POLITECNICO DI TORINO

Master's Degree in Energy engineering

Master's Thesis

Innovative solutions in the rooftop photovoltaic field: techno-economical feasibility and scenarios simulation

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Summary

Nowadays, the energy transition imposes a huge increase in renewable power sources. So, energy utilities, such as Edison S.p.A. are evaluating whether to increase the capacity installed of photovoltaic (PV) plants. Specifically, one of the sectors that this technology can reach is the rooftop application which presents specific aspects and problems. In this framework, this study aims to find technological devices that allow the increase of the techno-economical feasibility of rooftop PV plants. The work began with a literature review to find out the market trend in PV technology in order to establish which technology can become the golden standard in the near future. Furthermore, following the suggestion found in the literature, market research that identifies suitable panel models has been performed. The results of this part individuated 4 typologies of panels. Later, these devices have been tested on PV design software to compare their advantages with the actual standards in some case studies. Since the results of these simulations were not coherent, the individuation of a unique trend was difficult. As a result, the objective of this thesis was to develop a numerical simulation tool that is able to generalize the problem, in order to get results that can statistically quantify the advantages of new possible solutions on actual PV panels used commercially. The model evaluates the capacity of these devices on rooftops with different sizes and obstacle dispositions, with the goal to find the one that maximizes the revenue of the investments. In fact, the model allows to compare the financial performance of the different plants and to calculate a number of key performance indicators (KPI) to establish which is the best investment for each type of rooftop. Subsequently, to obtain a forecast for the next future market, a sensitivity analysis on some of the input parameters of the model, such as the price of energy and the energy load of the buildings, has been performed. To conclude the work, an analysis of actual Italian residential buildings has been done, to quantify the possible market share that the technologies can reach and so the possible revenue induced by the increase of the market dimension.

Table of Contents

List of Tables

List of Figures

Acronyms

PV
: Photovoltaic panel

IRR
: Internal rate of return

NPV
: Net present value

BU
: Business unit

POD
: point of delivery

IBC
: Interdigitated back contact

SHJ
: Silicon hetero junction

REC
: Renewable energy community

EC
: energy community

LCOE
: Levelized cost of energy

CEC

common energy community

KPI

Key performance indicator

BC

Benchmark

Chapter 1

Introduction

1.1 Motivation and context

The increasing electricity demand, coupled with concerns about climate change and the depletion of fossil fuels, has led to a growing interest in renewable energy sources such as photovoltaic (PV) systems. PV systems use semiconductor materials to convert solar energy into electricity and can be installed on rooftops or other surfaces to generate electricity at the point of consumption. Rooftop PV systems have the potential to reduce carbon emissions, improve energy security, and lower electricity costs. They can also contribute to the decentralization of the electricity grid and the integration of renewable energy into the built environment. However, the design and placement of PV panels on rooftops is a complex task that involves trade-offs between energy production, cost, and aesthetics. Optimizing the placement and orientation of PV panels can significantly increase the performance and economic viability of PV systems. There are several different approaches to PV panel allocation, including heuristic algorithms, optimization algorithms, and machine learning algorithms. Each approach has its own strengths and limitations and may be more or less suitable depending on the specific context and objectives. In this thesis, the principle aim is to individuate the best possible device currently available in the market by a techno-economic feasibility study.

1.2 State of Art

PV panels are based on the transformation of solar energy into electrical energy. This is possible using the photoelectric effect, in particular joining two or more layers with different concentrations of positive and negative charges. In the next part for simplicity, there will be two layers of silicon: one doped with Boron (P zone) and the second with Phosphorous (N zone). Due to the different charge concentrations, the silicon in the jointing zone has an initial electric potential. The charge will move according to the gradient creating a depletion region that avoids the other charge to pass through this region. In this way, the panel when not irradiated works as a diode. In fact, in case of external potential applied, the current is approximately zero in a direction according to the depletion region's electric potential (reverse current); while in the other sense in not changed (Forward current). In case of irradiation, the photons transfer energy to electrons. If the energy is enough, the electron escapes the atoms and tries to follow the voltage direction. In case of no recombination, the electron can leave the panel and go to the load, in this way a current is created. The imagine 1.1 resumes the general structure of a PV cell.

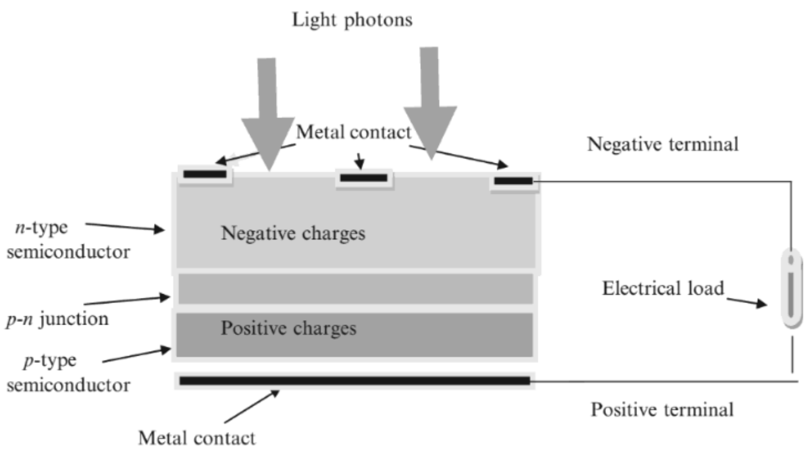

Figure 1.1: Schematic design of the key components of a PV cell [1]

The cells are linked in parallel or in series to create a panel. In order to connect the cell, connections called busbars or fingers are created which collect the current that should go to the load. The structure of a typical PV panel, also with the protection glass and the EVA encapsulation layer (insulation for the silicon) is shown in figure 1.2.

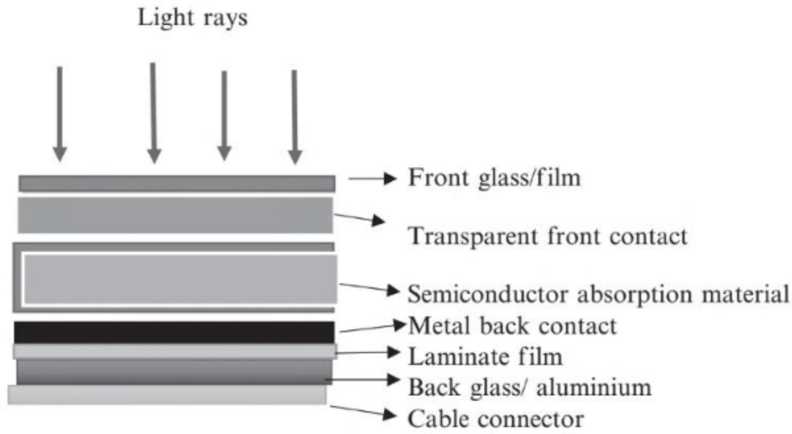

Figure 1.2: Schematic design of the multiple layers of a PV panel [1]

However, it is also important to explain the reason for energy losses. According with G. K . Singh [2] there are:

- The spectral response not matching with the irradiation. In fact, in case the photons' energy is not equal to the energy needed by the electrons, the energy not used is lost in form of heat.
- charge recombination, not every electron created is useful to create the current, part of them recombines with a vacancy that there is the depletion region.
- electric losses due to the busbars and the fingers due to electric resistance. Indeed that creates losses
- the panel is not perfectly insulated in the lateral direction, and that is another reason that creates electric loses

These four factors determine the efficiency in standard conditions. Other losses that are related to the environment can be:

- Thermal losses, the panel works better when the cell temperature is lower, which is due to the fact that the atomic agitation restricts the movement of the electrons
- degradation of the panel due to the reduction of electrons in the panel
- dust or other imperfections in the panel
- shadows

After this introduction on the technology, it is important to analyze the state of the art reached in the process of PV panel creation with different technical solutions and different materials adopted: Actually, the PV technologies commercially used are almost silicon-based and they are part of the II generation of PV technologies [3] with some other exceptions such as the CdTe and the CGIS that are mostly used in the thin film. Including also the most promising technology, it is important to talk about perovskite material, which is a solution that does not have already panels scale up but can be a possibility in the distant future. The table 1.1 summarizes the efficiency record for the different technologies found in the literature [4] [5] [6] [7]

	PERC	SHJ	IBC	IBC-SHJ	CdTe	CGIS	Perovskite
efficency	22.6%	24.7%	24.4%	26.1%	22.1%	22.6%	17.1%

Table 1.1: Efficiencies of different cell technologies at the actual state of art

1.2.1 Silicon technology

The state of art has the three most used solutions that are all based on monocrystalline silicon, in which the differences are the treatment applied or the position of the layer. In particular, there are:

- passivated emitter and rear locally diffused cell(PERC), this cell suffered from photocurrent losses due to shadowing from the front grid and non-radiative surface recombination due to the contacts.

- Interdigitated back contacts (IBC), in which all the contacts are positioned in the back of the panel to reduce the shadowing on the top and in order to reduce the resistive losses putting nearer the contacts

- Silicon hetero-junction (SHJ) that minimizes non-radiative recombination at the surfaces as a result of the contacts. Within the SHJ architecture, a thin film of intrinsic hydrogenated amorphous Si (i:a-Si) is introduced between the absorber (c-Si) and either an n-doped or a p-doped a-Si layer to decouple passivation from charge collection

Even if it is possible to combine the last two methods, the efficiency of the silicon technology has already reached a plateau and it is difficult to imagine another significant increase. In the image 1.3 a resume of the technology disposition can be found [5].

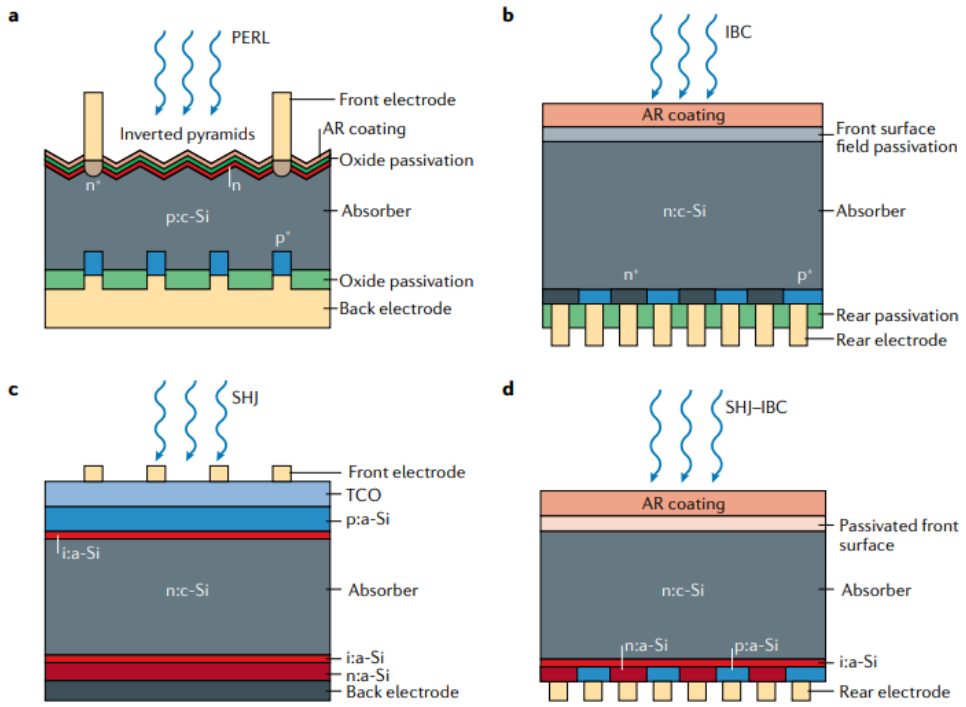

Figure 1.3: Schematic illustrations of different Si-based PV technologies [5]

1.2.2 Custom-shaped silicon panel

Custom-shaped PV panels are a type of photovoltaic panel that can be customized to fit specific surfaces or configurations, rather than being limited to a standard rectangular or square shape. These panels offer the potential to increase the coverage and efficiency of PV systems, particularly in situations where traditional panels may not be suitable, such as on curved roofs or between protrusions. Custom-shaped PV panels can also be used to create aesthetic or architectural effects, such as integrating PV panels into the design of a building or structure. While the design and manufacture of custom-shaped PV panels can be more complex and costly compared to traditional panels, they may offer benefits in terms of performance and aesthetics. Customization techniques for PV panels include laser cutting, water jet cutting, and flexible PV modules, and examples of custom-shaped PV panels include building-integrated photovoltaics, portable PV systems, and wearable PV devices. Factors that influence the performance and cost of custom-shaped PV panels include the efficiency and stability of the PV cells, the durability and reliability of the materials and processes, and the design and manufacturing techniques.

