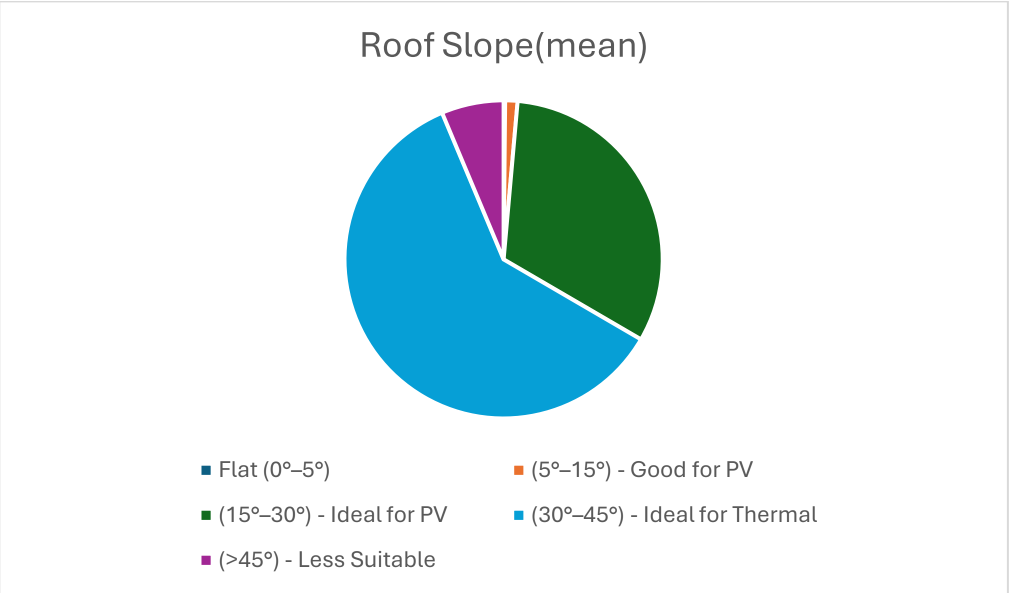

Figure 40 - % of roof slope classes

Roof area

Even if a building has a good orientation, a perfect roof tilt and an elevated solar irradiation; these characteristics will be not useful if the available roof area for the installation of solar panels is not big enough.

With the goal of improving the selection, the roof areas smaller than 5 m^2 were directly excluded since they are too small to hold an effective solar installation.

In the pre-selection were selected the buildings with a roof area greater than 100 m^2 to optimize the performance of the system.

Categorization according roof area	Criterion [m2]	Count
NULL		2210
Very Small	< 30	568
Small	>=60 and <100	769
Medium	>=30 and <60	1602
Large	>=100 and <200	3796
Very Large	>=200	4969

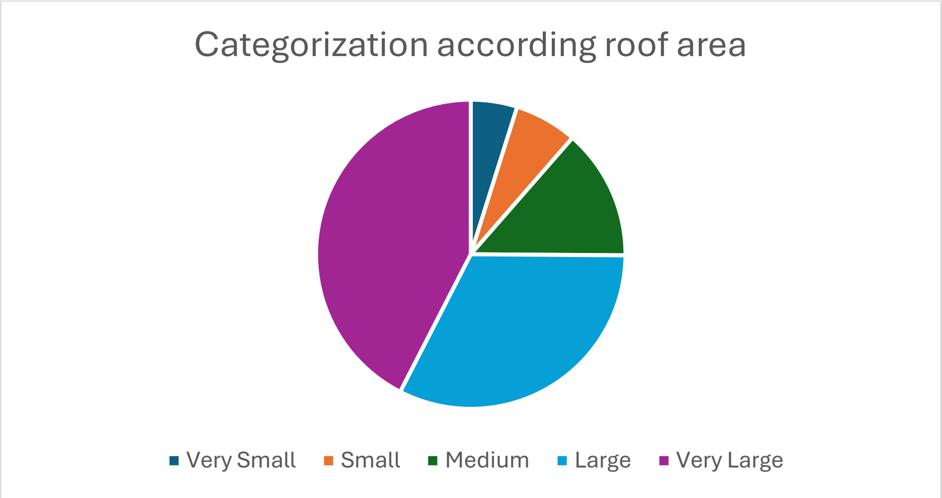

Figure 41 - % of roof area size classes

CONCLUSION

Using these last 4 criteria, it was arrived to the following values:

Building Classification	Count
Optimal	3145
Not Optimal	8559

This methodology allows to individualize the residential buildings with the greatest potential of solar energy production, optimizing the resources and ensuring a high return on investment.

4.7. Area used to install the PV panels and Thermal collectors

Once the optimal buildings were selected, the next step is to figure out the best areas inside each building's roof for installing the panels. In this way, it is also possible to determine what percentage or what area will be utilized in order to proceed with the PV or thermal production.

In the following, it is explained the methodology used:

1. Firstly, it was extracted from the solar irradiation raster file only the portion over the selected buildings (QGIS tool: Clip raster to buildings)
   Secondly, the pixels of this new raster were classified into ranges in order to simplify the analysis and to have a clear criterion to choose the areas.

   *("Solar_Irradiation" >= 1000) * 1 +*
   *("Solar_Irradiation" >= 1200) * 1 +*
   *("Solar_Irradiation" >= 1400) * 1*

   This will assign 1=moderate ; 2=good ; 3=excellent

   → QGIS tool: Raster calculator (it is still a raster file).

2. After that, this **filtered raster** was converted **to vector polygons** (shapefile). In this way, it is possible to have individual points with associated values to analyse.
   Then, the parts of the roofs with maximum solar exposure were gotten using the intersection tool (Vector → Geoprocessing).

   Filter areas with the highest irradiation (only pixels > 1400 kWh/m²/year)

3. Finally, the small (< 5 m²) and fragmented areas were deleted. As a result, the best solar-exposed areas per building were obtained and the method ensures that the panels will be installed in the most productive areas.

In the following is shown a image of the results obtained with QGIS, where the red pixels represent the optimal roof areas of each building.

Figure 42 - Useful roof area

Then, it is possible to observe two images. Firstly, the quantitative values of how many square meters can be used to install solar technologies in each building and, secondly, another picture representing what percentage of the total roof areas can utilized in each case.

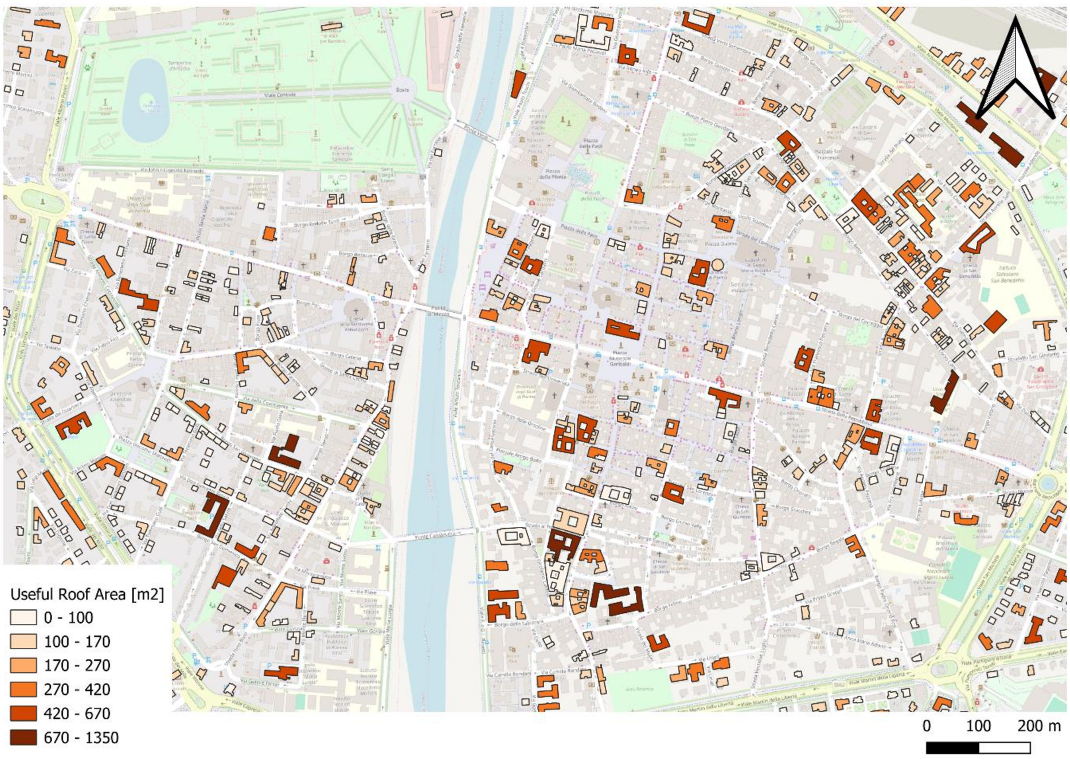

Figure 43 - Useful roof area in m2

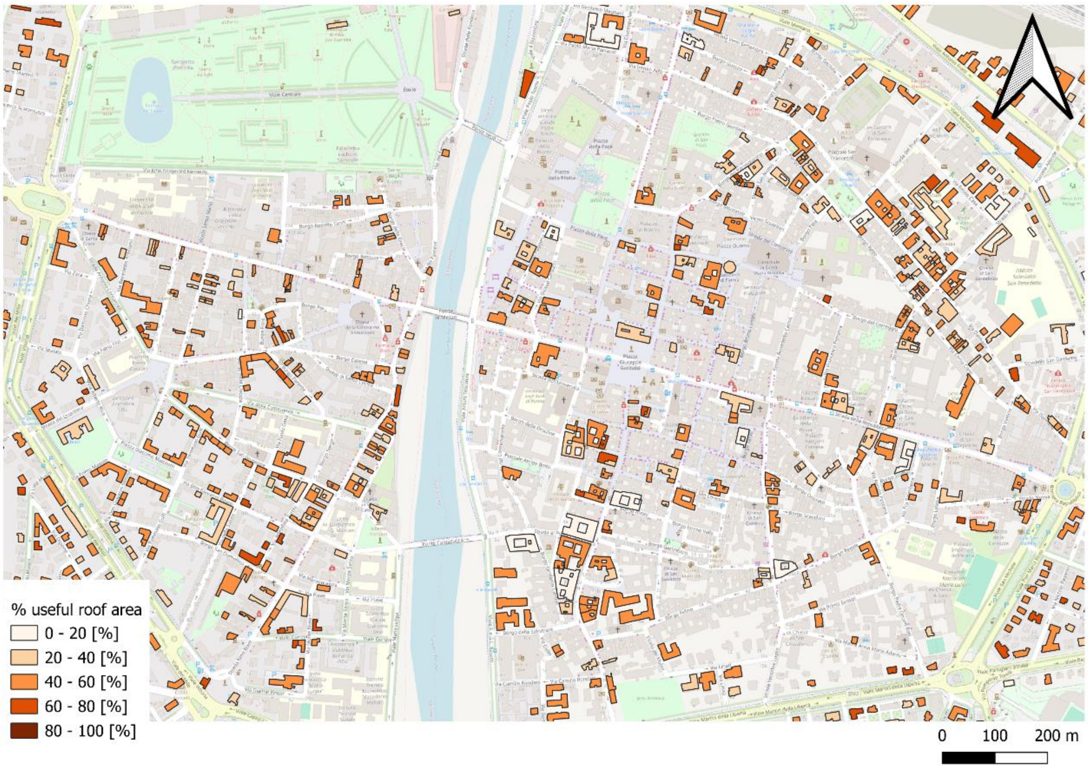

Figure 44 - Useful roof area in %

4.8. Renewable Energy production

4.8.1. Electric energy

With the aim of calculating the photovoltaic potential, different technologies have been analysed. Each solution has its own characteristics as for instance efficiency or size. Currently, the main two options are monocrystalline and polycrystalline silicon ones.

Depending on the PV panel selected, it will vary the necessary space for achieving a specific power and also the investment cost and payback period will be different. Therefore, this decision is of crucial importance.

In the following it will be given a brief explanation of the **working of the PV technology**.

As a starting point, it is described the composition of a photovoltaic panel. This one is made of modules, and these consist of photovoltaic cells. The cells are usually made of silicium, a common semiconductor found in nature.

Each cell contains two layers:

- The upper layer made of type N silicium, plenty of electrons
- The inferior layer made of type P silicium, plenty of holes (in other words, zones where electrons are missing).

These two layers create un negatively charged area and another positively charged one, forming in this way an **electrical field**.

Then, thanks to the photovoltaic effect is possible to create a current with the sun energy. In other words, when the sunlight (photons) hit a cell, the energy transported is transferred to an electron contained in the silicium. This extra energy frees the electron and now it can move freely.

Because of the electrical field created by the two layers (layer P and N), the electron is impulse in a precise direction, creating in this way a **direct current (DC) flow**.

To take advantage of this effect, all the cells are connected between them in serial or parallel inside the panels in order to:

- Increment the voltage (with serial connections)
- Increment the current (parallel connection)

Therefore, the panels generate continuous electrical energy, however, in this way is not useful for the residential consumption yet.

To address this issue, it is necessary to install an inverter in order to convert the direct current (DC) produced in the panel to alternating current (AC) useful in common buildings since the vast majority of electrical objects that are found in residential dwellings work with alternating current (AC).

Once it is started the transformation of solar energy to electricity, there are several options related to the distribution/use of the produced energy. It can be directly utilized to power electrical devices, also it can be stored in batteries (storage systems) or sent to the electrical grid (in the places where the sale of energy is an available option).

Last but not least, the topic of efficiency is now being addressed. The efficiency of conversion from solar energy to electricity of a PV panel depends on several factors:

- Type of cell (monocrystalline, polycrystalline, thin film)
  It will be explained in more detail in the next section.
- Temperature
  Contrary to popular belief a PV panel does not perform better with more sunlight, but rather with more sunlight and less heat. The efficiency decreases as the temperature increases.
  The panels have a temperature coefficient and the lower it goes, the better is the heat resistance. Therefore, in hot weathers is important to choose the appropriate panels for the climate.
- Orientation and inclination of the panel

In the north hemisphere the panels have to be oriented towards the south and, although the optimum inclination depends on the latitude of the place, in most European countries un angle between 30° and 35° is a good value.

- Presence of shading
  It is necessary to be careful regarding this aspect, since even small shadows can affect significantly the overall efficiency of the system.

Optimizing these aspects allow to maximize the performance of the photovoltaic system even with panels with the same nominal efficiency. Normally, a commercial solar panel has a nominal efficiency between 15% to 22%.

<u>Difference between mono and polycrystalline cells</u>

It is considered necessary to explain the difference between mono and polycrystalline cells since are the two main option for projects related to residential buildings.

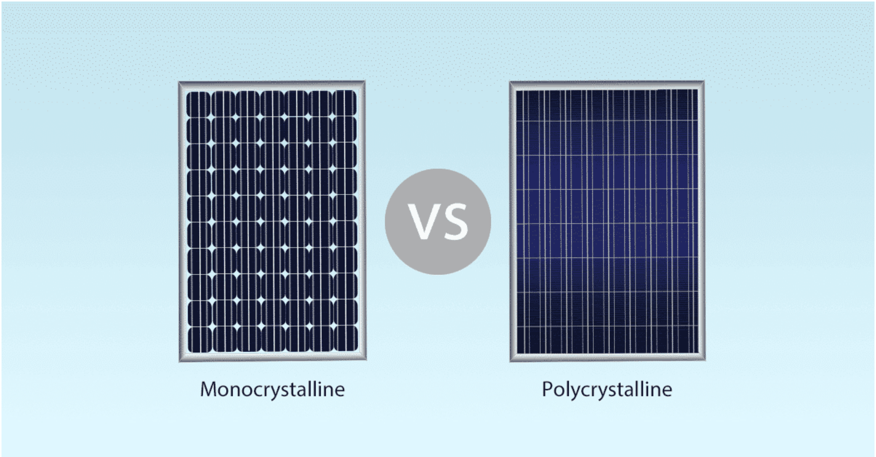

Figure 45 - Monocrystaline and Polycristalline panels [32]

Beginning with the **monocrystalline cells**, these are made with pure and uniform silicium. They have a dark black and homogenous aspect. Also, they are the most effective in transforming the most quantity of sunlight into electricity. Precisely for this reason, they are utilized when the available space is a limitation. Nonetheless, due to the more difficult production process, they are more expensive.

On the other hand, **polycrystalline cells** are made with several fragments of silicium that are joined (merged) together. They have a characteristic bright blue colour and an aspect a bit fragmentated. Moreover, since the production process is simpler, they are less expensive than monocrystalline cells but at the same time they are less efficient in the transformation of energy. In any case, they are a good option to consider when the space is not a limitation and when it is needed to lower the project cost (for instance, they are commonly used in medium to big solar farms). [33] [34]

Conclusion

In this analysis were utilized solar panels with polycrystalline cells since due to the reduced space in the roofs it is mandatory to improve the efficiency of the system as much as possible. Moreover, only optimal buildings were selected (according to the criteria mentioned above) for the installation of PV systems in order to increase the performance and reduce costs.

4.8.1.1. PV panel 1

It was utilized the solar panel Maxeon 6 AC with an efficiency of 23% in the conversion from solar energy to electricity [35].

MAXEON 6 AC SOLAR PANEL

420-445 W | Up to 23% Efficient

AC Factory-integrated microinverter

White backsheet, black frame

DC Power Data				
	SPR-MAX6-445-E4-AC	SPR-MAX6-435-E4-AC	SPR-MAX6-425-E4-AC	SPR-MAX6-420-E4-AC
Nom. Power[3] (Pnom)	445 W	435 W	425 W	420 W
Power Tol.	+5/0%	+5/0%	+5/0%	+5/0%
Module Efficiency	23.0%	22.5%	22.0%	21.7%
Temp. Coef. (Power)	−0.29%/°C			
Shade Tol.	Integrated module-level max. power point tracking			

Figure 46 - Technical data of Maxeon PV solar panel

Maxeon Solar Technologies is company from Singapore and is a global point of reference for the solar industry. It was born from the experience obtained from the brand SunPower. The company is distinguished to produce solar panels, with high efficiency and long duration. Over time these panels have become one of the most reliable and appreciated.

The model Maxeon 6 AC is one of the most advanced solutions that the market offers, since it provides a high power (between 420 and 445 watt) with an efficiency that can reach 23%. This gives an optimal energetic production, even in non-favourable external conditions.

An important characteristic of this specific solar panel, it is the presence of an integrated microinverter that allows to any panel to work independently from the others. This feature allows to minimize the loses in the efficiency due to the presence of partial shading and in this wat to increase the overall performance of the system.