1.2.3 Thin film technology

Thin film technology based on CdTe and CGIS are included in this category. These two technologies are distinguished by the overlapping of different materials in order to increase the solar spectrum that they are unable to absorb. The first one, Cadmium, is definitely more common and more distributed than silicon but is a toxic material. However, most companies create procedures that allow working with it safely. The second one has a definitely more complex structure but there is none that is toxic. It also has quite a good thermal coefficient that gives it an advantage in hotter environments but it has a higher price due to the more complex structure. Both of the technologies have an efficiency lower than the golden standard of Silicon monocrystalline but is comparable with polycrystalline silicon. The figures 1.4 1.5 show the different structures.

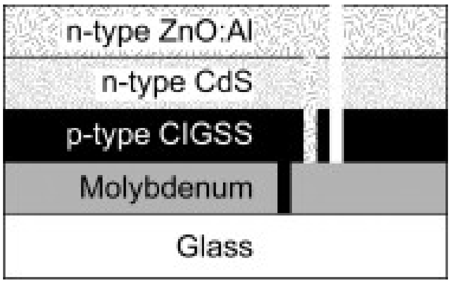

Figure 1.4: Composition and layers of a CIGS PV cell [2]

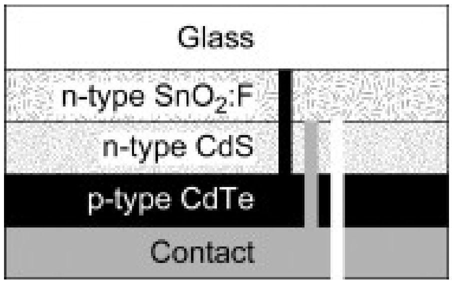

Figure 1.5: Composition and layers of a CdTe PV cell [2]

1.2.4 Perovskites cell

The goal of this cell is to increase the possible solar spectrum absorbed. In fact, this material which is as rare as silicon, has a better spectrum that currently allows reaching, in-lab test efficiency of around 25%, which also has to take into account the upscaling to the module that strongly reduces their efficiency. This material can be used in tandem with silicon or create an entire panel from it. The first solution is nowadays the most suitable because it combines the excellent manufacturing level of silicon with the advantage in terms of solar spectrum of Perovskite. Even if there are some issues in terms of coupling and also the current degradation of the perovskite cell is rapid, it is considerable for the future of PV technology. The image 1.6 is a possible scheme of this technology

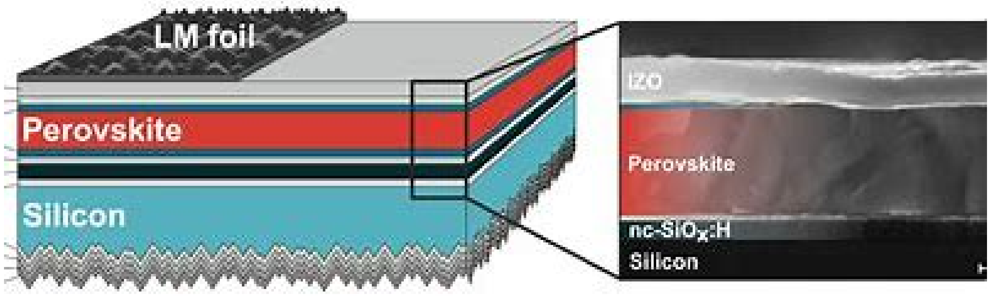

Figure 1.6: Scheme of a Perovskite cell in tandem solution proposed by [6]

1.2.5 PV diffusion in Italy per technology

In Italy, the market is actually saturated by silicon. In particular, now, polycrystalline silicon is the most used since it is the most affordable trade-off between efficiency and cost. The second most used is monocrystalline, and the rest of the market represents only 6%. Half of it is a thin film that is used in particular in considerably small size plants. Figure 1.7 shows the distribution of these technologies in Italy.

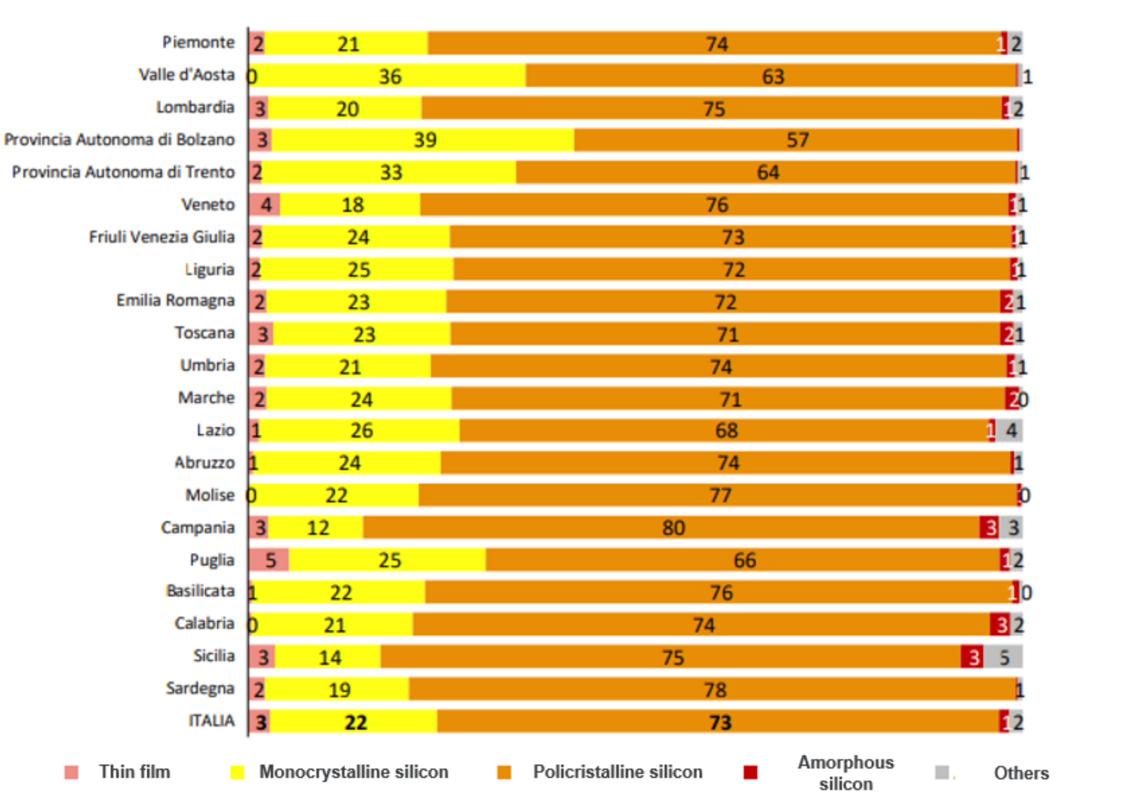

Figure 1.7: Percentual distribution of PV technology in Italy by region [8]

1.3 Rooftop Photovoltaic plant

Nowadays the world becomes more urban, with 54% of the population living in metropolitan areas [9] which is responsible for 60 to 70% of anthropogenic greenhouse gas emissions [10]. Cities themselves must become sustainable in their resources and demands. With limited available installation space, renewable energy generation within urban areas poses particular challenges due to limited space and high demand. For this reason, PV panels are a suitable solution for this problem since they can be installed on a small scale and decentralized on building rooftops in order to feed the energy demand of the city. Every year, rooftop plants are becoming more of an important resource, especially as it is financially profitable due to local politics that incentivize this technology.

1.3.1 Potential estimation

Establishing the technical potential capacity of a region (like a town) is becoming essential for institutions to decide how and where to invest in renewable energy.

The first path to establishing the potential of an area is to understand which type of potential exists, according to [11], is possible to figure out four types of potential:

- Physical potential refers to the amount of solar energy that is irradiated to the surface of the earth on an annual basis. This potential is influenced by factors such as the time of day, the position of the earth in its orbit, and the geographical location (longitude and latitude) of the site. As solar radiation passes through the atmosphere, it is subject to reflection, scattering, and absorption, which reduces the amount of radiation that reaches the surface. The fraction of incoming radiation that is reflected back into space is known as the albedo of the earth-atmosphere system. Physical potential can be evaluated in different ways depending on the application. In the study by Izquerdo[12], the physical potential is assessed as the horizontal irradiation, which is calculated using a process that involves calculating the monthly extraterrestrial radiation, determining the monthly clearness index for locations with hourly meteorological data, creating monthly irradiation maps, and accounting for the effect of hourly shadows on monthly values using geometrical calculations with a digital terrain model.

- Geographical potential refers to the influence of the built environment and location limitations on the potential for renewable energy generation. This potential is determined by eliminating areas that are reserved for specific purposes, such as roads, beaches, lakes, and rivers, as well as protected areas such as national parks. Geographical potential represents the portion of theoretical potential that can be utilized because the land or location is suitable and easily accessible. In the context of solar energy generation, geographical potential typically only includes roof surfaces that are suitable for solar installations. This is because only photovoltaic plants on roofs are taken into consideration when determining geographical potential. That is one of the most considered problems in this thesis since geometrical issues are one of the aspects that can affect the technical comparison between the different panels.

- Technical potential refers to each technical parameter that affects energy production. For example, the PV panel efficiency, the inverter efficiency, or the shading during the day. It is useful referring to corrected irradiation that takes into account those parameters.

- Economical potential refers to every aspect that affects the financial revenue of the plant: the cost of panels, the cost of the land or the rooftop renting, the cost of the auxiliary devices, the business model, and the electricity cost. In a few words, all the parameters allow estimating the profitability of the investments. This part is a crucial part of this work since the goal is to find out which panel guarantees the most profitable investments.

The two images 1.8 1.9 summarize the potential type:

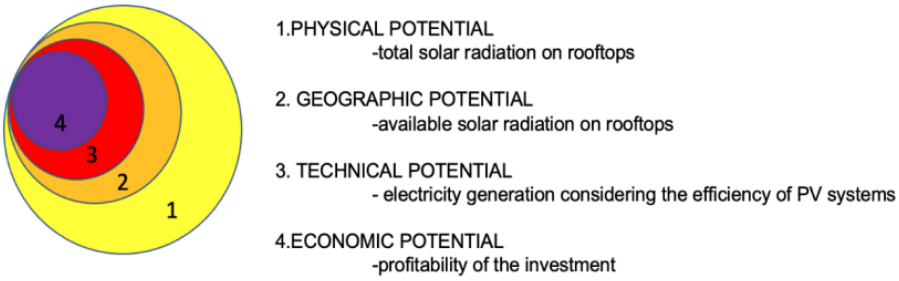

Figure 1.8: Hierarchical structure of the potential of a natural resource

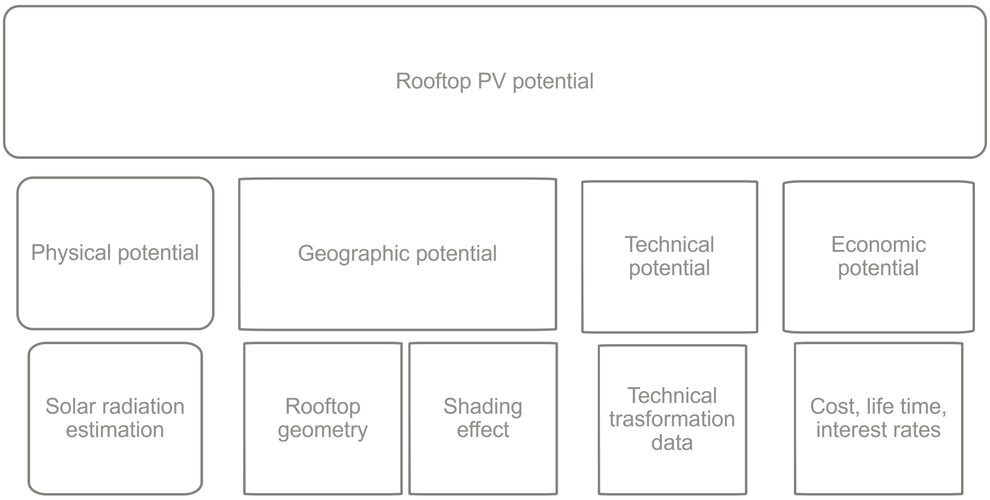

Figure 1.9: Classification of various categories of energy source potential

At this point, as the types of potentials are clear it is important to understand how it is possible to calculate this potential. It is possible to divide the procedure to estimate the potential in three methods according to Castellano [13] into

- Low-level methods, these methods try to link statistical data like population density with the characteristic of the buildings or rooftops. This method is less reliable since it assumes the homogeneity of the data.
- Medium-level methods, that combine the statistical sample with geographical data obtained by satellite (GIS) or by light detection method (LIDAR)

- High-level methods, the third category includes high-level analyses using advanced methods for scanning rooftops for detailed spatial information and analyzing solar irradiance. These methods generally incorporate sophisticated tools to estimate the role of roof pitch, aspect, and building.