Additionally, the cells are designed to be resistant to microfractures and with reinforced connexions. The manufacturer provides a warranty up to 40 years representing the high reliability of the product, both in terms of operation and performance.

In conclusion, the solar panel Maxeon 6 AC is suitable for residential, commercial and industrial situations, offering an efficient and sustainable solution with a minimal degradation over time.

4.8.1.1.1. PV power dependence on irradiance and module temperature

In order to **calculate the PV power output**, the most important factor for the energy output of a PV system is of course the amount of solar radiation that arrives at the PV modules. However, there are other factors that are important too. This chapter explains about the different effects that influence PV output and how they are calculated. [36]

An important definition to consider is the **nominal power of PV modules**. When the power of a PV module is measured in the laboratory or at the factory, this is done under standardized conditions, known as the **Standard Test Conditions (STC)**. The power measured at STC is called the nominal power or peak power (P_STC). These standard conditions are determined by the international standard IEC-60904-1 as:

- The light intensity (irradiance) should be 1000W/m^2 on the whole surface of the module. This value is about what you have at noon on a sunny day when the module is facing towards the sun, though under real conditions the irradiance may sometimes be even higher.
- The module temperature should be 25°C.
- The spectrum of the light should be equal to the global spectrum given in IEC 60904-3. This spectrum corresponds to the spectrum you find on a sunny day with the sun about 40° above the horizon and with the module inclined about 40° from horizontal facing the sun.

In the real life those conditions are not satisfied, therefore it is necessary **estimating the real power output of PV modules**. When the PV modules are mounted outdoors, the conditions can be very different from these standard conditions and therefore also the power output will be very different. Therefore, it is necessary to make corrections for several different effects that influence PV power. In the following the main ones are mentioned:

- Shallow-angle reflection
- Effect of changes in the solar spectrum
- **PV power dependence on irradiance and module temperature**
- **Module temperature**
- System losses and degradation with age
- Other effects not considered (e.g.: snow, dust and dirt, partial shadowing, etc)

In the QGIS calculations were introduced the effects of irradiance and module temperature. Below it is given the analysis.

PV power dependence on irradiance and module temperature

The efficiency of PV modules depends on the temperature of the module and on the solar irradiance. Generally, the efficiency decreases with increasing temperature, and the strength of this effect depends on the PV technology. For most module types, the efficiency is nearly constant for irradiances from about 400W/m^2 to at least 1000W/m^2 (for constant module temperature), but at lower irradiance the efficiency tends to decrease. Since the standard test conditions (STC) measure module power at high irradiance (1000W/m^2) and fairly low temperature (25°C) the overall result is that for most places the average module efficiency is a bit lower than the efficiency measured at the factory.

It is possible to calculate the effects of irradiance and module temperature using a model described in (*Huld et al., 2011*). The power is assumed to depend on irradiance G and module temperature Tm in the following way:

[**1**] $P = G/1000 * A*eff(G,T_m) = G/1000*A*eff_{nom} * eff_{rel}(G,T_m)$

[**2**] $eff_{rel}(G',T'_m)=1+k_1\ln(G')+k_2\ln(G')^2 +k_3T'm +k_4T'_m\ln(G') +k_5T'm\ln(G')^2 +k_6T'_m{}^2$

where $G'=G/1000$ and $T'_m=T_m-25$.

The coefficients k_1 to k_6 are found for each PV technology by fitting to measured data. The coefficients used are based on measurements performed at ESTI and are given in the next table.

Coefficient	c-Si	CIS	CdTe
k_1	-0.017237	-0.005554	-0.046689
k_2	-0.040465	-0.038724	-0.072844
k_3	-0.004702	-0.003723	-0.002262
k_4	0.000149	-0.000905	0.000276
k_5	0.000170	-0.001256	0.000159
k_6	0.000005	0.000001	-0.000006

Figure 47 - Coefficients k_1 to k_6 based on PV technology

Module temperature

When the sun shines on the PV modules the temperature of the modules will rise above the local air temperature. This means that the module temperature depends on both air temperature and the irradiance (strictly speaking the irradiance corrected for reflectivity since light that is reflected away will not heat the module). In addition, if there is wind it may help to cool the modules.

These effects are treated using a model suggested by Faiman (*Faiman, 2008*). The module temperature Tm can be calculated as:

$$[3]\ T_m = T_a + G/(U_0+U_1W)$$

Here, T_a is the air temperature and W is the wind speed. The table below shows the coefficients U_0 and U_1. The values for free standing modules are based on those reported by *Koehl et al, 2011*.

Module technology	**Installation**	**uo** W/(°C.m^2)	**u1** W.s/(°C.m^3)
c-Si	Free-standing	26.9	6.2
	BIPV/BAPV	20.0	3.2
CI(G)S	Free-standing	22.64	3.6
	BIPV/BAPV	20.0	2.0
CdTe	Free-standing	23.37	5.44
	BIPV/BAPV	20.0	3.2

Figure 48 - Coefficients U_0 and U_1 function of module technology and type of installation

Calculation for applying in QGIS simulations

The first step was to calculate Tm and after that T'm. The coefficients U_0 and U_1 were extracted from the table considering that it was worked with crystalline silicon (c-Si) panels and the installation type of them is BAPV (Building-Applied Photovoltaics).

$$T_m = T_a + G/(U_0+U_1W)$$

	Ta [C]	G [W/m2]	Uo [W/(˚C.m²)]	U1 [W.s/(˚C.m³)]	W wind speed*	Tm [C]	T'm [C]
January	5.8	245.8	20	3.2	0	18.1	-6.9
February	5.8	315.3	20	3.2	0	21.6	-3.4
March	11.2	368.7	20	3.2	0	29.6	4.6
April	12.3	405.2	20	3.2	0	32.6	7.6
May	17.0	430.9	20	3.2	0	38.5	13.5
June	22.3	428.0	20	3.2	0	43.7	18.7
July	25.4	426.9	20	3.2	0	46.7	21.7
August	25.7	422.4	20	3.2	0	46.8	21.8
September	21.8	390.7	20	3.2	0	41.3	16.3
October	17.7	326.2	20	3.2	0	34.0	9.0
November	9.1	253.2	20	3.2	0	21.8	-3.2
December	5.7	216.4	20	3.2	0	16.5	-8.5

**wind speed was assumed to be null to simplify the calculations*

The following step to take was the calculation of the 'relative efficiency $eff_{rel}(G',T'_m)$'. The coefficients k_1 to k_6 are function of the type of material of the panels, in our case crystalline silicon (c-Si). The table with the values is shown below:

Coefficient	c-Si
k_1	-0.017237
k_2	-0.040465
k_3	-0.004702
k_4	0.000149
k_5	0.00017
k_6	0.000005

Once gathered all the necessary coefficients and factors was possible to apply the following equation and from there the actual efficiency were obtained for our particular PV system and geographic place of installation.

$$eff_{rel}(G',T'_m)=1+k_1\ln(G')+k_2\ln(G')^2+k_3T'm+k_4T'_m\ln(G')+k_5T'm\ln(G')^2+k_6T'_m{}^2$$

where $G'=G/1000$ and $T'_m=T_m-25$.

	G [W/m2]	G'	eff_rel(G',T'm) [%]	Efficiency in standard conditions	ACTUAL EFFICIENCY
January	246	0.246	98%	0.23	0.225
February	315	0.315	98%		0.226
March	369	0.369	96%		0.220
April	405	0.405	95%		0.218
May	431	0.431	92%		0.212
June	428	0.428	90%		0.207
July	427	0.427	89%		0.204
August	422	0.422	88%		0.203
September	391	0.391	91%		0.208
October	326	0.326	93%		0.213
November	253	0.253	96%		0.221
December	216	0.216	97%		0.223

Finally, it is shown a summary table with the actual efficiency values to be considered in the QGIS simulations.

	Efficiency in standard conditions	Actual efficiency
January	0.23	0.225
February		0.226
March		0.220
April		0.218
May		0.212
June		0.207
July		0.204
August		0.203
September		0.208
October		0.213
November		0.221
December		0.223

4.8.1.2. PV Production

The values of photovoltaic energy production were calculated using the **Suri correlation** [37].

Equation 1 (energy that can be produced on buildings' PV rooftop)

With this formula it is possible to calculate the electrical energy produced in each building taking into account the particular characteristics of the PV system chosen and also the useful area dedicated to the technology.

$$E = PR \cdot H_S \cdot S \cdot \eta$$

Where,

E: electrical energy produced by year [kWh/year]

PR: performance index of the system ($\approx$ 0,75)

H_S: cummulative annual solar radiation [kWh/m^2/year]

η: conversion efficiency ($ratio\ of\ incident\ solar\ energy\ to\ produced\ energy\ \eta = W_p/(S * I_{stc})$)

W_p: peak power of the panel (1kWp is around $6 - 8m^2$ of PV)

S: working area [m^2]

$$\eta = W_p/(S^*I_{stc}) \quad (2) \text{ where:}$$

In the following, it can be observed the different grades of PV production in the residential buildings of Parma using the "PV system 1" (efficiency of 23%).

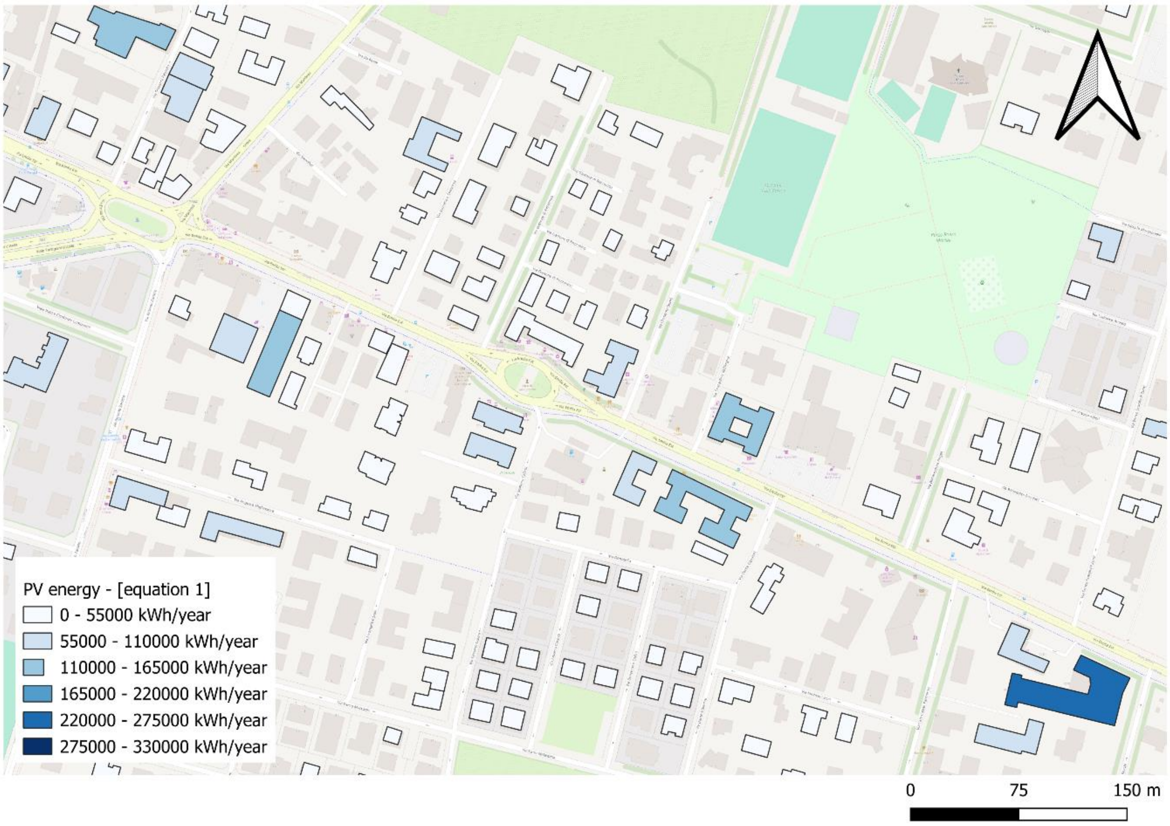

Figure 49 – Electrical energy produced [kWh/year] - (equation 1) ***23% efficiency***

<u>Equation 3</u> (energy that can be produced with 1 kWp of PV)

With the following equation it is possible to get independent results from the roof area of each building and from the PV technology since it was considered that 1 kWp is installed in each construction. In this way, it can be seen the potential of each place since the only variable in analysis is the solar irradiance available in each point.

Therefore, it was calculated in QGIS the values of electrical energy produced by 1kWp of PV using the solar irradiance obtained in previous steps.

$$E_{1kWp} = PR \cdot H_S \cdot \frac{W_p}{I_{stc}}$$

Next, the results are shown in graphical way.

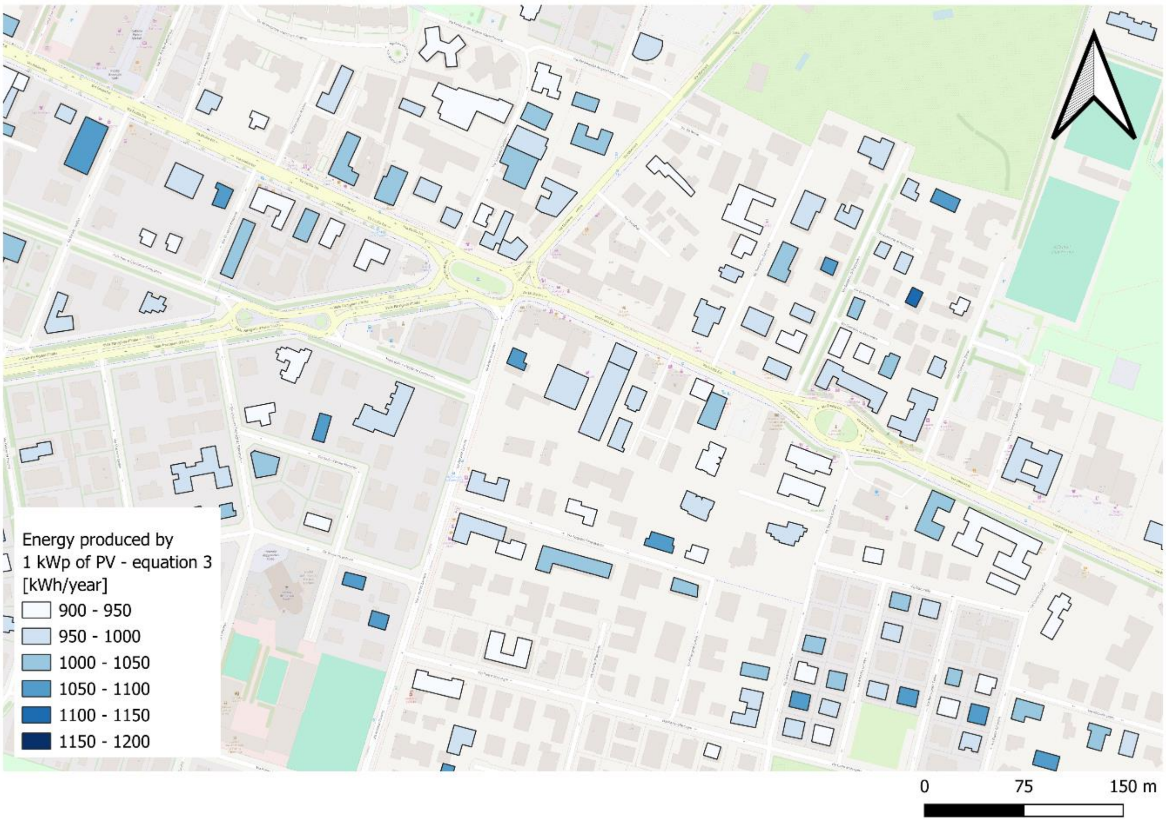

Figure 50 – Electrical Energy produced by 1 kWp [kWh/year] - equation 3

4.8.1.3. Comparison between QGIS results and PVGIS

It was made the comparison between the average and median monthly values calculated in QGIS of the electric energy produced by **1 kWp** installed in each building of Parma and the results extracted from the PVGIS website.

	E_kWp1		
	QGIS		PVGIS
	mean	median	
	[kWh/month]	[kWh/month]	[kWh/month]
January	51.6	51.7	69.7
February	68.1	68.1	85.2
March	100.6	100.6	125.4
April	120.9	120.9	131.5
May	146.4	147.0	141.1
June	147.7	148.7	146.1
July	149.4	150.3	156.1
August	136.7	136.9	148.3
September	109.4	109.5	130.1
October	82.7	82.7	100.6
November	54.0	54.1	65.8
December	43.8	43.9	62.1

Figure 51 - Monthly E_1kWp from QGIS and PVGIS

	ERROR	
	mean	median
	PVGIS	PVGIS
January	26%	26%
February	20%	20%
March	20%	20%
April	8%	8%
May	-4%	-4%
June	-1%	-2%
July	4%	4%
August	8%	8%
September	16%	16%
October	18%	18%
November	18%	18%
December	29%	29%
MAPE	**14%**	**13%**

Figure 52 - Monthly E_1kWp errors from QGIS and PVGIS

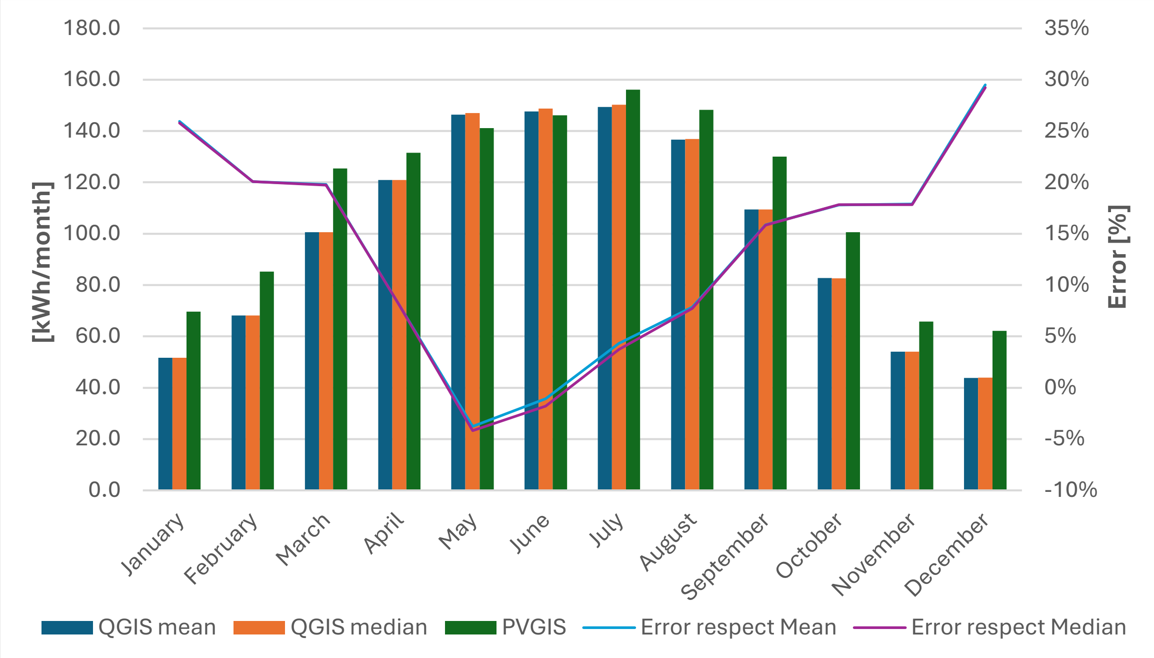

Figure 53 – Comparison of E_1kWp from QGIS and PVGIS

Then, the errors from the different sources of data were analysed.