Another possible categorization is made by Byrne et al. [14] that divided the methods in an analog way:

- Sample methodology. That estimates the available rooftop area of a certain region which is then extrapolated to the area fully analyzed. Evidently, they are not absolutely accurate but can provide a reliable estimate.

- Multivariate sampling-based methodologies identify correlations between the roof area and statistical data (e.g. population density, number of floors). The addition of variables increases the reliability of this method. Validation of the results obtained with these methods is also possible since the methodology is based on a sample-based approach.

- Complete census methodology is similar to the high-level methodologies described by Castellanos et al.. Such methods compute the entire rooftop area of the analyzed region by processing statistical datasets of building-related information (rooftop area, number of floors, total number of buildings) and digital spatial information of the region by applying state-of-the-art GIS technology software. The available solar irradiation incidence is also spatially analyzed by the use of big geodata sets of solar irradiance.

The table 1.2 compare the two categorizing method

	Castellano method	Byrne method
Less reliable	Low-level methods	Sample methodology
Affordable for big areas	Medium-level methods	Multivariate sampling-based
Affordable for small areas	High-level methods	Complete census methodology

Table 1.2: Comparison between different methods to calculate the potential of a technology

The biggest problem of the last method is usually the amount of data and their availability, so usually this type of analysis is accomplished only for limited zones like cities or islands, like the example of Nguyen et al [15] while for a bigger region like the European Union, an example of study can be the one made by Defaix et al. [16]. Using these methods is possible to estimate the free space available to install. And dividing by the dimension of the panel used as the benchmark, it is possible to easily compute the maximum capacity that is possible to reach in a region. For example in the Bodis study, [14] they established using a second type method that it is possible to install enough PV panels on the rooftop in Europe to cover around 25% of the electricity consumption.

1.3.2 Collective self-consumer and energy community

Collective self-consumption is based on sharing the cost of a big energy production plant, usually a renewable source of energy and later sharing the benefit due to the energy produced with a discount on the bill. This principle appears in contrast with the efficiency of a central production but it fits with the goal of energy security, emission reduction, and grid independence. For these reasons, a lot of institutions are supporting these realities like England [17], EU [18] and USA [19]]. In Italy, the self-consumption experiment began in 2008 with Reteenergia when eight citizens started to share the energy produced in the same plant [20]. After that, Energia positiva, founded in 2016, was a company that offered suppliers, that live close to the wind and PV plants and that invest on the project, a strongly discounted bill [21]. The next year, Forgreen, close to Verona, founded by a citizen, created a 1MWp PV plant that feeds the energy need of the ones that supported the project [22]. Actually the most recent action of the government decree-Law 162/19 that established the characteristic of renewable energy community (REC) that allows the participation of different entities with the limitation that participating is not their main professional activity [23]. The possible actors involved in this law, which is the Italian-specific law, and more in general in the EU Directive 2019/994 is explained below:

- owner of the grid that can have full access to the electricity market directly or in aggregation. At the same time, they interact with other actors, like the charges, for connection points or other services.

- Active prosumer that has access to the electricity market directly or in aggregation having their own plant of production

Noticeably, this system creates a problem in the grid. In fact, the grid operators can have some trouble due to the large number of small energy producers with limited knowledge of the electrical system. Specifically, the biggest problem is the forecasting of the electricity market and the prediction of power injected into the grid. These problems are called Energy trilemma [24] Energy Security, Energy Equity, and Environmental Sustainability. Another similar discussion can be done about ancillary services. This problem has, according to literature, three possible solutions: provision of ancillary services by micro-networks with energy storage [25], with aggregated prosumers [26], and some of them through the use of Blockchain technology [27].

Another important detail is that the law in Italy does not establish a maximum number of points of delivery (POD). But the only technical constraint is that all the prosumers must be in the same low-voltage grid. Under this hypothesis, two types of REC using the smart meter, a meter that allows calculating the net energy consumed, are allowed:

- Physical self-consumption in which every prosumer is physically linked to the energy sources so they can receive the energy. Usually, everyone has access to the same amount of energy. So, there is only one smart meter located on the POD that measures the net amount of energy that the REC consumes.

- Virtual self-consumption: The energy consumed is not the same as the one that is produced. It is usually bought from the grid and every prosumer has their own smart meter in order that each one pays exactly for what they consume. This last solution is preferred because since all the energy produced go into the grid, it is easier to estimate the energy that the grid obtained from the plant.

The imagine 1.10 taken in the [28] shows this two possible configuration:

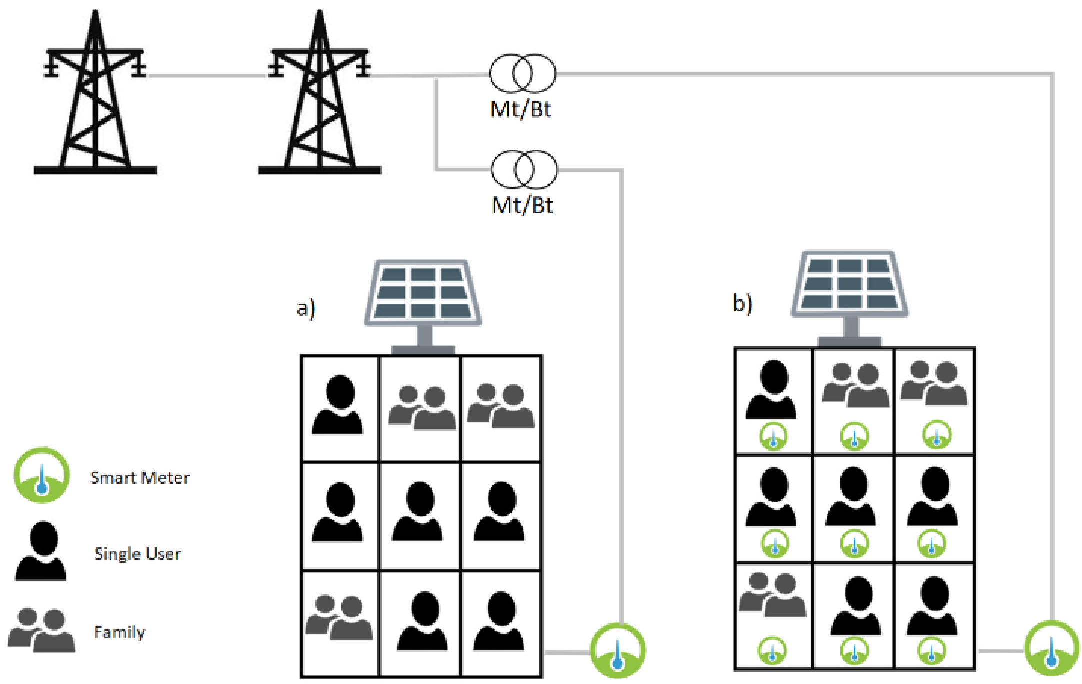

Figure 1.10: Proposed self-consumption schemes: a) physical model, b) virtual model. [28]

However, REC's creation needs an initial investment that can be the principal barrier to the creation of this reality. The bank sees these types of investments as extremely risky [29] and so the most suitable solution is the creation of a group of citizens that collaborate for the investments helped by the institution with an incentive in case of renewable sources used. The state has this goal in particular to reduce the energy poverty that is a problem for a developing country, but since with the increase in energy prices, it can also be a problem in the first world. However, investments of this type can have revenue profitable also without strong incentives. A cooperative in Germany, for example, is gaining as dividend the 4% that is higher than the normal interest rate given by bank [30]. The IRR of that is a good investment and should encourage the institution to focus on this reality. At this point, it is important to give some examples of how the energy community (EC) is organized around Europe.

1.3.3 European context

French

The Decree that transposes the RED II Directive has been approved in France, which simplifies the current legislation and encourages the establishment of EC and agreements for collective self-consumption. These communities have two different concepts, REC and common energy community (CEC), with different eligibility requirements. France has an absolute limit of 3 MW for CSC projects and uses a spatial limitation of 2 km, with exceptions for certain rural areas. In October 2020, feed-in tariffs were introduced for solar PV systems up to 500 kW on buildings, greenhouses, and parking canopies, leading to a significant increase in requests for grid connection. However, these tariffs are subject to revisions every three months, which can be destabilizing for promoters. There is also a ban on accumulating local aid with feed-in tariffs, which may hinder the development of energy communities. On the positive side, there is an obligation to install solar panels on new or renovated buildings larger than 500 m2 [31] [32] .

Germany

Germany has had a successful incentive system for the expansion of rooftop photovoltaic systems, but reductions in the remuneration rates and policy tools like the "breathing cap" have slowed the growth of these systems. However, the draft version of the EEG amendment plans to increase remuneration rates for PV roof systems and remove the EEG surcharge, and also offers more opportunities for local communities to receive financial support from operators of renewable energy plants. Additionally, the federally-owned development bank KfW finances the purchase of photovoltaic systems with low-interest loans. Currently, there is no nationwide obligation to install solar PV in new or renovated buildings in Germany, but some federal states have introduced or are planning to introduce this obligation. The "Mieterstrommodell," which enables the plant operator in multi-apartment buildings to sell electricity to tenants directly, has not been successful due to complications with the regulation. Energy sharing is not currently possible in Germany, but new regulations may change this in the future. Energy communities in Germany follow the rules for cooperatives in general and the rules for all market actors for the development of renewable energy projects, but there is no specific transposition targeting energy communities. There is a definition of CECs in the Renewable Act, but it is not in line with the EU definition [33]

Spain

the Royal Decree 244/2019 [34] in Spain introduced a simplified compensation system for generation surpluses from self-consumption, in which surpluses are compensated at the agreed price from a supplier or the market price. This system is exempt from charges and tolls but does not include any feed-in tariff or premium. The maximum installed capacity for this system is 100 kW, and no remuneration for surpluses is possible. The Royal Decree 477/2021 [35] allocates a budget of 660 million euros (expandable to 1,320 million euros) to support self-consumption and storage, with PV support ranging from 15% to 45% depending on the size and client (up to 50% for CSC). Power surpluses may be shared with nearby consumers or fed into the grid in Spain, but collective self-consumption using the public grid is physically and geographically limited. It is not currently possible to agree on dynamic percentages for the distribution of electricity, but there has been a recent modification to the Horizontal Property Law that simplifies the required majority for approval of solar PV installations in buildings. The RDL 23/2020 [36] in Spain introduced the figure of Renewable Energy Communities (RECs) for the first time, using the same wording as the RED Directive, but there is no explicit reference to Community Energy Communities (CECs). In November 2021, the Spanish Government opened a consultation process on the transposition of the Directive on local energy communities, but no draft has been published to date. Table 1.3 summarizes the incentives condition in the three state

Country	Incentives
Germany	Low-interest loans for PV systems, no nationwide obligation to install solar PV in new or renovated buildings, "Mieterstrommodell" for selling electricity to tenants, follows rules for cooperatives and market actors for renewable energy projects, the definition of CECs
France	State-guaranteed feed-in remuneration for PV systems, a draft version of EEG amendment plans to increase remuneration rates and remove surcharge, no nationwide obligation to install solar PV in new or renovated buildings
Spain	Simplified compensation system for generation surpluses from self-consumption, budget for self-consumption and storage, power surpluses may be shared or fed into the grid, collective self-consumption limited geographically, no dynamic percentages for distribution of electricity, modification to property law simplifies majority for approval of PV installations, the figure of RECs introduced, the consultation process for transposition of Directive on local energy communities

Table 1.3: Different incentive possibilities in the main states of Europe

1.3.4 Italian framework

Italy's potential for photovoltaic (PV) energy is significant due to the country's abundant solar resources and supportive policy environment. According to data from the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA), Italy has a theoretical PV potential of approximately 200 GW. This potential is largely concentrated in the southern and central regions of the country, which have high levels of solar radiation and clear skies for most of the year. As of 2020, the actual installed PV capacity in Italy was approximately 27 GW, which represents a significant portion of the country's total electricity generation. Figure 1.11 shows the average irradiation in Italy.

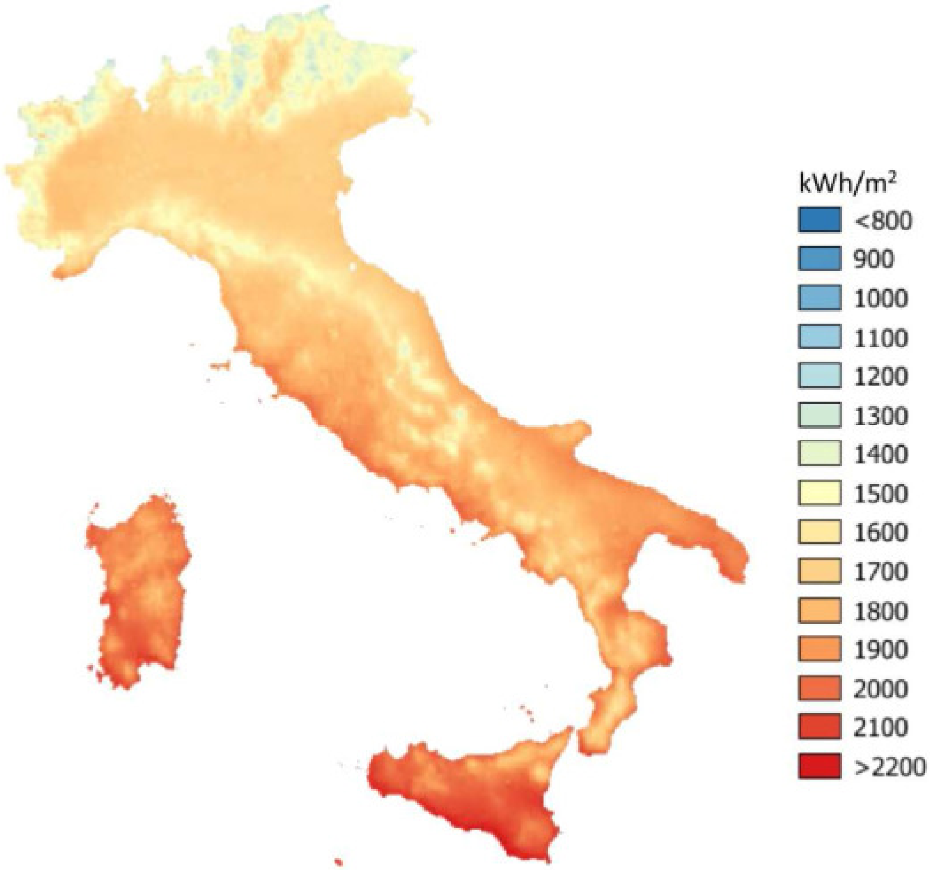

Figure 1.11: Italian irradiation distribution in kWh/m2 [37]

The 64% of the Italian capacity is installed on a rooftop that can be a residential or a third sector building or on a factory [3]. This is proof that this is an important sector for RES development that is continuously growing. This is confirmed by the data about the total capacity installed in Italy, published in 2021, around 938 MW in comparison with the 2022 data which is 751 MW so an increase of more than 100 MW, and this trend is the same in the last 10 years, [8]. In particular, the images 1.12 1.13 show the actual PV capacity installed by region and the evolution of the capacity installed in Italy on the time divided in the ground or in the rooftop. the images are taken from the gse report about PV solar [38]

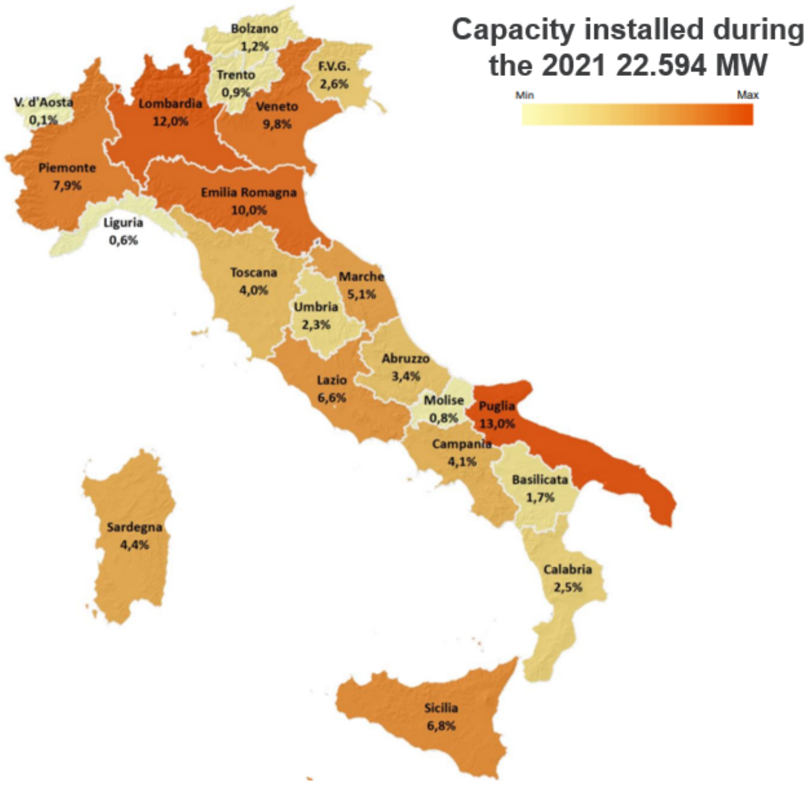

Figure 1.12: Current Italian PV capacity distribution by region expressed in MW

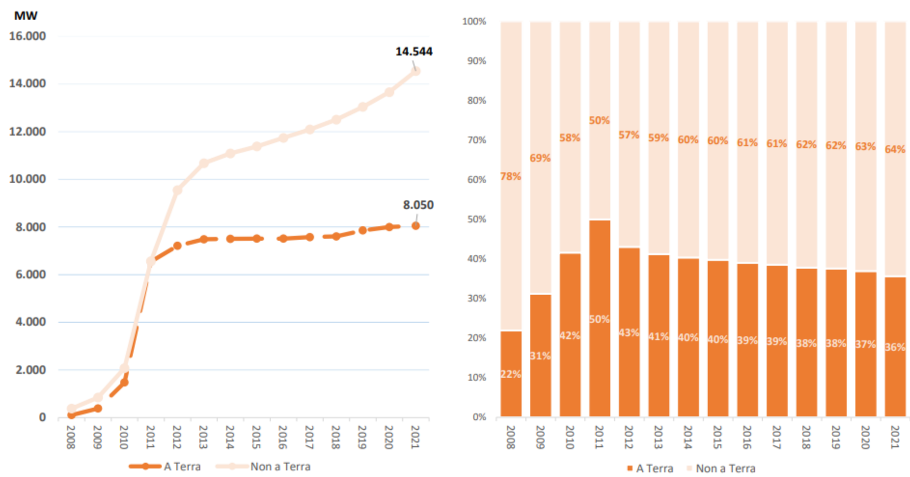

Figure 1.13: Comparison between the yearly grounded (dark) and not grounded (light) PV capacity installed in Italy between 2008 and 2021

This growth has been driven in part by favorable policy measures, such as the Conto Energia feed-in tariff program and the Quinto Conto Energia program, which have encouraged the development of PV energy in Italy. The strong PV manufacturing industry in Italy has also contributed to the growth of PV in the country, with a number of major international companies operating in the sector and helping to drive down the cost of PV systems. Overall, the potential for PV energy in Italy is substantial, and the country is well-positioned to continue expanding its capacity in the coming years. In Italy, the most recent law is in 2020 from Arera. The Italian energy regulations impose an incentive for the prosumers that take into account two parameters: that energy saved not injecting energy in the grid, avoiding connection losses, and the fact that the energy is produced by a renewable source. In particular, established a valorization for approximately 10 €/MWh for jointly acting self-consumption and 8 €/MWh for RECs. In September of next year, the Ministry of Economic Development will introduce an executive decree to increase the incentive to both of these two systems in order to try to reduce the net metering and support a new type of energy network. In particular, the valorization is also actually equal to 100 €/MWh self-consumed for joint producers and 110 €/MWh self-consumed for REC. Both of the cases are Feed in tariffs so the incentive is added to the price of the electricity market. This is useful to increase the forecasting possibilities of the grid regulator. For new buildings, it is also possible renounce to the incentives and receives the 110% bonus that covers all the cost of the plant. This possibility is offered by the GSE. In conclusion, the actual possibility to receive incentives are resumed in the table 1.14:

Shared energy valorization overview.

Shared Energy Valorization	Jointly acting self-consumption	Renewable Energy Communities
ARERA contribute	10 €/MWh	8 €/MWh
MISE Incentive	100 €/MWh	110 €/MWh
Other Incentives	Superbonus 110% (alternative to the MISE incentive)	
	Installation tax discount 50% (up to December 31, 2020)	

Figure 1.14: Valorisation of self-consumed energy

1.4 Techno-economic feasibility studies

The techno-economic feasibility of a photovoltaic (PV) rooftop plant refers to the ability of the plant to generate electricity at a cost that is competitive with other sources of energy, while also taking into account the technical and logistical factors that may impact the plant's performance and operation. When considering the feasibility of a PV rooftop plant, it is important to consider both the technical and economic aspects of the project, as well as the specific conditions and constraints of the site and the intended use of the electricity generated. By evaluating the techno-economic feasibility of a PV rooftop plant, developers and investors can make informed decisions about the viability of the project and the potential return on investment. The next paragraph explores the technical part and the economical part better.

1.4.1 Technical feasibility

The implementation of photovoltaic (PV) systems in buildings has been the subject of numerous studies that have evaluated their technical performance and economic feasibility. Impact factors on the technical performance of PV systems have been categorized into regional climate factors and building characteristics and physical features of the PV system [39]. Regional climate factors include latitude, monthly meridian altitude, monthly average daily solar radiation, and monthly average temperature. Building characteristics and physical features include the azimuth and slope of the installed panels, the type of panel and inverter, and the rooftop area. The efficiency of PV panels depends on the type of panel, with crystalline silicon panels having higher efficiency than other types. Monocrystalline silicon (mono-Si) panels have been shown to have the best energy output per square meter among the three generations of PV systems. Annual energy harvesting of PV systems can be calculated using indirect methods or direct methods [40]. Indirect methods involve calculating power capacity and then energy generation, while direct methods calculate energy generation directly. Indirect methods can be based on equivalent circuit models of solar cells, translation of known current-voltage (I-V) curves, or atmospheric parameters and information provided by manufacturers. Direct methods include calculations based on average annual radiation, conversion efficiency, generator area, installed power, the DC performance ratio, linear regression models, or energy rating characterization of modules [41] [42]. Usually, the indirect method based on the I-V curve needs a lot of measurements and it is, in general, more difficult to perform. Hence, the energy production is usually calculated using the meteorological data and the energy rating characterization of the modules written in the datasheet of the device. The table 1.4 resumes the possible system for calculating harvesting energy

Factors Affecting Technical Performance	**Description**
Regional Climate Factors	Latitude, monthly meridian altitude, monthly average daily solar radiation, monthly average temperature
Building Characteristics and Physical Features	Azimuth and slope of installed panels. Type of panel and inverter rooftop area
Type of Panel	Crystalline silicon panels have higher efficiency than other types Mono-crystalline silicon panels have the highest energy output per square meter among three generations of PV systems
Methods of Calculating Annual Energy Harvesting	Indirect methods: based on equivalent circuit models of solar cells, translation of known current-voltage (I-V) curves, or atmospheric parameters and information provided by manufacturers Direct methods: based on average annual radiation, conversion efficiency, generator area, and installed power, DC performance ratio, linear regression models, or energy rating characterization of modules

Table 1.4: Summary of the parameters needed to calculate the technical potential of PV

1.4.2 PV panel allocation algorithms

In order to estimate correctly the capacity in the rooftops is important to take into account different PV panel allocation algorithms. Heuristic algorithms are a type of PV panel allocation algorithm that uses rules of thumb or best practices to determine the placement of PV panels. These algorithms are based on the expertise and experience of the designer and do not necessarily guarantee an optimal solution. However, they can be faster and simpler to implement compared to optimization algorithms. Heuristic algorithms can be classified into three main categories: construction heuristics, improvement heuristics, and hybrid heuristics. Construction heuristics generate a solution from scratch, improvement heuristics modify an existing solution to improve it, and hybrid heuristics combine both approaches. Examples of heuristic algorithms include the nearest neighbor algorithm, which places PV panels next to each other in order to minimize shading, the bottom-up algorithm, which starts from the bottom of the surface and works upwards, and the greedy algorithm, which makes the local optimal choice at each step. [43]