As it can be seen there is a difference between results, especially in winter months. This can be due to the fact that in QGIS was analysed all the urban area of Parma meanwhile in PVGIS the values obtained are from a particular point of the city, therefore this can bring some differences to be taken into account.

Anyway, the **MAPE** with regard the mean and median values calculated with QGIS are 14% and 13% respectively, values more than acceptable for continuing with the posterior calculations.

4.8.2. Thermal energy

In this study case the focus related to thermal systems is evaluating the performance of a solar system to produce **domestic hot water (DHW)**.

Therefore, for this purpose **Solar Thermal Systems (STS)** are an ideal option since the continuous improvement in their performance in past years have allowed them to reach a low cost, easy operation and minimal maintenance. Due to this its installation is each time more common in buildings. They can be used to produce hot water and/or for heating/cooling uses.

Before starting to explain the main working of the system, it is important to highlight that up to 20% of the total utility bills is for heating domestic hot water (baths, showers, laundry, dishes, etc) and up to 90% of this necessary energy it could be achieved with clean renewable solar energy. This is possible to reach with **solar thermal**

technologies, where in this case solar thermal panels do not generate electricity, they generate heat.

Additionally, in the scenario where the solar water heater is used for getting domestic hot water, the following benefits can be achieved:

- It reduces the dependency on fossil fuels (while it also reduces the utility bill for the consumer)
- Excellent return on investment (a typical return on investment for residential use is between 10 to 20%, so it is possible even to finance the system and it will pay for itself).
- Most environmentally friendly way to heat water and these systems can last more than 20 years.
- Additionally, solar collectors can also be used to heat homes (radiant floor heating or hot water heating system), pools or hot tubes

Principle of Working

In general, these thermal systems are composed by six main components:

1. Solar collectors
2. Storage tank
3. Pump station
4. Control unit and Temperature sensors
5. Thermostatic mixing valve
6. Backup heater

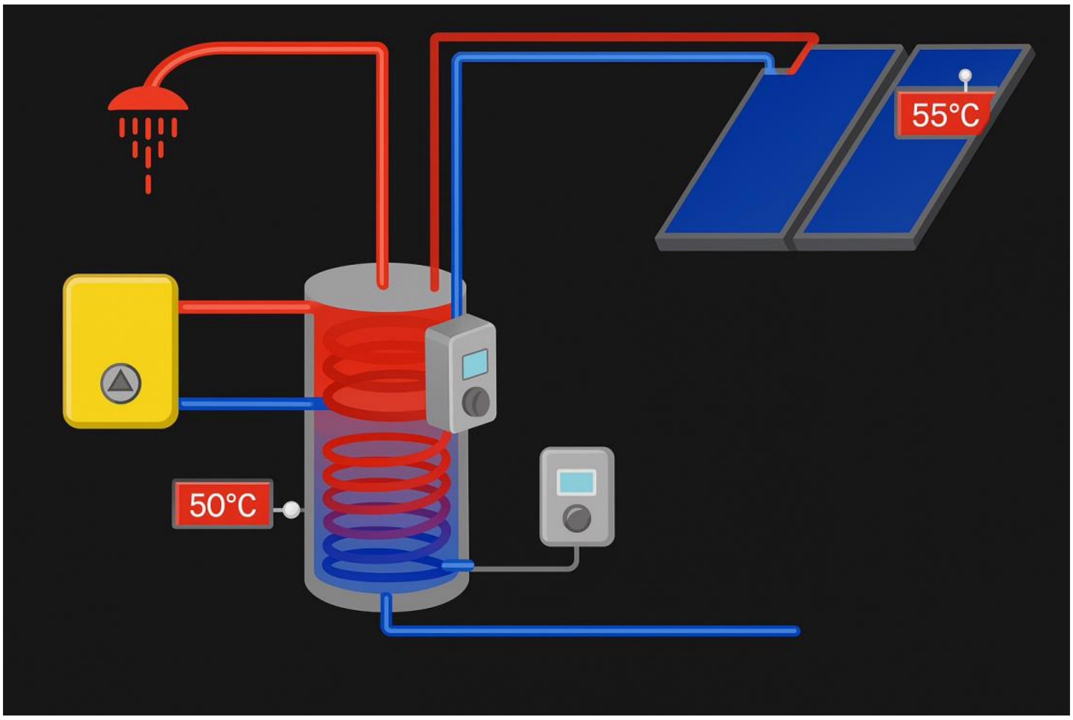

Figure 54 - Solar collector diagram

Beginning with the solar collectors, most of the time these are made of tubes that capture as much solar energy as possible and convert this energy into heat. Then, the heat is transferred to a special fluid (antifreeze liquid that avoids the freezing in the coldest night hours) passing through the interior of the tubes.

After that, the heated solar fluid is pumped down to a storage tank, where it circulates through a coil pipe known as a heat exchanger. This is how the heat is transferred from the solar-heated fluid (antifreeze fluid) to the potable water. The storage tank itself has two internal coil pipes: one at the bottom connected to the solar thermal panels via the 'solar circuit' (previously mentioned), and another at the top connected to a gas heater, providing additional heating if needed.

From the bottom of the storage tank enters the cold water coming from the external water supply and goes out heated by the upper part. However, since the heated water can reach too high temperature for the residential use, this hot water that goes out from the storage tank is mixed with water coming from the external supply in a **thermostatic mixing valve** (this valve has the function of anti-burn valve), and only after is sent to the users.

In addition, there is a **pomp unit** equipped with a **control unit** that is installed in the storage tank. This control unit is linked to a **temperature sensor** that is placed on the thermal panels and to another sensor installed in the bottom part of the storage tank. When the sensor in the panels measures a temperature 5 °C (this threshold value depends on the model and configuration chosen) greater than the temperature in bottom part of the storage tank, the control unit activates the solar circulator (solar circuit), and in this way it begins to transfer the solar liquid from the panels to the storage tank (bottom coil pipe) and therefore it is possible the transfer of heat from the panels to the domestic water inside the storage tank.

In the case that the heat produced by the solar system is not enough (for instance after several rainy days), the upper coil pipe connected to the classical water heater (gas or electrical type) is activated and heats the upper part of the storage tank in order to ensure a water temperature good enough for the users in all the possible cases. It is important to point out that even in the cases when the water heater has to intervene because the solar system does not achieve to cover all the demand, its participation is significantly inferior respect to a system where the solar system is totally missing, allowing in this case a huge saving in the utility bills (electricity or gas). [38] [39]

Thermal Energy Estimation Theory

The main element of STS is the **solar collector** that allows the transformation of the solar energy coming from the sun into thermal energy used to heat a vector fluid (in our case water). [40]

The performance of a solar collector can be defined applying an energy balance in the following way:

$$\eta_{coll,m} = \frac{Q_u}{Q_s}$$

Where:

Q_u: *useful heat transferred to the fluid carrier*
Q_s: *incident solar energy*

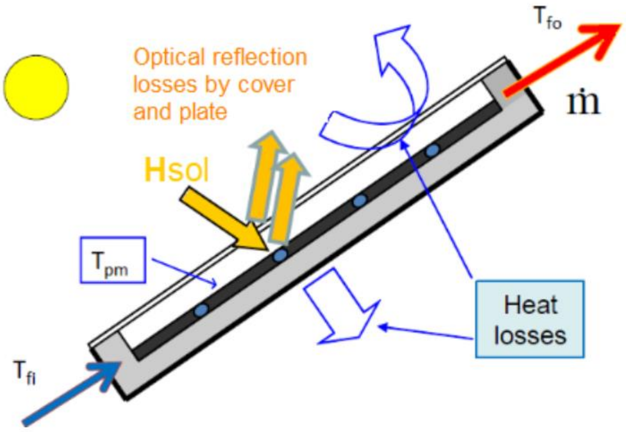

Figure 55 - Solar collector energy balance and thermal efficiency (Source: Duffle and Beckman)

Taking into account this energy balance, it is possible to calculate the **monthly useful thermal energy**. Basically, the fraction of the solar irradiation (H_{sol}) converted into thermal energy for each month.

$$Q_u = A_C \cdot H_{sol} \cdot \eta_{coll,m}$$

Where,
Q_u: *monthly useful thermal energy*
$A_C\ [m^2]$: *collector gross area*
$H_{sol}\ [\frac{Wh}{m^2}]$: *monthly incident solar irradiation intensity*
$\eta_{coll,m}$: *solar collector monthly efficiency*

The solar collector thermal efficiency helps to choose the best collector for a specific location and boundary condition of each site. In this case, it is evaluated according to the *European Standard EN 12975-2*:

$$\eta_{coll} = \eta_0 - \alpha_1 \cdot x - \alpha_2 \cdot I \cdot x^2$$

$$x = \frac{T_m - T_a}{I} = \frac{\Delta T_m}{I}\ [\frac{m^2 K}{W}]$$

$$\boldsymbol{\eta_{coll} = \eta_0 - \alpha_1 \cdot \frac{\Delta T_m}{I} - \alpha_2 \cdot I \cdot (\frac{\Delta T_m}{I})^2}$$

Where,
ηo [-]: *optical efficiency: the fraction of the incident solar radiation energy on the glass cover which is transferred as thermal energy inside the absorber surface.*

x [m^2K/W]: *reduced temperature difference.*

$a1$ [W/m^2K]: *heat loss coefficient.*

$a2$ [W/m^2K]: *temperature dependence of the heat loss coefficient.*

I [W/m^2]: *solar irradiance that can be calculated dividing the solar irradiation by the hours of light in each month:* $I = \frac{H_{sol}}{h}\ [\frac{W}{m^2}]$

The quality of a solar collector depends on:

- *Optical efficiency* η_0: it considers all the optical loses due to the conversion of solar radiation to thermal energy, it only depends on the optical properties of the collector.
- *Heat loss coefficient* α_1 : it can be thought as a thermal transmittance. It is useful to determine the quality of the collector, high quality corresponds to a low value of α_1 and vice versa. Linear dependency respect *x*.
- *Quadratic dependency* α_2 : it is introduced to take into account the non-linearity of the heat transfer to high temperatures. Quadratic dependency respect *x*.

Also, it is needed *"x", reduced temperature difference*, in order to calculate the collector monthly efficiency $\eta_{coll,m}$. This factor is defined as follows:

$$x = \frac{T_m - T_a}{I} = \frac{\Delta T_m}{I}\ [\frac{m^2K}{W}]$$

Where,
T_a: $external\ air\ temperature$
T_m: $mean\ fluid\ temperature$

The mean fluid temperature can be simplified and calculated as the average between the inlet T_{IN} and outlet fluid temperature T_{OUT}. Assuming the following values $T_{IN} = 15°C$ and $T_{OUT} = 45°C$, then T_m remains constant.

$$T_m = \frac{T_{IN} + T_{OUT}}{2} = 30\ °C$$

Lastly, η_0, α_1 and α_2 are the last parameters needed to calculate $\eta_{coll,m}$. These values depend on the type of collector, mainly existing the next two types:

- Vacuum Tube Solar Collectors
- Flat-plate Solar Collectors

In this work was analysed a case study with each type of collector and the values from the parameters were obtained from the table provided in the technical data sheet of each product.

Ultimately, the global useful thermal energy needed $E_{th,TOT}$ can be obtained as the summation of all the useful thermal energies of each month:

$$H_{th,TOT} = \sum_{i=1}^{12} E_{th,i}$$

Thermal panel 1 – Vacuum Tube type

It was used the solar collector SCV-25 from Beretta brand [41].

Figure 56 - Beretta Solar Collector

Berreta is a brand known for the high quality and the innovation in their solutions in the heating and renewable energy fields. The company stands out for the focus in the energetic efficiency, long lifetime and ease of use, making their products an ideal option for residential and commercial environments. Between them, the solar collector SCV-25 distinguishes from the rest since it is the working symbol of Berreta towards more sustainable and advanced solutions.

The SCV-25 model was designed to capture the solar energy and transform it into heat, suitable for heating or production of hot domestic water. It is composed of 14 vacuum glass tubes that give an excellent thermal isolation even in unfavourable climate conditions. Inside each tube is a U-shaped copper conduit, which absorbs the sun's rays enhanced by an integrated reflecting mirror.

As a result of its technology with circular absorbers and reflective surfaces, the SCV-25 is able to collect energy even when the sun is not perfectly perpendicular, thus improving the overall efficiency. The system is projected to be robust and reliable: the vacuum inside the tubes protects the components of the external agents, extending the lifetime. Furthermore, in the case of break, it is possible to change the individual tubes without having to intervene in the whole system.

With and elegant design and a versatile installation, the Beretta SCV-25 solar collector represents a solid and modern solution for who wants to take advantage of the solar energy during all the year, even in the least sunny periods.

Next, it is showed a section of the technical sheet of the solar collector from where some useful thermal parameter can be obtained.

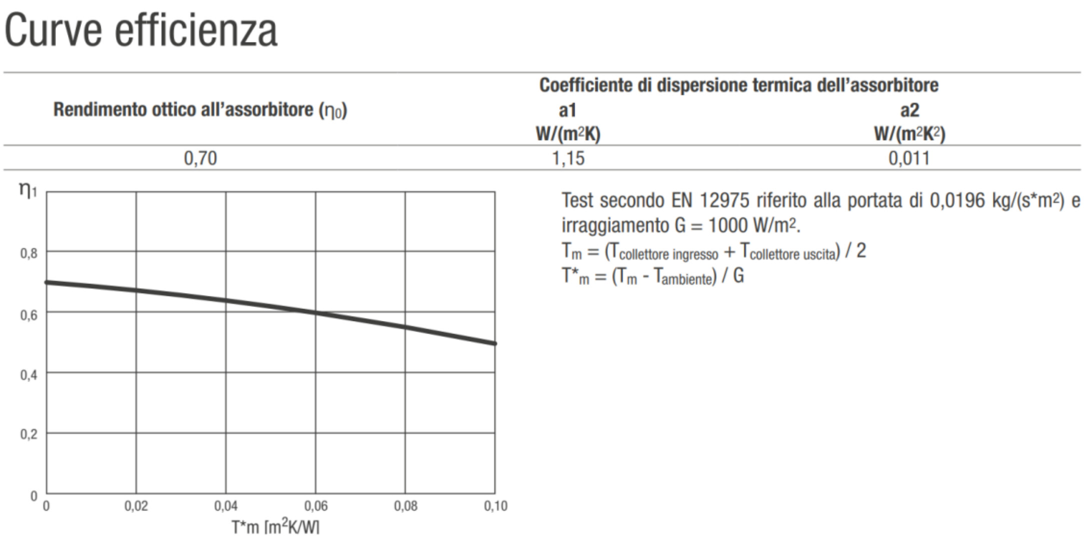

Figure 57 – Parameters η_0, α_1 and α_2 of Beretta solar collector

Thus, the parameters values to be used are: $\eta_0 = 0{,}70$; $\alpha_1 = 1{,}15\ W/(m^2K^2)$; $\alpha_2 = 0{,}011\ W/(m^2K^2)$

Calculation of Solar collector thermal efficiency η_{coll}

	n days	Ta [C]	Tm [C]	ΔTm [C]	average daylight hours [hs/day]	average daylight hours [hs/month]	H [Wh/m2]	I [W/m2]
January	31	5.8	30	24.2	9.0	280	31105	111.1
February	28	5.8	30	24.2	10.3	288	40964	142.3
March	31	11.2	30	18.8	11.7	364	62124	170.8
April	30	12.3	30	17.7	13.3	398	81450	204.6
May	31	17.0	30	13.0	14.6	453	106299	234.6
June	30	22.3	30	7.7	15.3	460	120366	261.7
July	31	25.4	30	4.6	15.1	467	118510	254.0
August	31	25.7	30	4.3	13.9	431	92938	215.4
September	30	21.8	30	8.2	12.5	374	68601	183.7
October	31	17.7	30	12.3	10.9	338	50617	149.8
November	30	9.1	30	20.9	9.5	285	32370	113.8
December	31	5.7	30	24.3	8.7	270	26443	98.0

Figure 58 - Data to get the solar collector's efficiency (part 1)

	η_0	α_1	α_2	$x\ [\frac{m^2K}{W}]$	$x^2\ [\frac{m^2K}{W}]$	η_{coll}
January	0.7	1.15	0.011	0.2179	0.0475	**0.391**
February	0.7	1.15	0.011	0.1701	0.0289	**0.459**
March	0.7	1.15	0.011	0.1101	0.0121	**0.551**
April	0.7	1.15	0.011	0.0865	0.0075	**0.584**
May	0.7	1.15	0.011	0.0554	0.0031	**0.628**
June	0.7	1.15	0.011	0.0294	0.0009	**0.664**
July	0.7	1.15	0.011	0.0181	0.0003	**0.678**
August	0.7	1.15	0.011	0.0200	0.0004	**0.676**
September	0.7	1.15	0.011	0.0446	0.0020	**0.645**
October	0.7	1.15	0.011	0.0821	0.0067	**0.594**
November	0.7	1.15	0.011	0.1837	0.0337	**0.447**
December	0.7	1.15	0.011	0.2478	0.0614	**0.349**

Figure 59 - Data to get the solar collector's efficiency (part 2)

Thermal panel 2 – Flat plate type

The second option was the CP4 XL **flat-plate solar collector** from Immergas, an Italian company. [42]

IMMERGAS
We are the energy of change

Figure 60 - Immergas CP4 XL flat-plate collector

Designed to be installed both in vertical and horizontal position, CP4 XL solar collectors can be also connected one each other in up to 6 collectors cascade configuration, thanks to the 4 connection pipes layout. The peculiar design of the connections, that allows the complete reversibility of the sides both for inlet and outlet, and the threadless copper connection pipes solution, fit for al large number of connecting

techniques, make CP4 XL an extremely flexible device, ideal for a wide range of different situations.
Thanks to the low weight, great manageability makes this kind of collector a very interesting product, even in the most difficult installation conditions. Special 4 mm thick tempered glass allows grants high protection level to the selective coating treated alluminium absorber, featured by 95% absorptivity coefficient.
Thanks to the thermal insulation given by 4 cm thick stone wool panels placed on the sides and on the back of the casing, heat losses are minimal.
The Solar Keymark Certification prove the compliance to the Technical Standard UNI EN 12975.