Optimization algorithms are a type of PV panel allocation algorithm that uses mathematical optimization techniques to find the optimal solution for PV panel placement. These algorithms consider various constraints and objective functions and seek to maximize the energy output of the PV system while minimizing costs and other factors. Optimization algorithms can be classified into three main categories: deterministic algorithms, stochastic algorithms, and metaheuristics. Deterministic algorithms guarantee an optimal solution, but may be slower and less flexible, stochastic algorithms use randomness to explore the search space, and metaheuristics use heuristics to guide the search. Examples of optimization algorithms include linear programming, which optimizes a linear objective function subject to linear constraints, mixed integer programming, which allows for the optimization of integer variables, and genetic algorithms, which use principles of natural evolution to search for an optimal solution. [44]

Machine learning algorithms are a type of PV panel allocation algorithm that uses data-driven approaches to learn from past experiences and improve the allocation of PV panels over time. These algorithms can be trained on large datasets of PV panel placements and energy outputs and can adapt to changing conditions and preferences. Machine learning algorithms can be classified into three main categories: supervised learning algorithms, unsupervised learning algorithms, and reinforcement learning algorithms. Supervised learning algorithms learn from labeled training data, unsupervised learning algorithms learn from unlabeled data, and reinforcement learning algorithms learn from interactions with the environment. Examples of machine learning algorithms include neural networks, which are inspired by the structure and function of the brain, support vector machines, which maximize the margin between different classes, and decision trees, which make predictions based on a series of binary splits. [45]

The table 1.5 resume these information

Type of Algorithm	**Description**
Heuristic algorithms	Use rules of thumb or best practices to determine the placement of PV panels
Optimization algorithms	Use mathematical optimization techniques to find the optimal solution for PV panel placement
Machine learning algorithms	Use data-driven approaches to learn from past experiences and improve the allocation of PV panels over time

Table 1.5: Different types of algorithm to calculate the best PV panel placement

Some other studies to optimize the displacement of PV panels are in terms of tilt angle like for latitude until +15° (Duffie and Beckman), for latitude higher but still lower than 65°(Chang) [16] [46] [47]. But in an urban context, where the available area is limited and the obstacle is a significant issue both in terms of shadowing and in terms of the area occupied, it is important to develop an optimization code to compute correctly the number of panels that is possible to displace for each rooftop. For this reason, it is important to analyze the optimization algorithms that have been developed to accomplish this goal. In particular, the problem is called The maximal PV panel coverage problem. The common version of this problem is used to optimize the positioning of points in a specific area or to individuate the most suitable area for a specific disposition of points. In this case, the problem is more complex because the parameter to optimize is energy production and the object to displace is a 2D panel. The complexity of this problem is due to the different tilt angles and at the same time the azimuth angle that can strongly change the optimum disposition. That is evident for example from this graph 1.15 taken by [48]

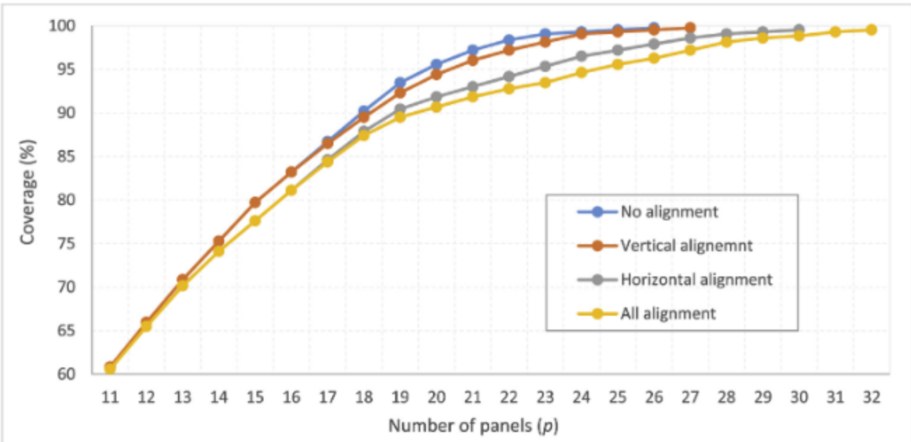

Figure 1.15: Percentages of covered area in function on the panel orientation chosen [48]

In which the optimum orientation is not horizontal or vertical and must be computed. Noticeably, this model should be used in tandem with a system that is able to detect rooftops from photos. For example, satellite image analysis algorithms are able to recognize rooftops and the possible obstacles on them from GIS images. This is currently another research field. A possible technique to achieve this goal is using GF-2 satellite images [49], and another method is using convolutions neural networks that produce optimum results with a good trade-off between speed and performance [50]. Another interesting possibility that is becoming popular now is the theme of smart cities. In fact, a possible digital twin of a city allows the possibility to import the city in already developed tools like PVgis or PVSYST and to analyze the rooftops in a carefully precise way. In fact, the biggest problem now is reaching high precision in the analysis. These are possible combinations between the optimization problem and the results of the aerial image data.

1.4.3 Economical feasibility

The economic analysis is performed by the estimation of KPI that is able to resume the investments. Some of them are used in a study that evaluated the potential of different financial support policies to promote the adoption of domestic PV systems on a multinational level [31]. The study used four economic criteria, one environmental criterion, and one policy-based criterion to assess the attractiveness of the policies for household users. The economic criteria included the magnitude of support for each customer (measured in terms of NPV), the speed at which customers would recover their investment (measured in terms of payback time), and the efficiency of the investment (measured in terms of IRR). The environmental criterion was a carbon assessment, and the policy-based criterion was the cost of the policy for the government (CFS). The study aimed to favor policies that were attractive to customers, minimized emissions, and limited government expenditure. Other important economic aspects of PV systems include renewable energy policies and economic feasibility from a life cycle perspective. Government incentives can have a significant impact on the PV market, with the industry potentially seeing rapid development with sufficient financial support and a decrease in development without such support. The levelized cost of energy (LCOE) is a common metric for evaluating the economic feasibility of PV systems, with lower LCOE indicating a more economically viable option. Life cycle assessment (LCA) is a method for evaluating the environmental impact of a system over its entire lifecycle, including the production, use, and disposal stages. LCA can be used to evaluate the sustainability of PV systems. A focus on the two most common has been done:

LCOE is a measure of the average cost of electricity generated by a power plant over its lifetime. It is typically used in techno-economic feasibility analyses to evaluate the economic viability of different power generation technologies. The LCOE is expressed in units of currency per unit of electricity generated (e.g. dollars per megawatt-hour) and is a useful metric for comparing the costs of different technologies and identifying the least-cost option The LCOE can be used to compare the costs of different power generation technologies, such as coal, natural gas, nuclear, hydro, and renewables (such as wind and solar). Renewable energy sources, such as wind and solar, tend to have lower LCOE than non-renewable sources because they have no fuel costs. However, their capital costs can be higher. Comparing the LCOE of different technologies can also provide valuable information on how the cost of electricity changes with the scale of the power plant, this will give an idea if a project should be small or large scale. Additionally, when the LCOE are considered together with the availability of the technology, the environmental and social impact, and the lifetime of the technology, among other factors, they can provide a more comprehensive view of the economic and environmental viability of different technologies. To calculate the LCOE, the total cost of building and operating a power plant over its lifetime is divided by the total amount of electricity generated by the plant over that same period. This includes both the initial capital costs (such as the cost of building the power plant) and the ongoing operating costs (such as fuel costs and maintenance expenses). The LCOE also accounts for the time value of money by using a discount rate to account for the fact that money is worth less in the future. The formula 1.1 resumes how to calculate the LCOE.

$$LCOE = \frac{\sum_{n=0}^{N} \frac{OP_N + I_n}{(1+IRR)^n}}{\sum_{n=0}^{N} \frac{Ep_N}{(1+IRR)^n}} \tag{1.1}$$

Where:

- I_n is the investments performed in that year
- Ep_N are the annual Energy of the plant
- Op is the annual cost of maintaining the PV system, including repairs and replacements.

Overall, the LCOE is a widely used metric for evaluating the economic feasibility of power generation projects and for comparing the costs of different technologies. It provides a simple, comparable way to express the costs of different power generation options and can be a useful tool for policymakers, investors, and project developers

IRR is a financial metric that is commonly used in project analysis and investment appraisal to evaluate the profitability of a project or investment. It is the discount rate at which the NPV of a project's cash flows is equal to zero. IRR is usually expressed as a percentage and it represents the expected compound annual rate of return for a project. To calculate the IRR, the project's cash flows are discounted over time using a discount rate. The discount rate is then adjusted until the net present value of the cash flows is equal to zero. The IRR is the discount rate at which this occurs. IRR is a widely used metric because it provides a single, easy-to-understand figure that expresses the project's profitability over its lifetime. It can be used to compare the profitability of different projects and to identify the project with the highest return on investment. For example, if project A has an IRR of 15% and project B has an IRR of 10%, project A is considered to be more profitable. When comparing projects, IRR is also useful because it takes into account the time value of money. It is a way of accounting for the fact that money received in the future is worth less than money received today. IRR can also be used together with LCOE to evaluate the techno-economic feasibility of the projects. LCOE gives the cost of electricity, while IRR gives the profitability of the project. Together they can help to identify the most economically viable project while providing a way to compare the costs and benefits of different projects. IRR is a widely used metric and is considered a standard in capital budgeting and investment appraisal. However, it has some limitations, for example, IRR does not account for the project's size or duration. It also assumes that the project's cash flows are reinvested at the IRR, which may not always be the case. Overall, IRR is an important metric that can be used to evaluate the profitability of a project or investment and to compare the profitability of different projects. It provides a single, easy-to-understand figure that takes into account the time value of money and can be a useful tool for policymakers, investors, and project developers. It is usually calculated according to the formula 1.2:

$$\sum_{n=0}^{N} \frac{CF_n}{(1+IRR)^n} - Capex = 0 \tag{1.2}$$

where:

- N = the life of the plant
- CF_n = cash flow of each year calculate the first year as the initial investments and the rest of the years as the total revenue of that year
- n = the year taken into account
- Capex = the initial investments

The table 1.6 resume so the possibilities and the advantage and disadvantage of some of the KPIs mentioned.

Criteria	Advantages	Disadvantages
Internal Rate of Return (IRR)	Provides a standard measure of the profitability of an investment	*Assumes a constant discount rate, which may not be accurate*
	Takes into account the time value of money & Can be used to compare investments with different time horizons	Can be affected by changes in the cost of capital
Net Present Value (NPV)	Provides a measure of the profitability of an investment in terms of today's dollars	Assumes a constant discount rate, which may not be accurate
	Takes into account the time value of money & Can be used to compare investments with different time horizons	Can be affected by changes in the cost of capital
Payback Time (PBT)	Provides a simple and straightforward measure of the time required to recover the initial investment	Does not take into account the time value of money or the profitability of the investment beyond the payback period
	Can be used to compare investments with different time horizons	Does not consider the risk or uncertainty associated with the investment
Levelized Cost of Energy (LCOE)	Provides a standard measure of the cost of generating electricity from a particular energy source	Does not take into account the time value of money or the profitability of the investment beyond the payback period
	Can be used to compare the cost of different energy sources or technologies	Assumes a constant discount rate, which may not be accurate

Table 1.6: Pros and cons between different possible economical KPI

1.4.4 Market share and cost of technology

The market share and cost of technology are important factors to consider when evaluating the competitiveness of PV systems. The market share of a PV technology refers to the portion of the total PV market that is served by that technology, while the cost of technology refers to the price of PV modules manufactured. Both of these factors can have a significant impact on the economics of a PV project and the ability of PV systems to compete with other sources of energy. By understanding the market share and cost of different PV technologies, developers and investors can make informed decisions about the most suitable and cost-effective PV solution for their needs. According to the National Renewable Energy Laboratory (NREL) report from 2020, [51], the manufacturing cost difference between the PERC technology and HTJ technology is relatively small, at only 20 €/KW. This suggests that HTJ technology has the potential to become more widely adopted in the future, as it offers similar performance to PERC technology at a similar cost. In addition, the NREL report notes that the efficiency of HTJ technology has the potential to improve over time, which could further enhance its competitiveness and market appeal. Given these factors, it is reasonable to anticipate that HTJ technology may gain a larger share of the PV market in the coming years. In fact, according to a recent market analysis, the adoption of HTJ technology in the photovoltaic industry is expected to grow significantly over the next 10 years. The analysis predicts that HTJ technology will occupy a market share of approximately 20% of the total PV market by 2032. This represents a significant increase from the current market share of HTJ technology and suggests that it is likely to become a major player in the PV industry in the coming years. The analysis attributes this expected growth to the numerous benefits of HTJ technology, including its high efficiency, fast processing speeds, and competitive manufacturing costs. As such, HTJ technology will likely continue to attract attention and investment from PV manufacturers and other stakeholders in the industry. [52] Both of these aspects are summarized in these two graphs 1.17 1.16, of which the images are taken from the reports already mentioned:

1.4.5 Italian Rooftops

In order to fully understand the potential for rooftop photovoltaic (PV) systems in Italy, it is important to consider the characteristics of the country's building stock. This includes analyzing the size and shape of Italian rooftops, as well as any structural or environmental factors that might affect the feasibility of installing PV systems. To this end, researchers can use datasets such as the ISTAT dataset on residential buildings in Italy, which provides detailed information on the characteristics of Italian homes and buildings. By analyzing this dataset, researchers can determine the average size of Italian rooftops and calculate the percentage of roofs that fall into different size categories. This information can be used to identify the most suitable PV panel technology for different types of roofs, as well as to assess the overall potential for PV in Italy. Additionally, researchers may want to consider other factors such as the orientation and inclination of rooftops, as well as the availability of space for PV installations, in order to more accurately

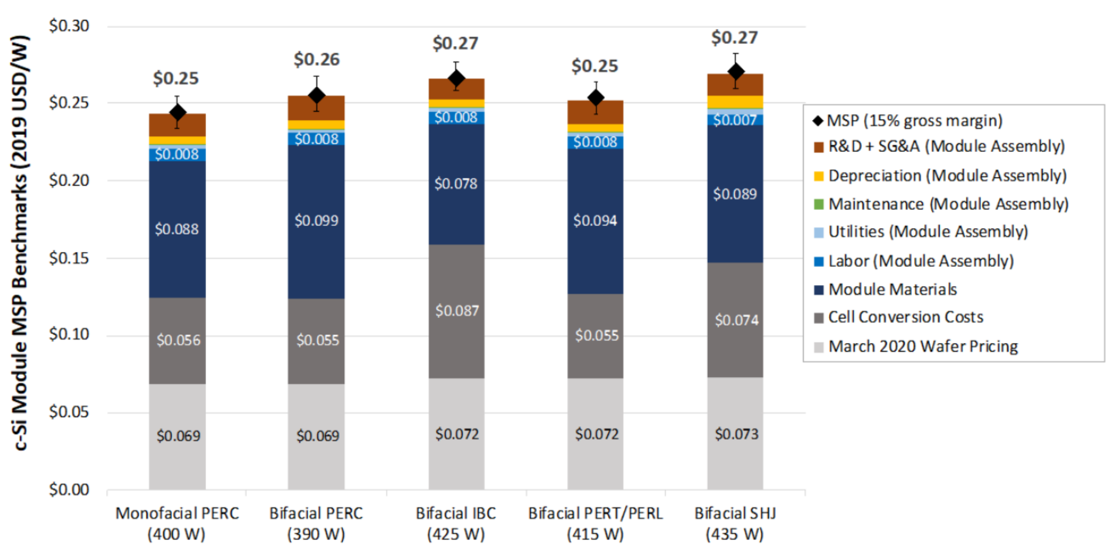

Figure 1.16: Manufacturing cost benchmarks per PV technologies expressed in USD/W

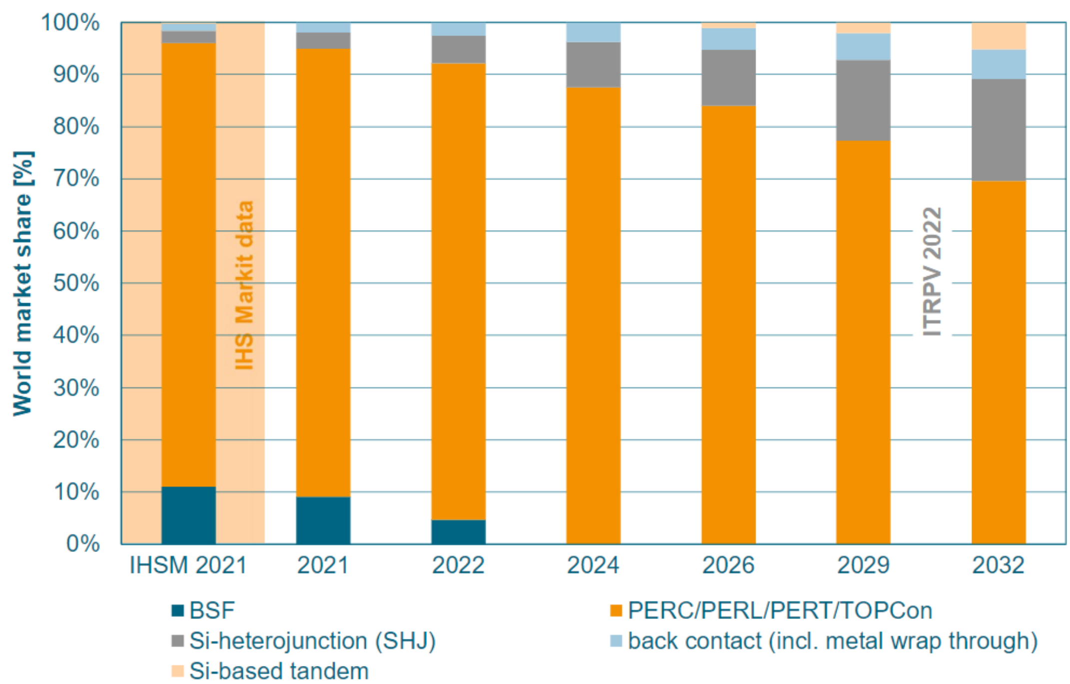

Figure 1.17: Yearly forecast of cell technologies diffusion between 2021 and 2032

estimate the potential for PV in Italy. The data are expressed in graph 1.18:

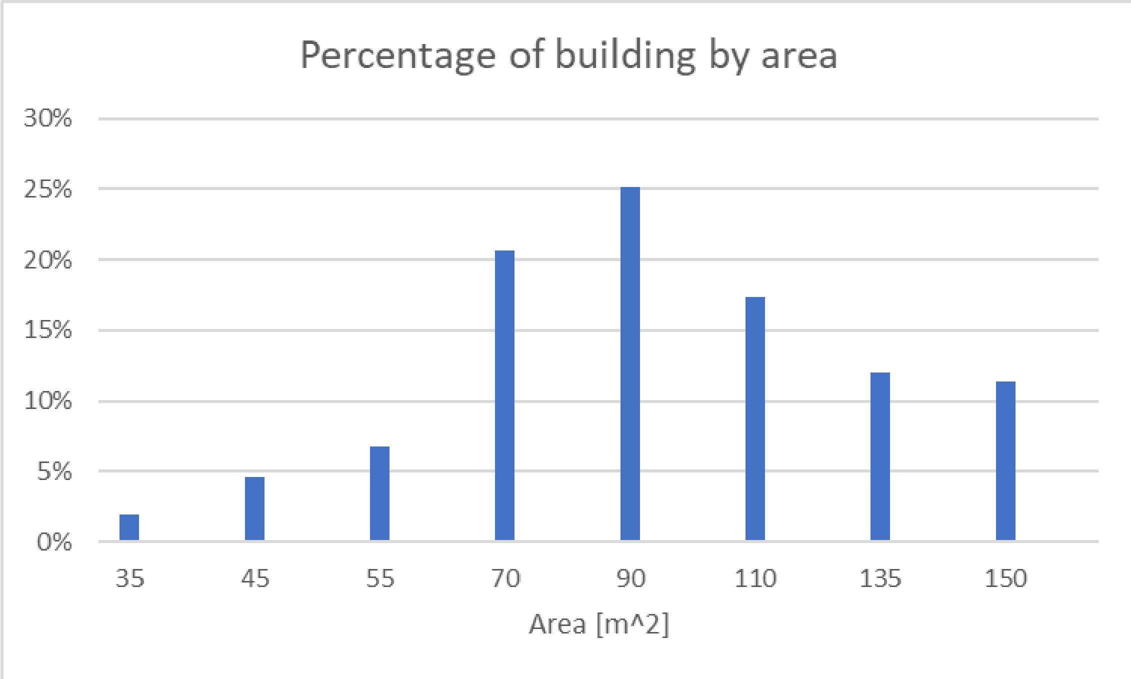

Figure 1.18: Italian rooftops distribution in function of area available for PV application

According to data from the ISTAT dataset [53] on residential buildings in Italy, the majority of Italian rooftops (around 60%) are between 70 and 110 square meters in size. These rooftops are likely to be found on apartment buildings and are therefore likely to have a relatively high energy consumption. In contrast, the highest category of rooftops (around 20% of the total) is likely to be found on larger buildings such as single-family homes or penthouses, which may also have high energy consumption. The smallest category of rooftops (those under 55 square meters) are likely to be found in studios or other smaller living spaces and may have lower energy consumption. It is important to consider these differences in roof size and corresponding energy consumption when determining the feasibility and potential impact of rooftop PV systems.

1.5 Aim and contribution

This work aims to investigate the actual PV panel market and to figure out an innovative product that can be suitable and more economically convenient than the average panels currently used in the market. Another goal is to analyze possible future scenarios and forecast the possible market share of the innovative panel in the future. This is useful in terms of corporate matters, to have a snapshot of the actual market and of the possible future market in the PV sector, but also in terms of universities and other research institutions that need information about the actual efficiency record of the products in the market and the feasibility of their use.

Chapter 2

Methodology

2.1 PV technology election

2.1.1 Market research

The possible products that have been found to improve the plants' capacity in the rooftop can be divided into 4 categories:

- High-efficiency panel: in particular products that use heterojunction (HTJ) and interdigitate back contact (IBC) technology that allows installing more kW in the same area. They can reach an efficiency of around 22.5% so 2 points more than a standard technology currently used
- Custom shape panel: This solution increases the area available on the rooftops. They can be square or triangle shaped and their efficiency is similar to classical panels.
- Shingle: this solution allows for a strong increase in the area available, but in contrast, has a strong reduction in technology efficiency. They are long rectangular pieces that efficiently cover the rectangular and trapezoidal rooftops.
- Tiles: This solution, This solution, along with the previous two, allows maximization of the rooftop area but severely reduces the efficiency. Furthermore, there were issues with the installation, because in order to use those devices rebuilding the rooftop is necessary, so we excluded this solution from the analysis.

2.1.2 Devices election

The four best devices that the market actually offers include: two in the category of high efficiency and the other two that allow an increase in the area covered. In addition to that, it is important to have a device used as a benchmark that represents the actual common technology. The devices are:

- Solar Hihero by Canadian Solar: because it's the high-efficiency product with the lowest price found in the market.
- Maxeon 3 by Sunpower: since it was, at that time, the best device in the market
- TRI240 by the Italian company Trienergia, it is the only square-shaped device available now, from an Italian established company.
- Apollo II by CertainTeed: it's a shingle produced by a big company (Saint Gobain) so the data sheet is reliable. In fact, these types of products are new in the market and most of them are produced by startups. For many products, the data in the datasheet are not coherent.

The data of these five devices are resumed in the table 2.1:

Company	Model	Efficiency	Technology	Size [mm]	Capacity [Wp]
Canadian solar	HiHero	22.5%	HTJ	1722x1134	440
Sunpower	Maxeon 3	22.6%	IBC	1690x1046	400
Trienergia	TRI240DM-BB	19.6%	Perc	1016x1189	240
CertainTeed	Apollo II	17.80%	mono PERC	1168x336	70
Actual	benchmark	20.4%	mono PERC	2000x1000	410

Table 2.1: Summary of the outcome of the market research

2.1.3 PV simulation with reference software

The two most promising devices seemed to be the ones by Canadian and Trienergia. Two panels have been tested using two software: Solaredge design and Aurora solar which allow the construction of the geometry of the rooftop and simulate the installation of panels in order to quantify how many kW is possible to install on the buildings.