Next, it is shown a section of the technical sheet of the solar collector from where it was possible extract some useful thermal parameters.

aperture area of 1.924 m^2:

η_{0a} = 0.759

a_{1a} = 3.480 W/m^2K

a_{2a} = 0.0161 W/m^2K^2

Figure 61 - Parameters η_0, α_1 and α_2 of Immergas solar collector

Calculation of Solar collector thermal efficiency η_{coll}

	n days	Ta [C]	Tm [C]	ΔTm	Average daylight hours [hs/day]	Average daylight hours [hs/month]	H [Wh/m2]	I [W/m2]
January	31	5.8	30	24.2	9.0	280	31105.4	111.08
February	28	5.8	30	24.2	10.3	288	40964.0	142.27
March	31	11.2	30	18.8	11.7	364	62124.0	170.80
April	30	12.3	30	17.7	13.3	398	81450.0	204.65
May	31	17.0	30	13	14.6	453	106299.0	234.60
June	30	22.3	30	7.7	15.3	460	120366.0	261.67
July	31	25.4	30	4.6	15.1	467	118509.9	254.01
August	31	25.7	30	4.3	13.9	431	92938.0	215.43
September	30	21.8	30	8.2	12.5	374	68601.0	183.67
October	31	17.7	30	12.3	10.9	338	50616.8	149.80
November	30	9.1	30	20.9	9.5	285	32370.0	113.78
December	31	5.7	30	24.3	8.7	270	26443.0	98.05

Figure 62 - Data to get the solar collector's efficiency (part 1)

	η_0	α_1 [W/m^2*K]	α_2 [W/m^2*K^2]	$x\ [\frac{m^2K}{W}]$	$x^2\ [\frac{m^2K}{W}]$	η_{coll}
January	0.759	3.480	0.0161	0.218	0.047	**0.000**
February	0.759	3.480	0.0161	0.170	0.029	**0.101**
March	0.759	3.480	0.0161	0.110	0.012	**0.343**
April	0.759	3.480	0.0161	0.086	0.007	**0.433**
May	0.759	3.480	0.0161	0.055	0.003	**0.555**
June	0.759	3.480	0.0161	0.029	0.001	**0.653**
July	0.759	3.480	0.0161	0.018	0.000	**0.695**
August	0.759	3.480	0.0161	0.020	0.000	**0.688**
September	0.759	3.480	0.0161	0.045	0.002	**0.598**
October	0.759	3.480	0.0161	0.082	0.007	**0.457**
November	0.759	3.480	0.0161	0.184	0.034	**0.058**
December	0.759	3.480	0.0161	0.248	0.061	**0.000**

Figure 63 - Data to get the solar collector's efficiency (part 2)

Thermal production

Once calculated the solar collector thermal efficiency coefficients $\boldsymbol{\eta_{coll}}$, it was possible to get the **monthly useful thermal energy** with the following formula:

$$Q_u = A_C \cdot H_{sol} \cdot \eta_{coll,m} \quad [kWh]$$

Where,

$A_C\ [m^2]:\ collector\ gross\ area$

$H_{sol}\ [\frac{Wh}{m^2}]:\ monthly\ incident\ solar\ irradiation\ intensity$

$\eta_{coll,m}:\ solar\ collector\ monthly\ efficiency$

Finally, the **global (annual) useful thermal energy**:

$$Q_{u,TOT} = \sum_{i=1}^{12} Q_{u,i} \quad [kWh]$$

4.9. Energy consumption

In this section will be calculated the consumption of the residential buildings both for electricity and thermal energy (natural gas).

4.9.1. Electricity consumption

Global yearly electrical consumption:

$$E_{el} = E_{el,per\ family} \cdot Number\ of\ families$$

Province of Parma (Emilia-Romagna region):

$$E_{el,per\ family} = 2100\ \frac{kWh}{year}$$

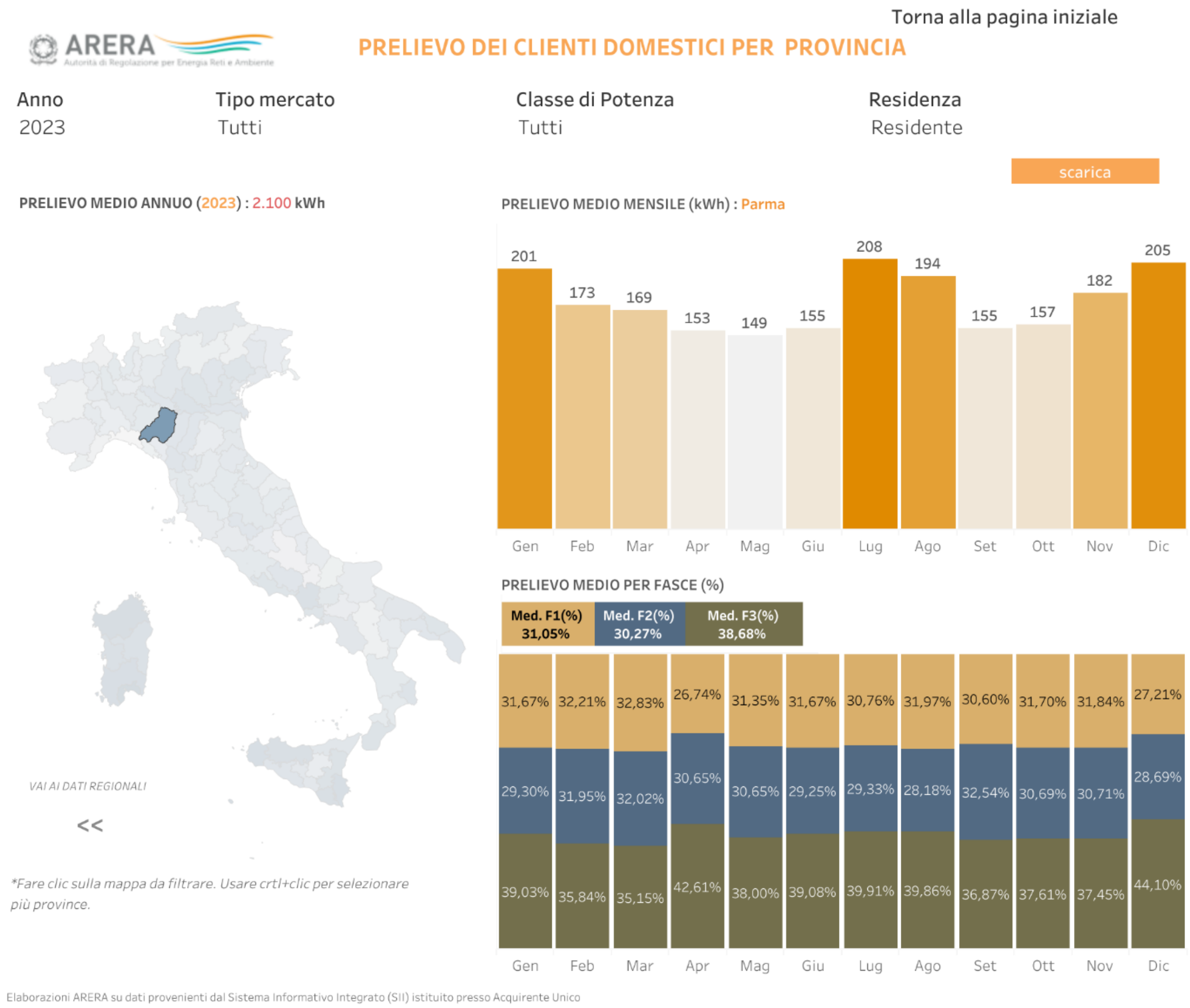

Figure 64 – Data about the electricity consumption in the province of Parma by ARERA [43]

	Days	Electricity consumption [MWh/month]
January	31	9604
February	28	8675
March	31	9604
April	30	9294
May	31	9604
June	30	9294
July	31	9604
August	31	9604
September	30	9294
October	31	9604
November	30	9294
December	31	9604

Figure 65 - Electricity consumption

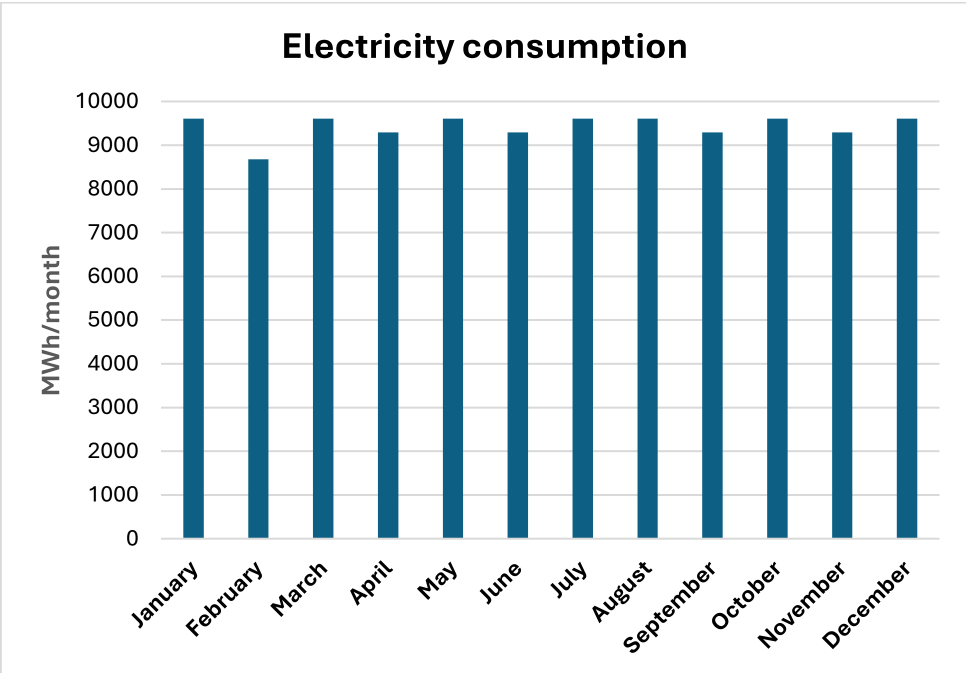

Figure 66 - Graph of Electricity consumption

4.9.2. Thermal energy consumption

The first thing to do is calculating the **water volume needed for residential buildings** V_w. For this, it was utilized the Italian technical standard UNI/TS 11300-2 (Evaluation of primary energy need and of system efficiencies). [44]

$$V_w = a * S_u + b \quad [\frac{liters}{day}]$$

where:

$$a: parameter\ in\ \frac{liters}{m^2 * day}\ from\ table$$
$$b: parameter\ in\ \frac{liters}{day}\ from\ table$$
$$S_u: useful\ area\ of\ the\ residential\ dwelling\ [m^2]$$

Superficie utile S_u [m²]	S_u <= 35	35 < S_u <= 50	50 < S_u <= 200	S_u > 200
Parametro *a* [litri/(m² x giorno)]	0	2,667	1,067	0
Parametro *b* [litri/giorno]	50	-43,33	36,67	250

Figure 67 – Parameters 'a' and 'b' in function of dwelling area [44]

It was assumed to be in the range of $50\ m^2 < S_u < 200\ m^2$ for the average dwelling. Also, it was considered that the average size of a dwelling in Parma is around $S_u = 90\ m^2$

$$a = 1{,}067\ {}^{liters}/_{m^2 * day}$$
$$b = 0{,}1327\ {}^{m^3}/_{day * family}$$
$$S_u = 90\ m^2$$

Finally,

$$V_w = 132{,}7\ \frac{liters}{day * family} = 0{,}1327\ \frac{m^3}{day * family}$$

Remembering that in the city of Parma there are 195.436 inhabitants and 92.324 families, it can be calculated in an approximate way that each family is composed in average per **2,12 people.**

Thus, the **consumption of how water per person** is:

$$V = \frac{V_w}{people\ per\ family} = \frac{0{,}1327\ \frac{m^3}{day * family}}{2{,}12\ \frac{people}{family}} = 0{,}063\ \frac{m^3}{day * person}$$

Once it is obtained the previous value, it is possible to calculate the **daily per-capita energy consumption for domestic hot water $Q_{u,d}$**

$$Q_{u,d} = V \cdot \rho \cdot c_p \cdot \frac{\Delta T}{\varepsilon} = V \cdot \rho \cdot c_p \cdot \frac{(T_{OUT} - T_{IN})}{\varepsilon} \quad [\frac{kWh}{person}]$$

Where,

$V = 63 \frac{liters}{day} = 0{,}063 \frac{m^3}{day} \rightarrow daily\ volume\ of\ hot\ water\ consumed\ by\ a\ person$

$\rho = 1000 \frac{kg}{m^3} \rightarrow water\ density$

$c_p = 4{,}186 \frac{kJ}{kg\ K} = 1{,}163 * 10^{-3} \frac{kWh}{kg\ K} \rightarrow water\ specific\ heat$

$\Delta T = (T_{OUT} - T_{IN}) = (45 - 15)°C = 30°C = 30\ K$

$\varepsilon = 0{,}85 \rightarrow efficiency\ of\ heat\ exchanger\ or\ heat\ boiler$

The result is for a **single person**; therefore, it is needed to multiply it for the number of days of the month or year and by the number of inhabitants to get the final consumption. Hereunder, the consumption per month and the comparison against the production in the optimal cases are showed:

	n° of days	Thermal Energy Consumption [MWh/month]
January	31	9083
February	28	8204
March	31	9083
April	30	8790
May	31	9083
June	30	8790
July	31	9083
August	31	9083
September	30	8790
October	31	9083
November	30	8790
December	31	9083
YEAR	365	183589

Figure 68- Thermal consumption

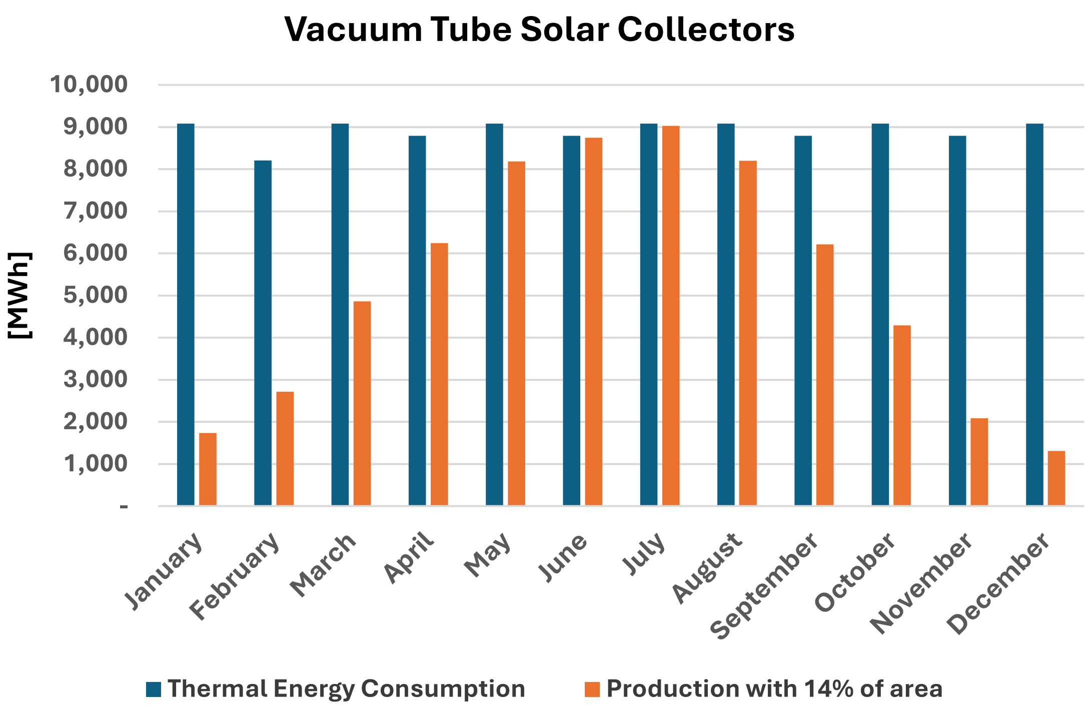

Figure 69 - Thermal energy - Vacuum Tube SC

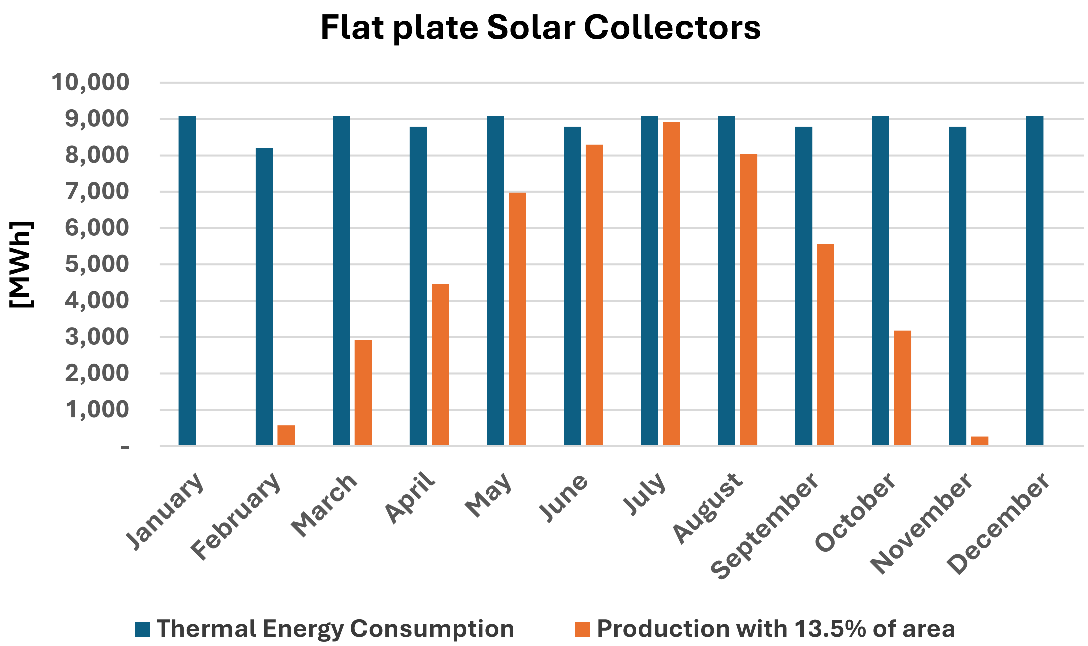

Figure 70- Flat plate SC

4.10. Standard hourly profiles

The objective of this section is to get the **hourly consumption and PV production profiles** in order to be able to compare them during the day. In this way, it would be possible to analyse in which moments the PV production covers partially, totally or exceeds the electrical demand. This information is also useful in the economic analysis of the project since it makes possible to do a detailed breakdown, getting to know how much energy is auto-consumed and how much is surplus energy (important since these two are valuated differently from the economic point of view).

4.10.1. Consumption profiles

It is started with the consumption profile. Since the specific data for the city of Parma was missing due to there are no real time measures of the consumption or at least they are not available freely, it was decided to continue with the **standard profiles of consumption** for residential buildings provided by GSE (Gestore Servizi Energetici). In fact, these profiles are commonly used to the estimations in all the cases that the real ones are not available. [45] [46]

The standard profiles developed by the GSE are dependent on:

- Type of user
- Type of renewable energy production plant
- Typology of connection point to the electrical grid (puro prelievo, pura immissione, misto)

There are 4 types of standard profiles according to the type of user. However, only the residential profile is relevant to the project so this one will be analysed. Next, the extract from the document where it is described which buildings are part of the profile:

" a) for low-voltage household utilities, where contracts relating to the electrical energy used to supply:

> *ii) applications in rooms used for family or group housing, with exclusion of hotels, schools, colleges, boarding schools, hospitals, prisons and similar facilities;*
>
> *ii) general service applications in buildings of up to two units, applications related to the power supply of private charging infrastructures for electric vehicles, the applications in adjoining or housing-related premises used for studies, offices, laboratories, consulting rooms, cellars or garages or for agricultural purposes, provided that the use is made with a single point of collection, for the dwelling and the premises connected, and the available power does not exceed 15 kW; "*

In the following it is shown the **standard consumption profile** for **residential buildings**:

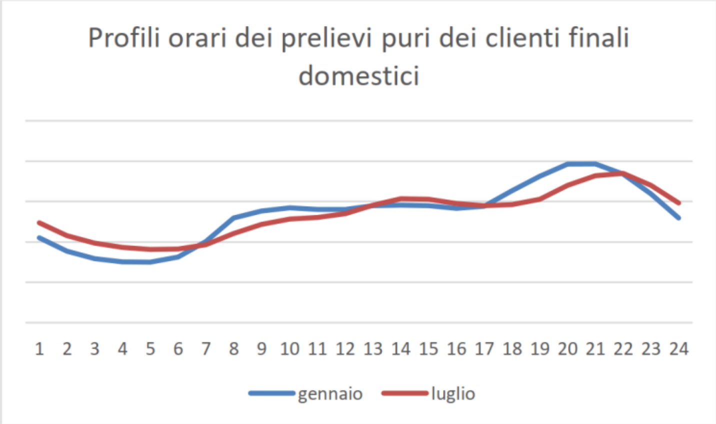

Figure 71 - Standard consumption profile for final users by GSE [47]

To consider the effect of the seasons in the consumption, it was calculated the profile for 2 different months. It is reported the comparison between the month of January and July. The profiles are expressed in percentual coefficients defined according to weight that each hour has during the day.

4.10.2. PV production profiles

GSE profiles [45]

It is also provided by the GSE the **standard profiles** for the production of energy. In our case the profile due to **PV panels production** is analysed.

For the construction of the curve, municipal irradiation data has been processed. This methodology allows to evaluate the energy injected into the grid during actual irradiation hours, without being affected by various factors such as self-consumption, system malfunctions, or the reconstruction of the curve by the Distribution System Operator (GdR), which could influence the use of real curves available from the GSE.

Moreover, to account for the seasonal effects on photovoltaic energy production, it was calculated again the standard profile for different months. This was done for **January** and for **July**, two characteristic months of very opposite seasons.

The profile is expressed in **percentage coefficients**, defined based on the weight that each hour has within the day. The full detailed profile is attached below.

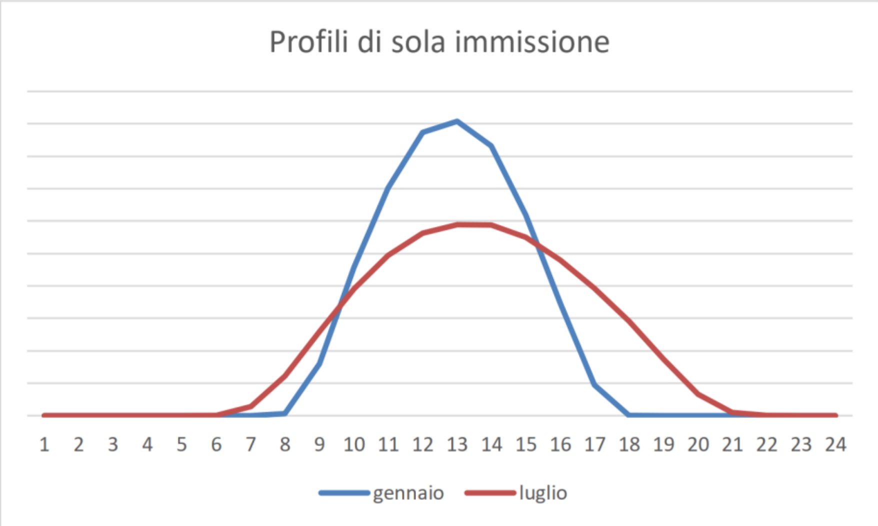

Figure 72 - Standard profile of PV production by GSE [47]

Also, it is presented the profile in the case of **mixed points** (both withdrawal and injection) and considering instant self-consumption, which modifies the original injection and withdrawal profiles. It also considers that a photovoltaic system has been installed.

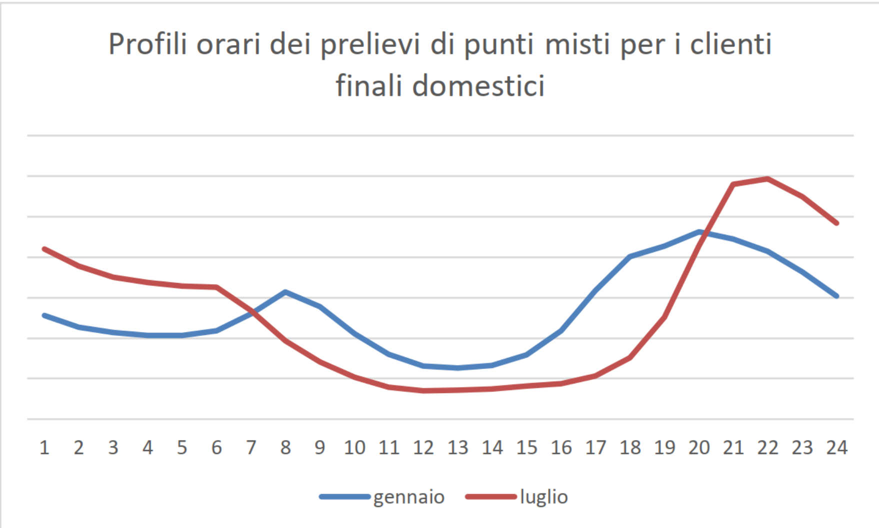

Figure 73 - Standard profile for final users of mixed points [47]

From the standard profiles it is possible to do a **qualitative analysis.** It can be observed that the PV production has a bell shape with its peak around the 12/13 hs. Then, when the production is combined with the consumption, the final profile of electricity demand has two peaks (one in the early morning when people wake up to go to work and the other in late afternoon/night when people come back from work and relax/eat before going to sleep) and a deep valley between them (due to people are out of their houses and even more lowered due to self-consumption as result of PV production). This typical profile is usually called the **'duck curve'**.

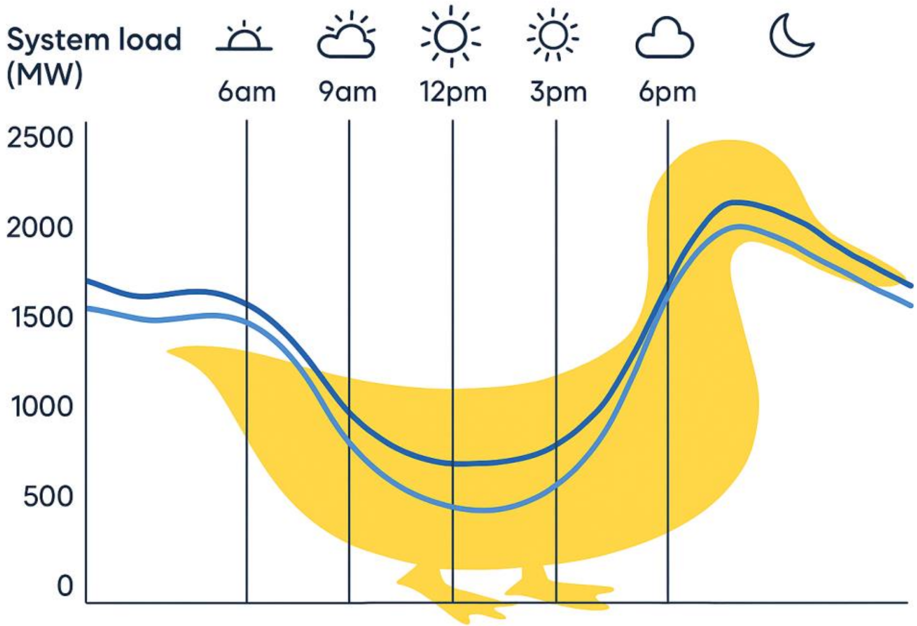

Figure 74 - Duck curve

It is evident that even if the total energy consumption is fully covered over a month or year, this does not necessarily imply complete self-consumption. During certain periods, photovoltaic (PV) systems may generate surplus energy that cannot be consumed on-site. This issue can be addressed either by integrating an energy storage system (**not** analysed in this study) or by selling the excess energy back to the grid, although the selling price is typically lower than the economic benefit derived from direct self-consumption. This last option will be chosen for the project, and it will be analysed in more detail in the '5. ECONOMIC ANALYSIS'.

PVGIS profiles

Even though the PV production profiles from the GSE are valid, it was decided to use the profiles from **PVGIS website** (https://re.jrc.ec.europa.eu/pvg_tools/en/) since they allow to consider the orientation and inclination of the panels, aspect very useful for our goal of analysing the possibility of adding the North-West face orientation or not. Those profiles allowed to observe the difference in relative production, the shape of the production profiles and also the time period where they are located (for instance, start, peak and ending of PV production at different times according to the orientation selected for the panels).

Moreover, it was possible to get the data for every day of the last years. Therefore, it was selected the one characteristic day for each month and for selecting the year it was decided to use the data from the typical meteorological year (TMY). A TMY is a dataset representing average weather conditions for a specific location, compiled from multiple years of historical data, in this way reflects typical long-term climate patterns.

It was also provided the percentages of the profiles in order to be able to escalate them later with the actual daily production of our CER. Next, it is shown an image of these PV profiles for the months of July and January.

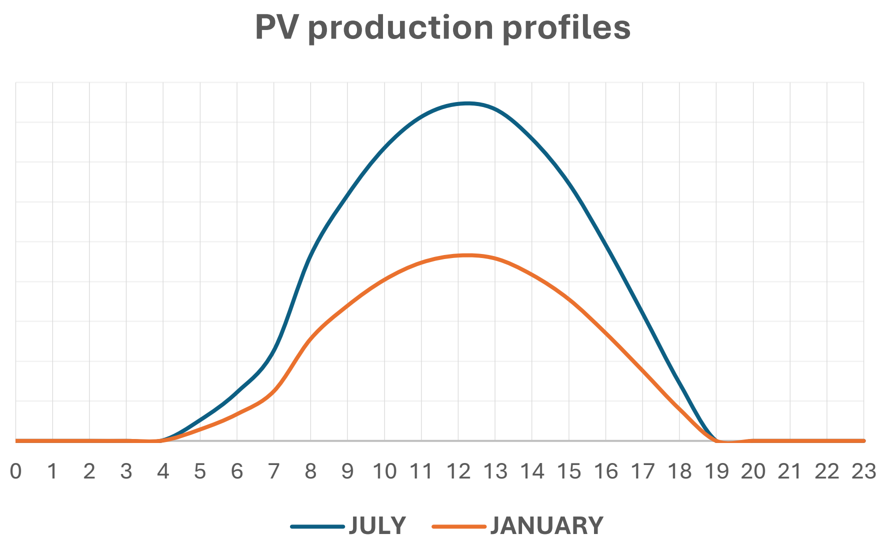

Figure 75 - PV standard production profiles by PVGIS

<u>Combined profiles</u>

Later, in the section "4.12. Final Calculation" the consumption and PV production profiles will be analysed simultaneously and with the corresponding values of the case scenarios. In this way, it will be possible to identify the auto-consumption and the surplus energy generated, information of vital importance for doing lastly the economic analysis.

4.10.3. Quantitative Analysis

In order to do a **quantitative analysis** and being able to get a more precise economic estimation, the standard profiles were escalated with the daily values of consumption and PV production. This was done for all the months getting in this way a characteristic curve hourly curve for each month. In the following are shown only the curves of January and July (for the 3 case scenarios) since are the most representative of each season.

- PV system with a nominal efficiency of 23% using the 100% of the useful area

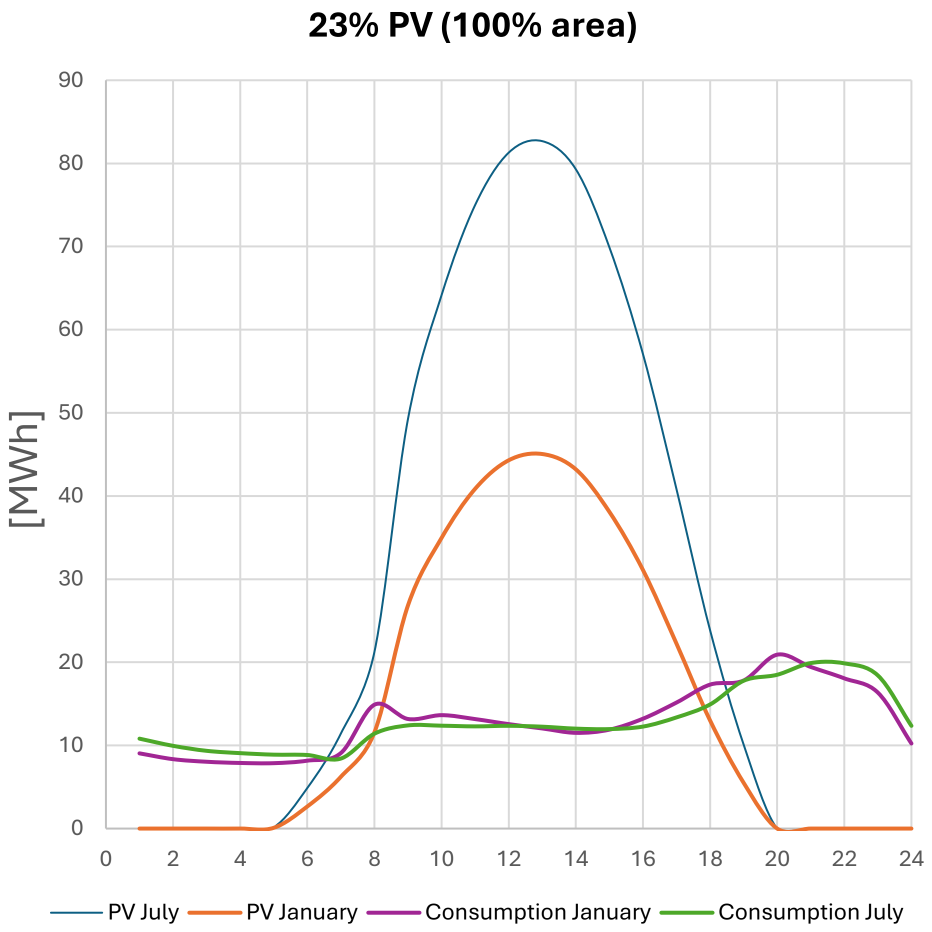

Figure 76 - Quantitative analysis for 23% PV system with 100% of useful area

- PV system with a nominal efficiency of 23% using the 86% of the useful area, in the remaining area were located the Thermal system.

It was used only this graph since the two case scenarios with thermal systems are quite similar from the electrical point of view (one uses 86% of the useful area and the other 86,5%). Therefore, to give an overall idea is more than enough showing just the following case.

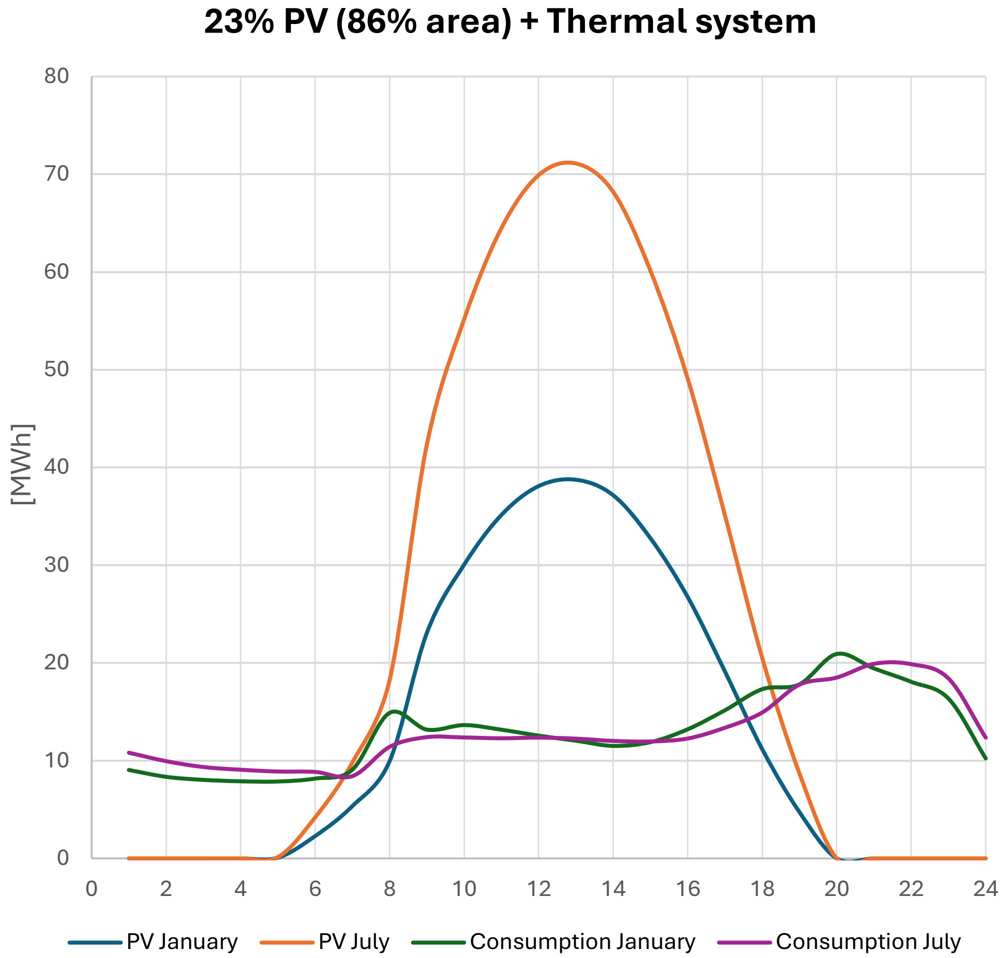

Figure 77 - Quantitative analysis for 23% PV system with 86% of useful area

<u>Conclusion</u>

The availability of hourly data allows for an accurate assessment of both the percentage of PV energy that is self-consumed and the proportion that results in surplus. This level of detail makes it possible to estimate the annual revenue, as energy production and consumption can now be tracked day by day throughout the year. These results will serve as key inputs in chapter '5. ECONOMIC ANALYSIS', which focuses on the Economic Analysis.