Selection of the testing software

Doing the analysis described in the next paragraph, it became evident that the best software is Aurora Solar, so it has been used for the rest of the study because, after a comparison, some advantages of using this software were found. The advantages are the following:

- The construction of the geometry: Aurora solar allows to use of pre-setted objects and HD images from the satellite, while Solaredge uses only low-definition ones. In addition, creating geometries is more complicated and less precise.
- The 3D construction is simplified in Aurora solar since it allows the use of the Lidar map and to adapt the 3D building to that map, in addition, there is a 3D geometry already constructed available for some cities in the world. Instead, in Solar edge to create a precise 3D geometry, Google earth is necessary to accurately calculate the height of the building.
- The positioning of the panel in Aurora Solar is easier and more accurate. In fact, it allows to set a maximum level of shadow that a panel can tolerate, and according to that, it calculates the best position of the panel, taking into account obstacles on the rooftop. In Solaredge, that function is not present and in order to take into account the shadow of the obstacle, calculating the dimension of shadows and putting a bigger obstacle is necessary.
- The last aspect that has been considered is the difficulty to change technology and to make a comparison between different panels. In fact, Aurora solar allows importing of any device, both panel and inverter. In contrast, Solaredge only allows the use of their own inverter. In addition, Aurora allows saving geometry and different technology solutions that allow easy comparison between different solutions.

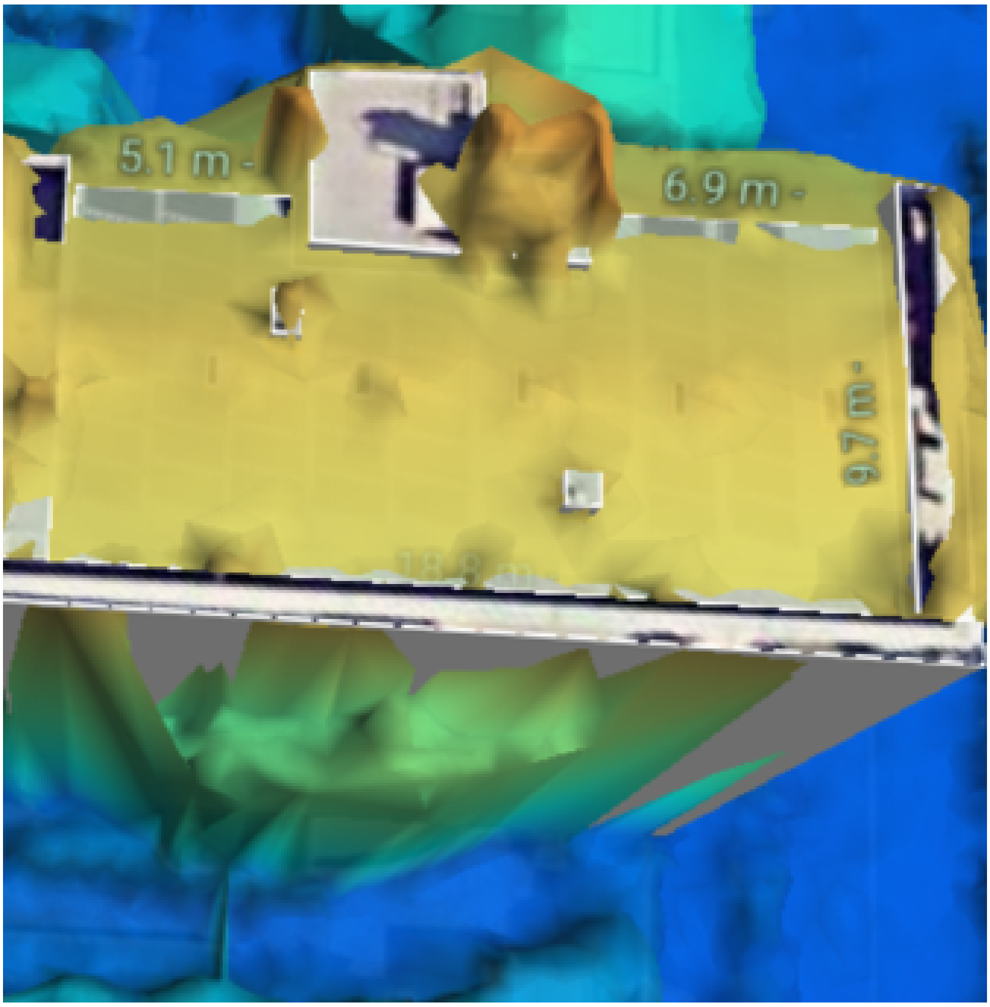

Figure 2.1: Example of a Lidar view of one of the case studies analyzed by the Aurora Solar software

Results obtained by software

Using Aurora solar, the possible capacity installed in 10 cases study has been calculated. The results are resumed in the table 2.2, and shown in the graph 2.2:

Analyzing the results expressed in the figure 2.2, and finding a clear trend is difficult, the results are divided into 3 categories:

- In the last two case studies, the increase of capacity using the innovative technology is around 10% so a considerable increase.
- In the other two, the innovative technology allows exceeding the goal of 20 kW. That limit has been set to conclude the feasibility of the investment

	Canadian [kW]	Trienergia [kW]	benchmark panel [kW]
case study 1	9.24	10.56	8.2
case study 2	21.12	21.36	20.09
case study 3	22	22.08	20.09
case study 4	20.24	20.16	20.5
case study 5	23.3	24.48	22.96
case study 6	24.2	24.72	23.78
case study 7	36.08	31.2	28.7
case study 8	38.28	36.72	34.03
case study 9	54.1	50.4	52.5
average	20.02	20.56	19.27

Table 2.2: Summary of the capacity reached with different technologies

- In other cases, the new devices do not give any advantage or reduce the capacity.

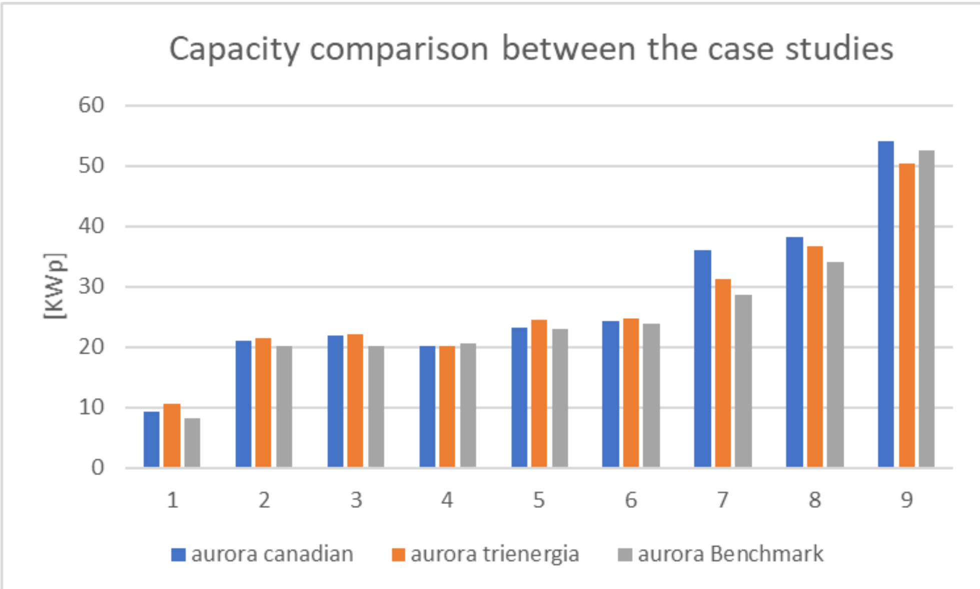

Figure 2.2: Comparison between the predicted installed PV capacity in kWp per panel in each case study

To summarize, although, they did showcase the possible advantages of these new devices, it seemed impossible to conclude with these 10 case studies alone. The necessity of a numerical model that allows the encapsulation of the problem and the statistical quantification of the technical and economical advantages of this new solution is apparent.

2.2 Modelling PV allocation over different rooftops

The goal of the model is to simulate random combinations of shapes and obstacles and to calculate how much capacity is possible to install on them. Afterward, the model receives the meteorological data and the energy load of the building as input. Using all this information, it estimates financial KPIs that help to make decisions about which product is the best investment. The image 2.3 show the flowchart of my model.

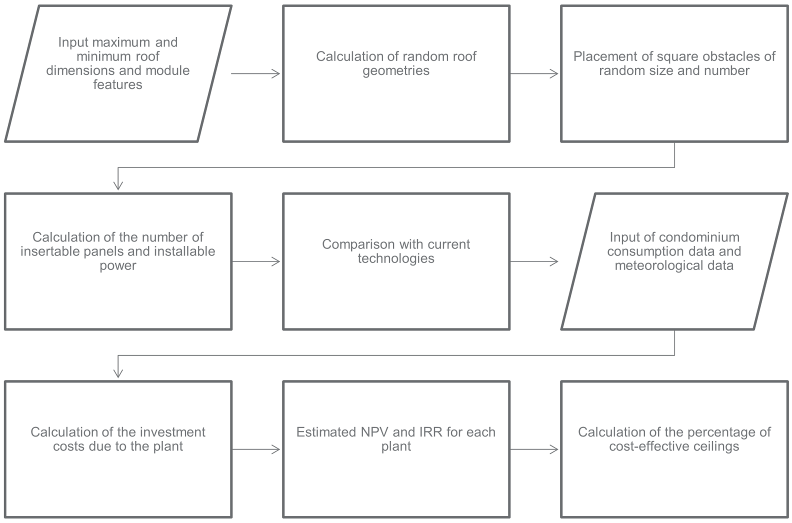

Figure 2.3: Flowchart of the key steps, inputs, and outputs of the developed model

2.2.1 Input of the model

For the model to work, it needs some input that can be hypotheses or real data. Resuming, it is possible to divide them into 3 categories:

- Geometrical: such as the dimension of the rooftop or its tilt, but also the shape and the dimension of the panel
- Geographical: such as the position of the building, the meteorological data of this place, and the hours of sunset and sunrise

- Economical: such as the energy load of the building, the method to calculate the revenue, and the cost of the panel and the plant in €/kW

All the input and the hypotheses are summarized in the table 2.3:

Geometrical	**Geographical**	**Economical**
All the obstacles are squared shaped and they are random in position and in number	The building is located in Milan	Normalized energy load on a real case, energy load for each PODs 2750 kWh/year
The basis of the figure are between 15 and 30	The panel is placed on the rooftop without any tilt changing support	Capex and opex are assigned from BU
The height between 5 and 10	Tilt angle of 25°	13 PODs each b
Obstacles' dimension between 0.5 and 2.5 metres	Panel orientation: South	Cost panel obtained by the company or on e-commerce
Obstacles' number between 3 and 8		Revenue calculation method in according with GSE rules, minimum IRR for an affordable investment: 2%
		PUN established: 0.062 euro/kWh

Table 2.3: Resume of the main hypothesis to calculate different types of potential

2.2.2 Design of different rooftop technologies

In order to create the different types of rooftops the next characteristics are taken into account:

The geometry

In accordance with the case studies, the most common rooftop shape is rectangular, triangle, or trapezoidal. So, in this model, random rooftops with these shapes have been created; by choosing randomly the length of the side between the biggest and the shortest rooftop from the case studies. In this way, it is possible to simulate the most common rooftops, but also strange combinations, for example, a big trapezoidal rooftop with a small height. This allows for taking into account every rooftop and every possible geometry. A possible improvement to this work is to establish which shapes are more probable than others and implement this condition in the algorithm.

The obstacles

The model puts a random number of obstacles between 3 and 8 in random positions on the rooftop. They are square shaped and the dimension depends on the height of the obstacle, this is also random and can be between 0.2 and 1.5 metres. This parameter establishes also the dimension of the obstacle because the side will be long as the shadow created by the obstacle when the sun is at 30 degrees from the horizontal. In this way, the model can create random obstacles and displace them in different ways on the rooftop creating on the same geometry different combinations of obstacle. With this method, it is possible to take into account also this variable in the analysis.

Capacity calculation

To calculate the number of panels that can be displaced in the rooftop, the model starts from the left-down corner of the random geometry and calculates, using the geometry formula, the starting point that allows placing the panel to lose the minimum area. It goes horizontally until it does not find an obstacle that restrains the displacement of a panel. At this point, it counts how much panel is possible to put in the distance between the corner and the obstacle. After that, the model restarts, starting from the end of the obstacle found. When the end of the rooftop is reached, it goes up by a quantity equal to the height of the panel, and it comes back to the left side and restarts the process until it is possible to put a new row of panels. In this way, it is possible to count how many panels are possible to place. Evidently, that algorithm is not the best one possible but as it will be explained during the validation, it is enough precise to be used for the objective of this analysis. At this point, it is easy to calculate the capacity of the plant, by multiplying the number of panels placed by the capacity of each panel.