Moreover, this data enables an evaluation of the potential benefits of integrating a storage system, which could store excess energy for use during periods with no PV generation. Such a solution would enhance the overall self-sufficiency of the system. However, it is important to note that <u>this potential improvement will **not** be explored within the scope of this thesis</u>.

4.11. Costs

4.11.1. Electrical Energy withdrawn from the network

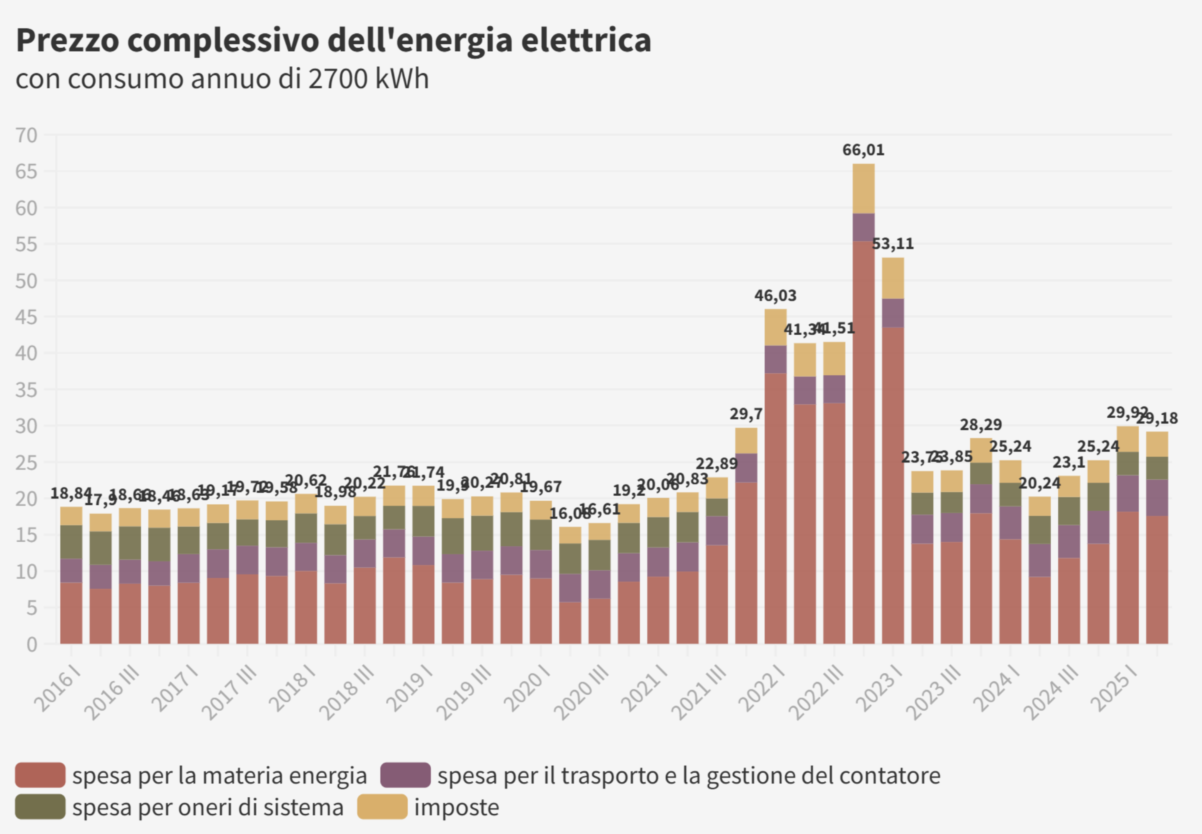

Figure 78 – Electrical Energy withdrawn prices by ARERA [48]

Thus, the result price for *Electrical Energy withdrawn from the network* is: **29,18 c€/kWh = 0,2918 €/kWh**

4.11.2. Electrical Energy injected to the network

The data was extracted from the **GSE (Gestore dei Servizi Energetici)** website, and it was utilized the report about the mean monthly prices of 2024. [49] [50]

According to the day and ranges of times are defined the time bands:

- F1: Fascia 1
- F2: Fascia 2
- F3: Fascia 3

<table>
<tr><th></th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th></tr>
<tr><td>lunedi-venerdi</td><td colspan="7">F3</td><td>F2</td><td colspan="11">F1</td><td colspan="4">F2</td><td>F3</td></tr>
<tr><td>sabato</td><td colspan="7">F3</td><td colspan="16">F2</td><td>F3</td></tr>
<tr><td>domenica/festivi</td><td colspan="24">F3</td></tr>
</table>

Figure 79 - Time bands [50]

Assuming that the PV panels will produce energy approximately from 8:00hs to 18:00hs (hours with solar irradiance different from zero), it can be observed from the last figure that along the days the energy will be sold in all the three band times (fascia 1, 2 and 3). This will be considered in the follow calculations introducing a weighted average to get the final result.

Then, the prices according to market zone and time band can be seen in the following tables:

Prezzi 2024 (Euro/MWh)												
Fascia	**F1**											
Zona	**gen.**	**feb.**	**mar.**	**apr.**	**mag.**	**giu.**	**lug.**	**ago.**	**set.**	**ott.**	**nov.**	**dic.**
Centro Nord	103,60	90,82	90,02	76,12	90,75	99,92	106,41	116,88	115,57	112,93		
Centro Sud	101,75	86,00	89,59	75,54	88,94	99,83	106,35	116,63	113,11	109,12		
Nord	103,42	90,34	89,79	76,60	90,50	99,56	105,87	116,77	115,73	114,48		
Sardegna	93,82	84,99	63,45	47,17	73,37	96,66	86,11	117,70	92,67	99,24		
Sicilia	98,95	87,45	83,24	73,78	86,45	99,14	107,30	117,73	113,88	122,28		
Sud	100,85	85,04	83,69	73,86	82,33	99,82	106,52	116,72	112,23	111,11		
Calabria	100,51	84,39	83,70	73,65	82,78	99,56	106,25	117,51	113,39	110,92		
Fascia	**F2**											
Zona	**gen.**	**feb.**	**mar.**	**apr.**	**mag.**	**giu.**	**lug.**	**ago.**	**set.**	**ott.**	**nov.**	**dic.**
Centro Nord	96,96	83,30	79,34	74,81	83,59	87,03	110,08	120,40	102,53	102,77		
Centro Sud	95,27	81,03	70,97	74,36	80,51	86,41	107,43	116,38	97,80	97,34		
Nord	97,39	84,17	78,74	77,19	86,34	91,26	103,30	116,36	104,55	108,15		
Sardegna	98,87	79,88	69,68	64,69	84,24	95,23	122,60	131,05	89,91	86,29		
Sicilia	94,51	84,46	68,31	71,30	81,52	91,07	106,81	119,46	102,98	114,43		
Sud	98,88	85,36	73,00	75,39	82,16	88,65	107,37	116,32	100,82	102,81		
Calabria	98,74	85,73	73,17	74,40	84,59	89,96	107,53	118,75	104,42	102,18		
Fascia	**F3**											
Zona	**gen.**	**feb.**	**mar.**	**apr.**	**mag.**	**giu.**	**lug.**	**ago.**	**set.**	**ott.**	**nov.**	**dic.**
Centro Nord	85,75	72,02	65,74	58,12	60,60	71,34	100,45	117,11	85,38	99,27		
Centro Sud	82,22	71,65	58,71	56,32	57,70	73,58	99,80	116,07	81,52	96,29		
Nord	87,48	72,48	66,03	63,32	65,88	76,47	96,94	116,14	90,79	100,07		
Sardegna	84,60	65,28	54,86	54,47	58,08	81,38	105,96	120,17	82,11	91,42		
Sicilia	84,59	70,30	48,14	54,87	56,77	73,11	99,35	117,17	80,06	102,27		
Sud	83,34	71,73	56,39	59,03	62,71	74,38	100,19	116,25	85,11	96,25		
Calabria	84,89	73,00	57,23	56,37	62,34	78,37	100,02	117,03	86,32	99,30		

Figure 80 - Monthly average prices by time band and market zone [50]

The ubication of Parma is in the market zone defined as "**Nord**", constituted by the following regions of Italy: Valle D'Aosta, Piemonte, Liguria, Lombardia, Trentino, Veneto, Friuli Venezia Giulia and **Emilia Romagna**.

In order to obtain a single value of the selling price of the excess of electricity, firstly, it was extracted the relevant data for the case that it would be the prices of the Nord market.

	Prezzi 2024 (Euro/MWh) - NORD									
	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**
Fascia 1	103.42	90.34	89.79	76.6	90.5	99.56	105.87	116.77	115.73	114.48
Fascia 2	97.39	84.17	78.74	77.19	86.34	91.26	103.3	116.36	104.55	108.15
Fascia 3	87.48	72.48	66.03	63.32	65.88	76.47	96.94	116.14	90.79	100.07

Figure 81 - Monthly average prices for Nord market

Then, it was calculated the average price for each time band (fascia).

	Average price	
	[€/MWh]	[€/kWh]
Fascia 1	100.306	**0.100306**
Fascia 2	94.745	**0.094745**
Fascia 3	83.56	**0.08356**

Figure 82 - Average prices for Nord market

Lastly, since the excess of electricity will be sold in all the three different types of time bands along the week or month it was necessary to do a weighted average to obtain the final price.

Fascia	Days	Weight factor	Average price	Weighted value	Final price [€/kWh]
1	5	0.71	0.10031	0.07165	**0.0971**
2	1	0.14	0.09475	0.01354	
3	1	0.14	0.08356	0.01194	

Figure 83 - Final price for selling the excess of electricity

Thus, the price of the *Electrical Energy injected to the network* is: **0.0971 €/kWh**

4.11.3. Self-consumption Electricity

Self-consumption Electricity: → **0 €/kWh**

4.11.4. Natural gas

Combustibile	valore energetico
gasolio	10 kWh/l
gas liquido	12,8 kWh/kg
gas metano	9,8 kWh/m³
pellet	4,8 kWh/kg
minuzzoli di legno (cippato)	4,2 - 4,9 kWh/kg
legna spezzata (mista)	4,3 kWh/kg

Consumo annuale di 7.000 kWh

Combustibile	Prezzo unitario medio	Prezzo medio per kWh	Confronto %
Gasolio	1,365 €/l	0,137 €	100%
Gas liquido (in cisterna)	3,485 €/kg	0,272 €	199%
Gas metano (fornitore più favorevole)	1,313 €/m³	0,134 €	99%
Pellets	0,406 €/kg	0,085 €	62%
Minuzzoli di legno (cippato)	0,153 €/kg	0,034 €	25%
Legna spezzata (mista)	0,186 €/kg	0,043 €	32%
Teleriscaldamento (biomassa)*	0,26 €/kWh	0,126 €	93%

Situazione: 1 ottobre 2024
tutti i prezzi incl. IVA
* incl. eventuale tassa fissa annuale

Figure 84 – Energetic value and Price per kWh of Natural gas [51]

Conversion factor of natural gas: 9,8 $kWh/_{m^3}$

$$\frac{1{,}313 \ {}^{€}/_{m^3}}{9{,}8 \ {}^{kWh}/_{m^3}} = 0{,}134 \ {}^{€}/_{kWh}$$

Finally, the price of *natural gas is:* **0,134 €/kWh**

4.11.5. PV panel cost

Parameter	Value
PV system investment cost	1,000 €/kWh if P>20kW; 1,600 if 6≤P≤20 and 2,000 €/kWh if P<6kW*
PV O&M cost	2%/y (of Inv. cost)
BT investment cost (with extra-cost of hybrid inverter)	500 €/kWh*
BT replacement cost	250 €/kWh
BT lifetime	10 years
Maximum BT SOC	1
Minimum BT SOC	0.1
BT discharging efficiency	0.95
BT charging efficiency	0.95
Cost of PV electricity sold to the grid	0.10 €/kWh
Cost of electricity withdrawn from the grid	0.22 €/kWh
Discount rate	5%
System lifetime	20 years

*https://www.solareb2b.it/documenti/ (in Italian)

Figure 85 – PV system investment cost [52]

4.11.6. Thermal collector cost [53]

Vacuum Tube Solar Collectors: 1200 ${}^{€}/_{m^2}$

Flat-plate Solar Collectors: 800 ${}^{€}/_{m^2}$

4.12. Final Calculation

Once the solar radiation simulations, the estimation of the useful roof areas and the calculation of PV and thermal production were done, the next step was the integration of all the data obtained to calculate the feasibility of the project.

For each case scenario, the following values were calculated:

- PV production
- Thermal solar production
- Electricity and thermal consumption
- Auto consumption
- Surplus energy
- Losses due to orientation

The final calculations allow to observe what percentage of the total residential consumption can be supplied by local renewable sources. Also, it was determined the surplus production of electricity, which opens the possibility of injecting this extra energy into the grid (selected option in this thesis) or using a storage system (not analysed here).

These results constitute the bases for the subsequent economic analysis, where it is evaluated the cost-benefit analysis of each configuration of technologies. Overall, the final calculation shows the technical potential of the city of Parma to establish a Renewable Energy Community (CER), with a good grade of auto-sufficiency from the exploitation of the urban solar energy.

In the following are shown the results of the final calculations of the three case scenarios:

Case scenario 1: *23% nominal efficiency PV (100% useful area)*

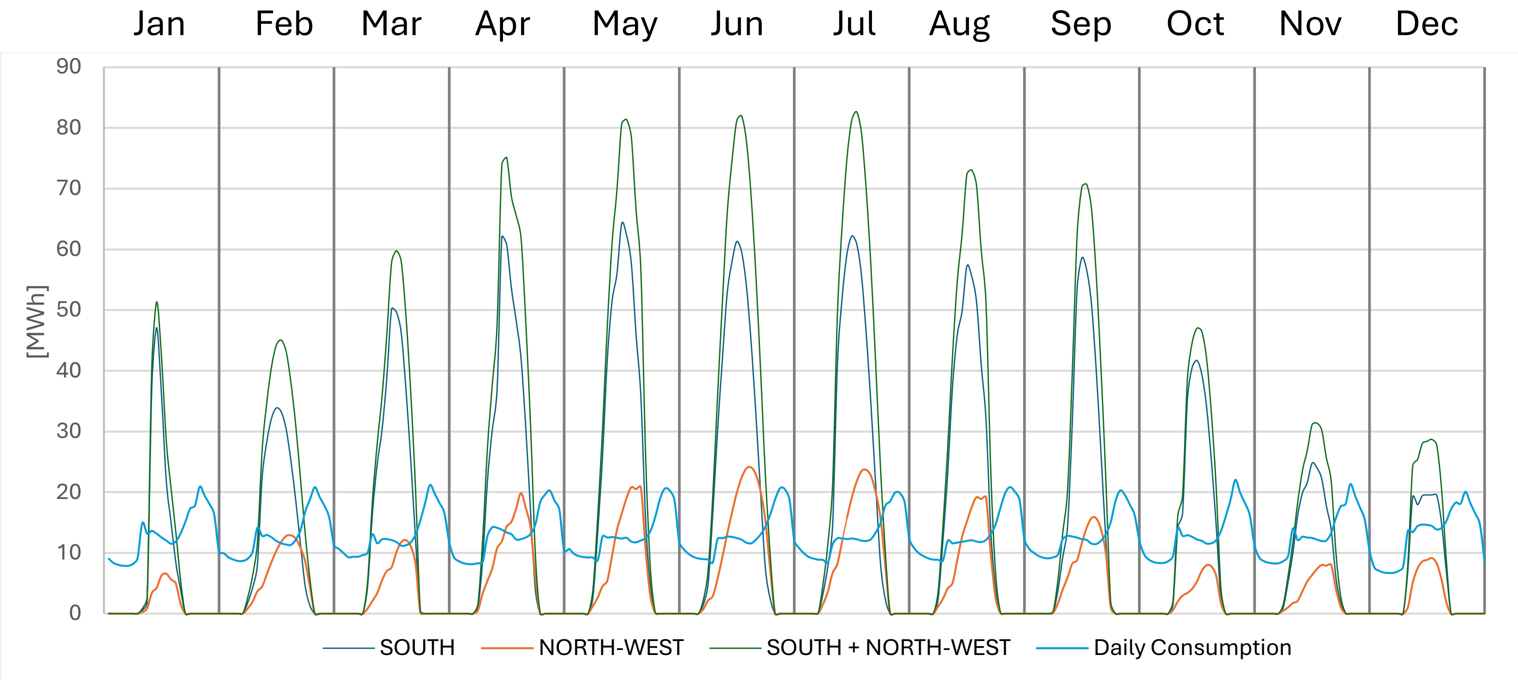

Figure 86 – Daily PV production and consumption - Case scenario 1

	Electrical production		
	SOUTH+ NORTH-WEST		
	[kWh/day]	Days	[kWh/month]
January	206,306	31	6,395,480
February	365,711	28	10,239,915
March	415,325	31	12,875,063
April	559,797	30	16,793,921
May	625,373	31	19,386,562
June	692,769	30	20,783,071
July	671,184	31	20,806,717
August	561,574	31	17,408,807
September	468,804	30	14,064,114
October	314,615	31	9,753,069
November	241,104	30	7,233,111
December	144,457	31	4,478,175

SOUTH + NORTH-WEST

Month	DAILY Auto-consumption [kWh/day]	DAILY For selling (extra) [kWh/day]	Days	MONTHLY Auto-consumption [kWh/month]	MONTHLY For selling (extra) [kWh/month]
January	83,810	122,495	31	2,598,120	3,797,360
February	149,500	216,211	28	4,186,012	6,053,903
March	126,047	289,277	31	3,907,467	8,967,595
April	151,289	408,508	30	4,538,671	12,255,250
May	143,491	481,882	31	4,448,213	14,938,348
June	164,410	528,359	30	4,932,309	15,850,762
July	161,211	509,974	31	4,997,537	15,809,180
August	139,154	422,421	31	4,313,764	13,095,043
September	130,673	338,130	30	3,920,200	10,143,913
October	118,052	196,563	31	3,659,624	6,093,445
November	131,586	109,518	30	3,947,570	3,285,541
December	116,715	83,735	31	3,618,158	2,595,797

SOUTH + NORTH-WEST	
ECONOMICAL	
Auto-consumption	For selling (extra)
€ 758,131.39	€ 368,723.68
€ 1,221,478.29	€ 587,833.96
€ 1,140,198.90	€ 870,753.51
€ 1,324,384.22	€ 1,189,984.76
€ 1,297,988.67	€ 1,450,513.61
€ 1,439,247.86	€ 1,539,108.98
€ 1,458,281.36	€ 1,535,071.34
€ 1,258,756.22	€ 1,271,528.70
€ 1,143,914.49	€ 984,973.97
€ 1,067,878.32	€ 591,673.53
€ 1,151,901.05	€ 319,026.02
€ 1,055,778.47	€ 252,051.91
€ 14,317,939.24	€ 10,961,243.95
€ 25,279,183.20	

Case scenario 2: *23% nominal efficiency PV (86% area) + vacuum SC*

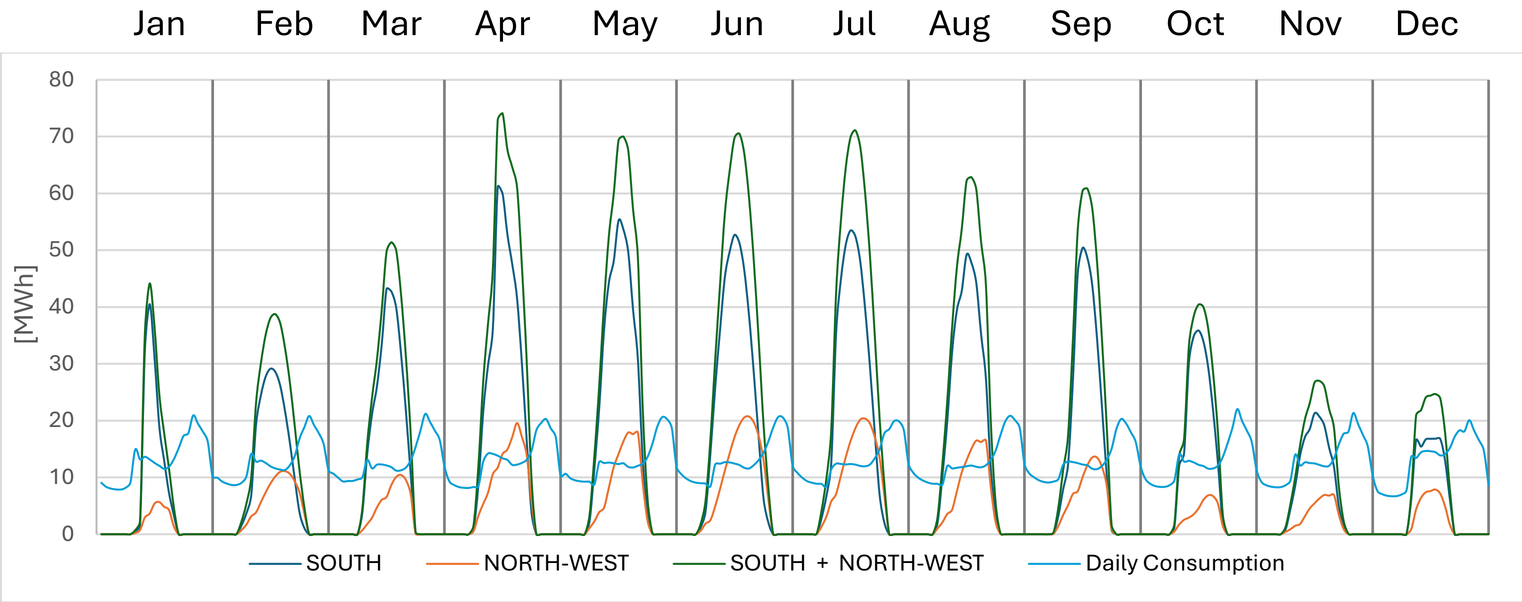

Figure 87 - Daily PV production and consumption - Case scenario 2

	Electrical production		
	SOUTH+ NORTH-WEST		
	[kWh/day]	Days	[kWh/month]
January	177,423	31	5,500,113
February	314,512	28	8,806,327
March	357,179	31	11,072,554
April	552,035	30	16,561,045
May	537,821	31	16,672,443
June	595,781	30	17,873,441
July	577,219	31	17,893,776
August	482,954	31	14,971,574
September	403,171	30	12,095,138
October	270,569	31	8,387,640
November	207,349	30	6,220,476
December	124,233	31	3,851,231

	SOUTH + NORTH-WEST				
	DAILY			MONTHLY	
Month	Auto-consumption [kWh/day]	For selling (extra) [kWh/day]	Days	Auto-consumption [kWh/month]	For selling (extra) [kWh/month]
January	82,168	95,255	31	2,547,212	2,952,901
February	144,031	170,480	28	4,032,876	4,773,451
March	125,239	231,940	31	3,882,405	7,190,149
April	151,133	400,902	30	4,533,982	12,027,064
May	141,888	395,933	31	4,398,517	12,273,926
June	161,827	433,955	30	4,854,795	13,018,646
July	159,091	418,128	31	4,931,806	12,961,971
August	137,708	345,246	31	4,268,951	10,702,623
September	128,735	274,436	30	3,862,044	8,233,094
October	116,995	153,574	31	3,626,838	4,760,802
November	127,069	80,280	30	3,812,080	2,408,395
December	114,308	58,080	31	3,543,533	1,800,468

SOUTH + NORTH-WEST	
ECONOMICAL	
Auto-consumption	For selling (extra)
€ 743,276.46	€ 286,726.68
€ 1,176,793.23	€ 463,502.05
€ 1,132,885.65	€ 698,163.49
€ 1,323,015.86	€ 1,167,827.87
€ 1,283,487.12	€ 1,191,798.26
€ 1,416,629.29	€ 1,264,110.51
€ 1,439,100.88	€ 1,258,607.37
€ 1,245,680.01	€ 1,039,224.65
€ 1,126,944.30	€ 799,433.44
€ 1,058,311.19	€ 462,273.88
€ 1,112,365.08	€ 233,855.18
€ 1,034,002.88	€ 174,825.49
€ 14,092,491.97	€ 9,040,348.87
€ 23,132,840.83	

THERMAL

	Total consumption [MWh/month]	Total production [MWh/month]	Self-consumption [MWh/month]	Revenue
January	9,083	1,737	1,737	€ 232,725.91
February	8,204	2,715	2,715	€ 363,818.82
March	9,083	4,860	4,860	€ 651,185.81
April	8,790	6,245	6,245	€ 836,795.53
May	9,083	8,184	8,184	€ 1,096,672.10
June	8,790	8,743	8,743	€ 1,171,511.82
July	9,083	9,030	9,030	€ 1,209,999.46
August	9,083	8,194	8,194	€ 1,098,025.67
September	8,790	6,212	6,212	€ 832,401.86
October	9,083	4,288	4,288	€ 574,566.61
November	8,790	2,082	2,082	€ 278,932.52
December	9,083	1,307	1,307	€ 175,153.86
				€ 8,521,789.96

Case scenario 3: *23% nominal efficiency PV (86.5% area) + flat SC*

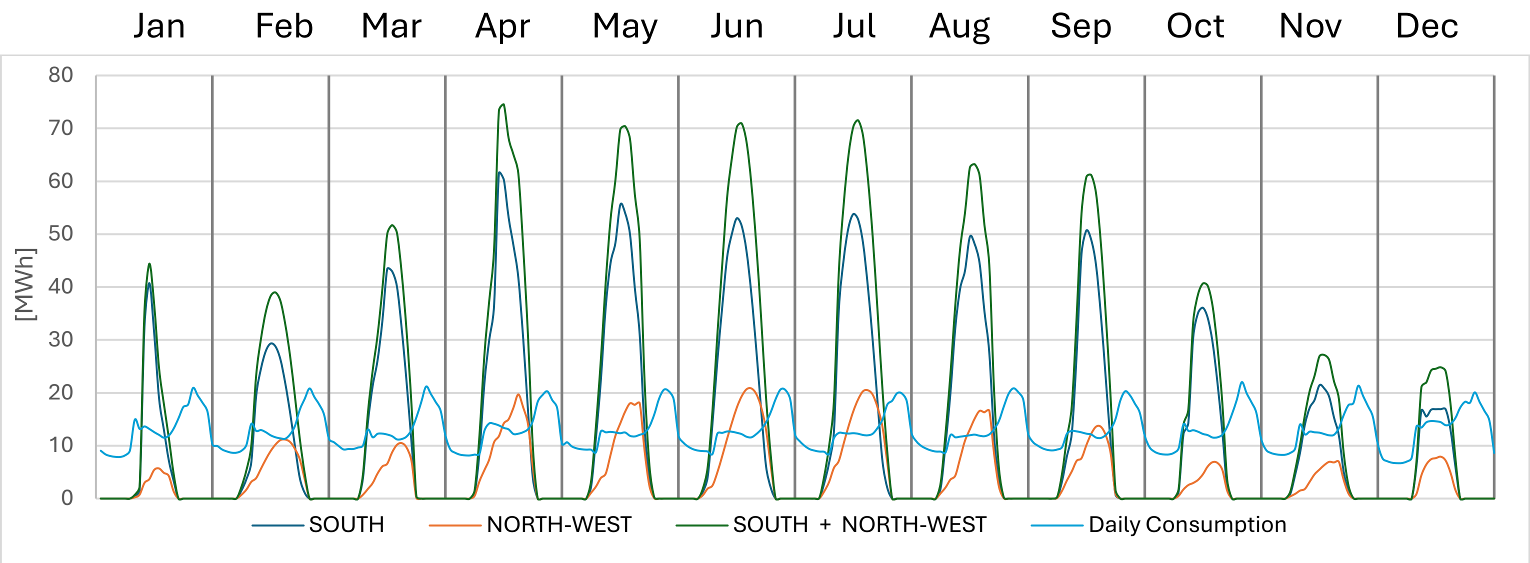

Figure 88 - Daily PV production and consumption - Case scenario 3

	Electrical production		
	SOUTH+ NORTH-WEST		
	[kWh/day]	Days	[kWh/month]
January	178,455	31	5,532,090
February	316,340	28	8,857,526
March	359,256	31	11,136,929
April	555,244	30	16,657,330
May	540,948	31	16,769,376
June	599,245	30	17,977,357
July	580,575	31	17,997,810
August	485,762	31	15,058,618
September	405,515	30	12,165,458
October	272,142	31	8,436,405
November	208,555	30	6,256,641
December	124,956	31	3,873,621

	SOUTH + NORTH-WEST				
	DAILY		Days	MONTHLY	
Month	Auto-consumption [kWh/day]	For selling (extra) [kWh/day]		Auto-consumption [kWh/month]	For selling (extra) [kWh/month]
January	82,280	96,175	31	2,550,681	2,981,410
February	144,227	172,114	28	4,038,345	4,819,181
March	125,268	233,988	31	3,883,300	7,253,629
April	151,197	404,047	30	4,535,921	12,121,410
May	141,945	399,003	31	4,400,291	12,369,084
June	161,919	437,326	30	4,857,564	13,119,793
July	159,166	421,408	31	4,934,153	13,063,657
August	137,760	348,002	31	4,270,552	10,788,066
September	128,841	276,675	30	3,865,216	8,300,242
October	117,106	155,036	31	3,630,298	4,806,107
November	127,231	81,324	30	3,816,919	2,439,722
December	114,393	58,996	31	3,546,198	1,828,873

SOUTH + NORTH-WEST	
ECONOMICAL	
Auto-consumption	For selling (extra)
€ 744,288.65	€ 289,494.87
€ 1,178,389.12	€ 467,942.48
€ 1,133,146.84	€ 704,327.42
€ 1,323,581.63	€ 1,176,988.89
€ 1,284,005.03	€ 1,201,038.09
€ 1,417,437.10	€ 1,273,931.89
€ 1,439,785.90	€ 1,268,481.08
€ 1,246,147.02	€ 1,047,521.22
€ 1,127,870.16	€ 805,953.48
€ 1,059,320.92	€ 466,673.00
€ 1,113,777.08	€ 236,897.00
€ 1,034,780.58	€ 177,583.58
€ 14,102,530.03	€ 9,116,832.98
€ 23,219,363.01	

THERMAL

	Total consumption [MWh/month]	Total production [MWh/month]	Self-consumption [MWh/month]	Revenue
January	9,083	-	-	€ -
February	8,204	576	576	€ 1,099,335.01
March	9,083	2,919	2,919	€ 1,217,120.90
April	8,790	4,467	4,467	€ 1,177,858.94
May	9,083	6,971	6,971	€ 1,217,120.90
June	8,790	8,294	8,294	€ 1,177,858.94
July	9,083	8,922	8,922	€ 1,217,120.90
August	9,083	8,041	8,041	€ 1,217,120.90
September	8,790	5,557	5,557	€ 1,177,858.94
October	9,083	3,178	3,178	€ 1,217,120.90
November	8,790	261	261	€ 1,177,858.94
December	9,083	-	-	€ -
				€ 11,896,375.26

5. ECONOMIC ANALYSIS and ENERGETIC INDEXES

ELECTRICAL ENERGY

Costs

Electrical Energy withdrawn from the network: → **0,2918 €/kWh**

Electrical Energy injected to the network: → **0.10 €/kWh**

Self-consumption Electricity: → **0 €/kWh**

Photovoltaic Panel Cost (1 kWp about 5-8 m2) → (I took 1kWp = 7m2)

1,000 €/kW if P > 20 kW; 1,600 €/kW if 6 ≤ P ≤ 20 and 2,000 €/kW if P < 6 kW

Revenue [R] = [€/year]

1. If PV energy production is equal or lower to user consumption, the revenues R are equal to:

$$(E_{el,PV} - E_{el,user}) \leq 0 \quad \Longrightarrow \quad R = E_{el,PV} \cdot 0{,}2918 \quad [€]$$

2. If PV energy production is higher than user consumption (with over-production), the revenues are:

$$(E_{el,PV} - E_{el,user}) > 0 \quad \Longrightarrow \quad R = E_{el,user} \cdot 0{,}2918 + (E_{el,PV} - E_{el,user}) \cdot 0{,}10 \quad [€]$$

Simple Payback Time (SPT)

The SPT is the amount of time (in years) necessary to recover the investment (not considering discount cash flow methods). It can be defined as:

$$\boldsymbol{SPT = C_{inv,PV}/R} \quad [\boldsymbol{years}]$$

Where:

The 'initial investment cost $\boldsymbol{C_{inv,PV}}$'depends on the power of the PV systems. Therefore, the value of $\boldsymbol{C_{PV}}$ is going to vary between 1000 €/kWp, 1600 €/kWp or 2000 €/kWp according to the power of each PV system installed in the buildings

$C_{inv,PV} = C_{PV} \cdot kW_p$ [€] and the potential PV power is: $kW_p = \frac{A_C}{6-8} [kW]$

W_p $[W]$: Peak/Nominal Power of PV system (generally $1\ kW_p$ corresponds about $5-8\ m^2$).

$A_C\ [m^2]$: *area for PV system (values from QGIS analysis)*

THERMAL ENERGY

Costs

Natural gas: → **0,134 €/kWh**

Solar Thermal Collector: → Vacuum Tube Solar Collector: **1200 €/m2**

→ Flat-plate Solar Collector: **800 €/m2**

Revenue [R] = [€/year]

In this case we only have one option since the overproduction cannot be sold.

When the ST energy production is equal or lower than the user consumption, the revenues are equal to:

$$(E_{th,ST} - E_{th,user}) \leq 0 \quad \Longrightarrow \quad R = E_{th,ST} \cdot 0{,}134 \qquad [€]$$

When ST energy production exceeds user consumption, excess heat can only be dissipated and no money is made. Then, because the hot water cannot be fed into a network (like electricity), it is inconvenient to generate more energy than is needed.

Simple Payback Time (SPT)

$$SPT = {C_{inv,PV}}/{R} \qquad [years]$$

5.1. Case scenario 1 (only PV)

In this case scenario was assumed that all the optimum useful area is utilised for the installation of photovoltaic panels with a maximum efficiency of 23%

PV panel – 23% efficiency

PV system - 23% efficiency		
Revenue		
Autoconsumed electricity	€	14,317,939.24
Surplus sold electricity	€	10,961,243.95
	€	25,279,183.20
Initial investment		
PV panels and system	€	109,332,640.84
	€	109,332,640.84
Simple Payback Time [years]		**4.3**

Table 1 - Economic Analysis

5.2. Case scenario 2 (PV + Vacuum Tube SC)

In this case was searched the optimal combination between the PV panels and **Vacuum Tube** solar collectors. In order to achieve this goal, it was analysed the data obtained in the case scenario 1 (all optimum area for each technology). It can be observed that the main problem was in the thermal energy production because it had been obtained a huge overproduction in all the months of the year. The issue with thermal overproduction is that it cannot be stored or sold in the market, therefore there is no point of exceeding the consumption. Also, reaching such levels of production imply an extremely high investment cost, making harder recover it over time.

Taking all this in consideration, firstly it was dimensioned the solar collectors in order to equal the consumption of the summer months (in this case it was chosen July), where the solar irradiation is greater hence also the thermal production. In this way, the excess of thermal energy is never reached, solving the problem related to overproduction. To achieve this, it was calculated that is necessary to dedicate a **14%** of the total optimal roof area of the buildings for the solar collectors.

All the remaining optimal area (86%) was utilized for the PV panels since with them is easier reaching a good SPT value.

Summarizing, these are the optimized values of area used for each type of technology:

- **Vacuum Tube Solar collectors** → 14% of OPTIMAL roof area
- **PV panels (23% efficiency)** → 86% of OPTIMAL roof area

Finally, the tables related to the initial investment, revenues and SPT values are showed:

PV panels [23% efficiency] + Vacuum Tube Solar Collectors		
Revenue		
Autoconsumed electricity	€	14,092,491.97
Surplus sold electricity	€	9,040,348.87
STC hot water production	€	8,521,789.96
	€	31,654,630.80
Initial investment		
PV panels and system	€	98,268,614.38
Solar collectors system	€	79,914,582.62
	€	178,183,196.99
Simple Payback Time [years]		5.6

Table 2 - Combined Economic Analysis

5.3. Case scenario 3 (PV + Flat tube SC)

Lastly, it was analysed the optimal combination between the PV panels and **Flat-tube solar collectors**.

The same procedure that in the "case scenario 2" was used to determine the percentage of the useful roof area to be utilized for each technology.

Summarizing, these are the optimized values of area used for each type of technology:

- **Flat-Tube Solar collectors** → 13,5% of OPTIMAL roof area
- **PV panels (23% efficiency)** → 86,5% of OPTIMAL roof area

PV panels [23% efficiency] + Flat plate Solar Collectors		
Revenue		
Autoconsumed electricity	€	14,102,530.03
Surplus sold electricity	€	9,116,832.98
STC hot water production	€	11,896,375.26
	€	35,115,738.27
Initial investment		
PV panels and system	€	98,631,280.93
Solar collectors system	€	51,373,660.26
	€	150,004,941.19
Simple Payback Time [years]	**4.3**	

Table 3 - Combined Economic Analysis

5.4. Energy Indexes (SSI and SCI)

In order to make the cost-benefit analyses, the evaluation of the self-sufficiency and the self-consumption is compulsory. The ratio between the self-consumption and the total consumption is the **self-sufficiency index (SSI)** and the ratio between the self-consumption and the total production is the **self-consumption index (SCI)**. The first index is important from an environmental and social point of view, meanwhile the second index considers the technical and economic investments and benefits. The optimization of project could be reached with high SSI and high SCI, however, due to the nature of the sun (daily and seasonal behaviour) solar technologies can have an annually SSI lower than 50%. [54]

$$SSI = \frac{Self\ consumption\ *}{Total\ consumption}$$

$$SCI = \frac{Self\ consumption\ *}{Total\ production}$$

**Where the self-consumer is defined as a user that generates renewable energy for its own consumption without any commercial activity*

Following, the indexes were calculated for the three case scenarios. The data utilized was always from the **South+North-West** analysis.

ONLY PV TECHNOLOGY

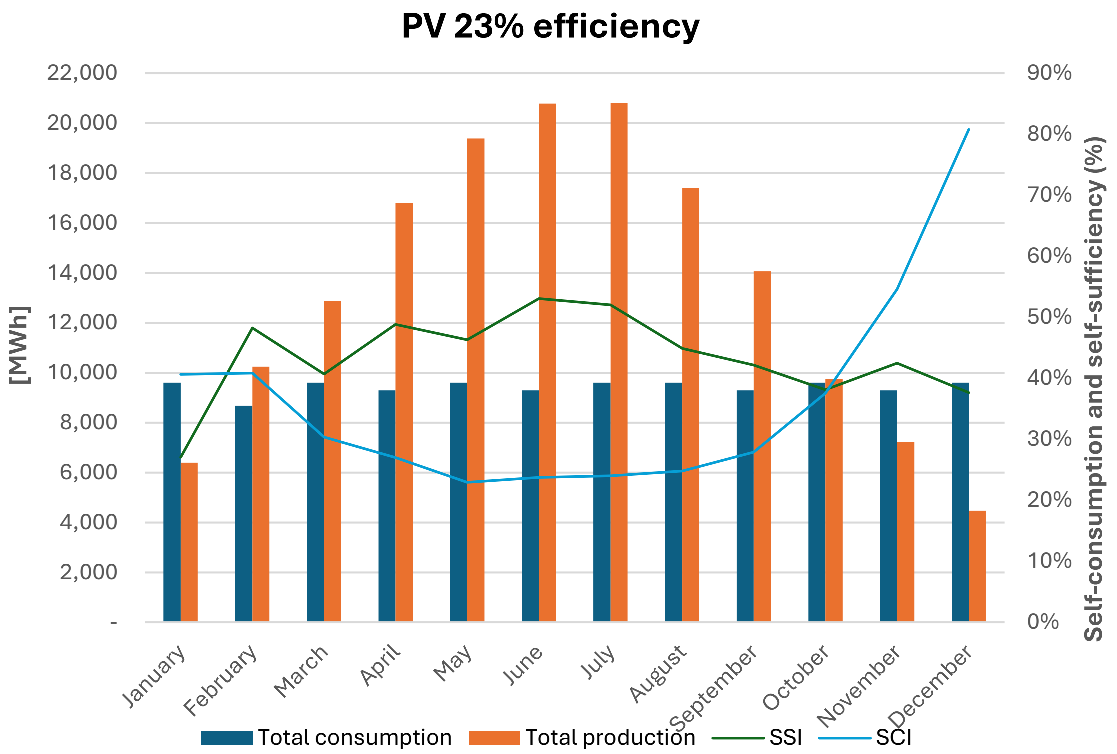

Figure 89 - Monthly energy consumption for electricity and PV production with 100% of optimal roof area

PV system + Vacuum Tube SC

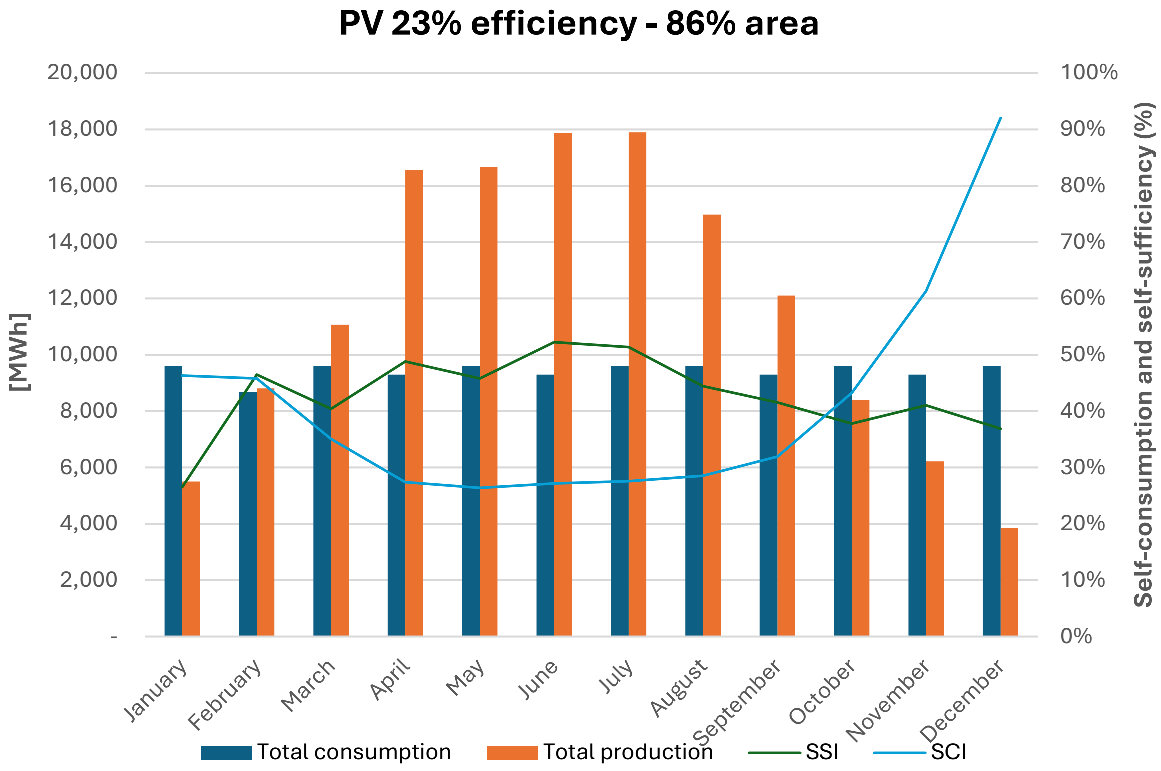

Figure 90 - Monthly energy consumption for electricity and PV production with 86% of optimal roof area

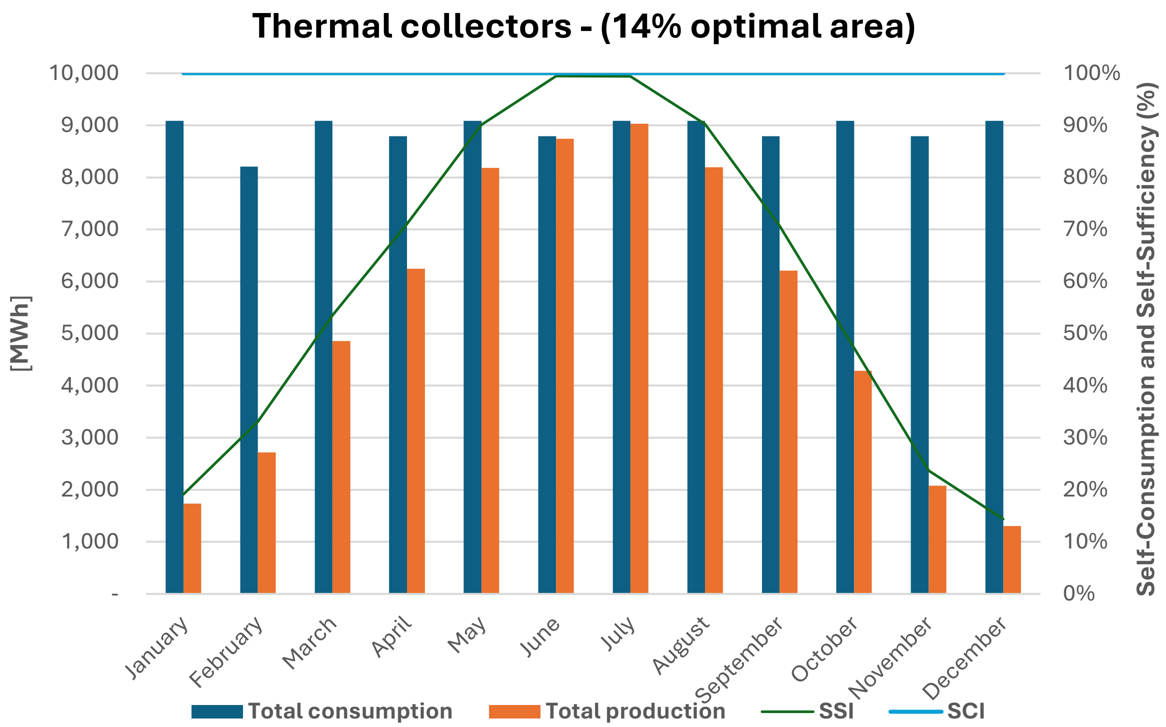

Figure 91 - Monthly energy consumption for DHW and production by STC with 14% of the optimal roof area

PV system + Flat Tube SC

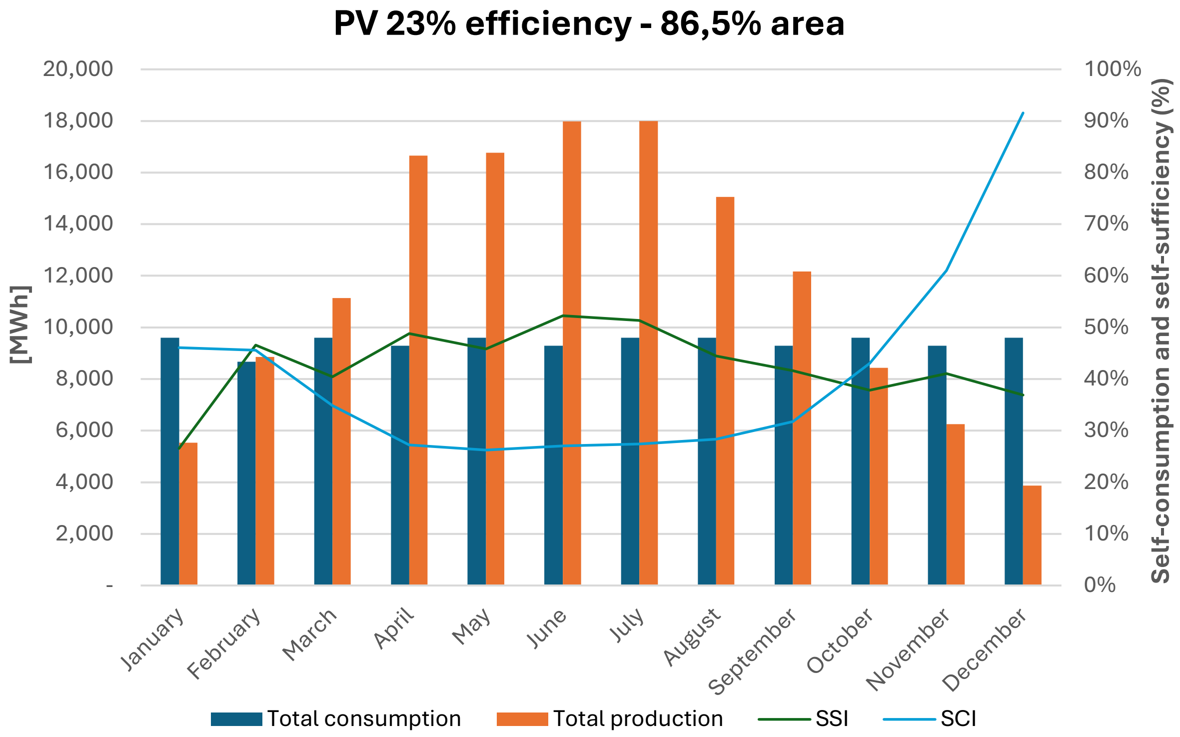

Figure 92 - Monthly energy consumption for electricity and PV production with 86.5% of optimal roof area

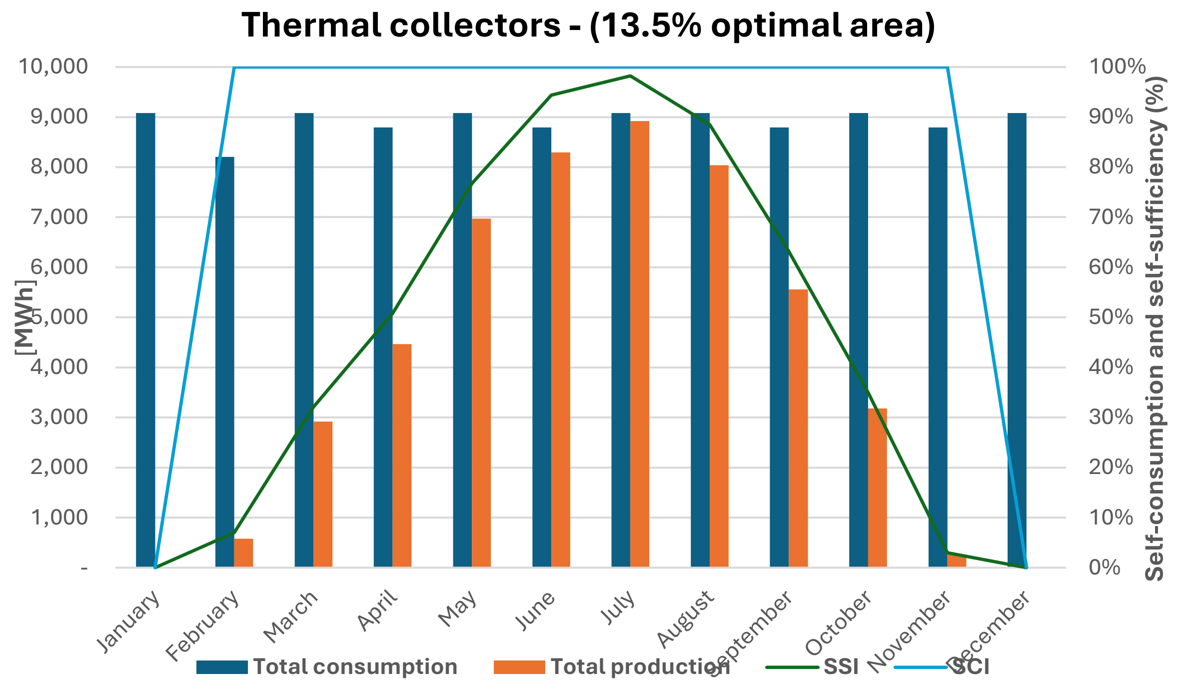

Figure 93 - Monthly energy consumption for DHW and production by STC with 13.5% of the optimal roof area

Conclusion

The main goal of the analysis was to maximize the collective energy auto-consumption and auto-sufficiency in the Renewable Energy Community (CER), guarantying at the same time the economic feasibility of the project through a cost-benefit analysis. For this reason, not only the energy production and consumption were considered, but also the surplus electricity generated that can be sold to the grid and the available incentives for the creation of a CER. On the other hand, the production of surplus thermal energy was minimized since it does not bring a direct economic benefit and it is also not possible to storage it. In conclusion, the priority was to achieve a greater local energy independence in a sustainable and profitable way, more than simply obtaining the highest possible economic return.

6. CONCLUSIONS

This thesis explored the feasibility of implementing a Renewable Energy Community (REC or CER in Italian) in the city of Parma, with a comprehensive analysis considering technical, economic, and regulatory aspects.

With the help of GIS software, particularly QGIS, a detailed simulation of annual solar irradiation on the roofs of residential buildings was carried out, considering parameters such as slope, orientation, and shading. The results were cross-validated with reliable data sources like PVGIS and ENEA, demonstrating good accuracy with an acceptable Mean Absolute Percentage Error (MAPE). Based on this, buildings were filtered and selected using defined geometric and energy-based criteria to identify the most suitable for the installation of photovoltaic (PV) and solar thermal systems.

The simulations showed that while Parma's solar potential is moderate compared to southern Italian cities, it is sufficient to support meaningful renewable energy generation. This is especially true when installation strategies focus on maximizing use of high-irradiance roof surfaces (above 1,400 kWh/m^2/year).

From an economic point of view, the three analysed case scenarios (only PV, PV + vacuum tube solar collectors, PV + flat plate collectors) indicated that the project is financially viable. The most effective configuration, combining both PV and thermal technologies, demonstrated the best performance in terms of energy self-consumption and reduction of energy dependence. In addition, the economic benefits are further amplified by government incentives and reduced transmission losses.

On the regulatory side, the recent approval of Legislative Decree No. 199/2021 has given a clearer and more supportive framework for the development of CERs in Italy, including national rates for feeding electricity into the grid and investment contributions, in particular for municipalities with less than 5,000 inhabitants. Although some gaps remain (e.g., lack of support for geothermal energy), the legislative context is becoming increasingly favourable.

In conclusion, the city of Parma demonstrates strong technical, social, and regulatory conditions to support the development of a Renewable Energy Community. The results confirm the initial expectations and show that local energy production, combined with efficient use and active citizen participation, offers a practical and replicable model toward a more sustainable energy future in Italian urban environments.

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