2.2.3 Financial KPI calculation

In order to estimate the affordability of the investment of each plant for each random rooftop, the IRR has been used as the main KPI since it is the methodology used in other research. In order to calculate that indicator, the cost of each panel and the cost of the auxiliaries, and the cost of the maintenance for each rooftop are estimated. Later, using the energy consumption profile and the meteorological data of Milan, an estimation of the yearly consumption has been calculated. The production and the consumption has been matched to estimate the quantity of energy produced and the part that has been self-consumed. At this point, in accordance with the GSE calculation method, the revenue, the IRR, and the payback time (PBT) of the investment have been estimated. The next section explains each step.

Cost estimation

The cost is divided into 6 cost elements, each one obtained in the form €/kW of the plant:

- Panel
- Inverter
- Placement
- Structure
- Optimizer
- BOP

Every cost, excluding the panels, is a realistic cost obtained online as a table that contains the cost related to the size of the plant. In this way, it is possible to take into account the scale effect. The value of the cost for each category is resumed in the table 2.4.

Size	**Inverter**	**Optimizator**	**Structure**	**Placement**	**BOP**
<=20 kW	115	56	158	210	230
60 kW	110	53	148	200	195
99 kW	105	50	138	185	175
149 kW	95	47	131	175	165
199kW	95	44	128	175	165
249 kW	90	41	127	172	162
350 kW	84	38	125	170	157
499 kW	78	35	123	170	151
1000 kW	72	30	121	170	148
3100 kW	68	26	120	170	146

Table 2.4: Summary of the main costs used to calculate the Capex of the plant

Summing all this data for columns and interpolating with a line, it is possible to create a function that estimates the cost of the plant as function of its capacity.

For the panel cost estimation, different possibilities can be found:

- Benchmark, the cost represents a realistic price for a panel in the average rooftop plants nowadays
- Sunpower panel, the cost found in the e-commerce of the company for a really small quantity has been used. The price is 1000 €/kW
- CertainTeed, it has been possible to find only the cost of the plant, so this value has been estimated by dividing by 3 the cost of the plant. The price estimated is 2100€/kW
- Trienergia, The seller of the company gives the price for small quantities of panels equal to 720 €/kW
- Canadian solar, The seller gives a price equal to 360 €/kW for a large number of panels. Even if, on the website of the company, the price for a small amount is 930€/kW

Some of the prices are for small quantities and other for bigger quantities, so the comparison has been divided into two blocks: the panels that take into account the scale effect in their prices and the ones that do not. At this point, it is possible to estimate the cost of the plant as the sum of all the other items and multiply by the capacity of the plant.

The revenue estimation

The model that has been used is a virtual self-consumption business model that can be resumed in the formula 2.1

$$R = (E_p \cdot PUN + E_{sc} \cdot I_{gse} - OPEX) \tag{2.1}$$

Where:

- R is the revenue
- E_p is the Energy produced in a year
- PUN is the price of energy at that moment, setted at 0.062€/kW
- E_{sc} is the energy self-consumed in a year calculate comparing the consumption and the energy production
- I_{gse} is the incentive that GSE gives for the self-consumption and is equal to 108€/MW
- $OPEX$ is the operational cost that included the monitoring of the production and the cleaning of the panel and is set at 1400 €/kW

In order to calculate E_p, the meteorological data has been downloaded from PVgis. The area of the plant, calculated with the model, has been used in the formula 2.2:

$$E_p = I_p \cdot A_{pan} \cdot \eta_{pan} \tag{2.2}$$

where A_{pan} is the area occupied by the plant, η_{pan} is the efficiency of the panel calculated as the product of the all technology efficiency, and I_p is the irradiance that arrived perpendicular to the panel. The last two parameters are calculated following the standard model of producibility explained in appendix A. This count has been made for every hour in the year and the amount of energy produced has been summed under the hypothesis that the production is constant for an hour. Later, the quantity of energy that is possible to self-consume has been calculated, making a comparison between the production and the energy load of the building for every hour in the year and the energy production. Finally, it is possible to calculate the revenue of every year, the payback time, and the net present value (NPV). Ultimately, the internal rate of return (IRR) has been calculated. These data have been used to make a comparison between different panels in order to estimate which is, under these hypotheses, the best panel to do possible investments.

2.2.4 Model validation

Before using the model, it is necessary to validate it, in order to be sure that it is representative of the actual values and to estimate the uncertainty associated with the results. In order to accomplish this goal, a comparison between the results obtained by Aurora solar and the one obtained simulating the case studies with my model has been made. The graph 2.4 and the table 2.5 resume the relative error that the model commits for the 8 case studies that are tested.

	Canadian	**Trienergia**	**Benchmark**
absolute average error	1,9%	2,5%	1,8%
relative error	-0,3%	-1,7%	1,8%

Table 2.5: Results discrepancy of the developed model and Aurora

It is comprehensible that the model has more difficulties managing with devices that have a small size because there are more combinations possible and so, it is more difficult to find the best disposition for the panel. Nevertheless, it is possible to assume that, on average, the model is accurate enough since the error of 2.5% in the rooftop application means that there are 3 or 4 panels of difference between the solution made by Aurora solar and the solution purpose by the model. In addition, we can deduce from the relative error that the model underestimates the capacity installable with innovative technologies since it is more difficult to find the

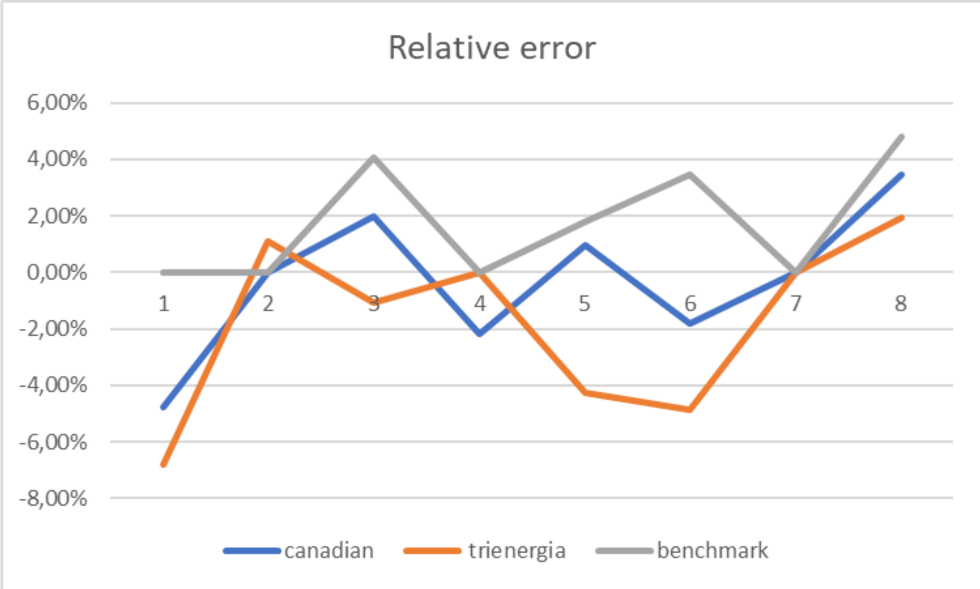

Figure 2.4: Results discrepancy between the developed model and Aurora in terms of percentage capacity

optimum disposition with shorter panels. In conclusion, according to these results, the technical part of the model is validated.

Chapter 3

Results

3.1 Technical results

The model calculates 3 different KPIs regarding the technical part:

- Global efficiency
- Capacity
- Percentage increase between the actual technology and the innovative panel

That analysis is done with the goal to identify the panel model that maximizes the number of rooftops in which it is possible to install at least 20 kW. This value has been chosen with the goal to allocate 1.5 kW for each PODs. The other parameters are used to give an overview of each panel and establish which is the one that allows the maximization of the capacity for each category of rooftops. In fact, the rooftops are divided by obstacles and dimensions. All these results are obtained by simulating 10000 rooftops.

3.1.1 Global efficiency

The global efficiency is the product between the technological efficiency: η_{std}, η_d, η_T and the fill factor (FF) that is calculated as the ratio between the area available on the rooftop and the one covered by panels. In particular, η_T is calculated according to the (A.10) with T_{env} fixed at 55 °C degrees, and η_d is calculated by the (A.8) with an age equal to half the life expected of the plant. Those parameters allow the establishment of which panel will produce more energy during the lifetime of the plant. The results are summarized in the two graphs 3.1 3.2: the first shows the statistical results with every 10000 rooftops, and the second is a linear regression of the data, done in order to obtain a better comprehension of the phenomena.

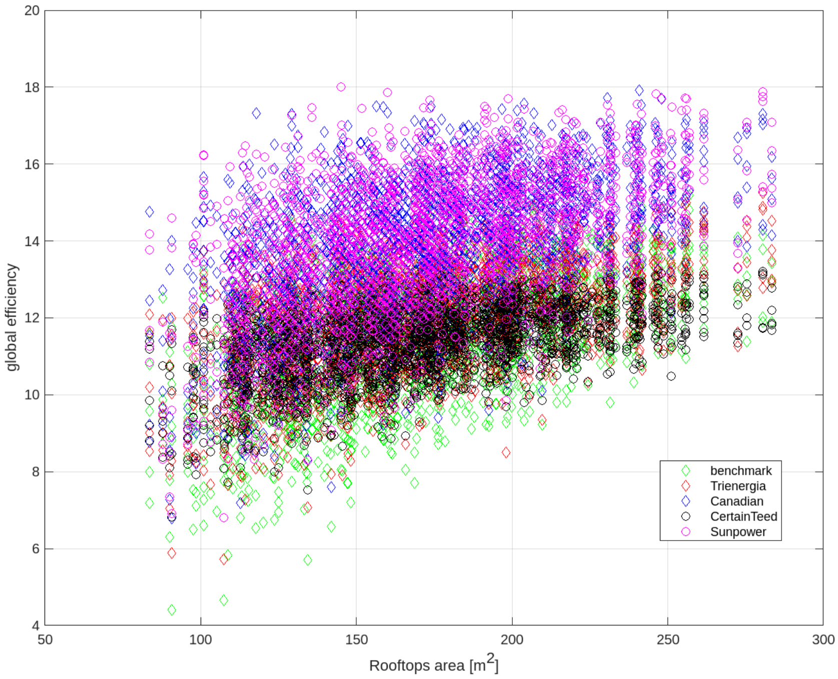

Figure 3.1: Global efficiency in function of the available surface: sampled data

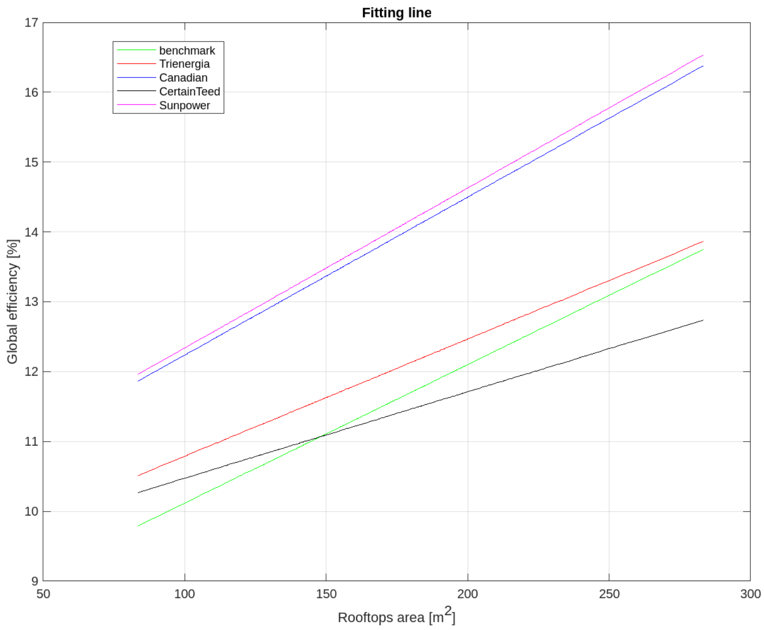

Figure 3.2: Global efficiency in function of the available surface: linear interpolation

It is evident from the graph 3.1 that the Trienergia panel and the CertainTeed panel have a big advantage for rooftops with an area of 150 square metres or less since the global efficiency is on average higher for this rooftop category. For rooftops bigger, the performance of the benchmark panel is definitely better than CertainTeed and it becomes, for a big ceiling, similar to Trienergia which compensates for the little disadvantage of technological efficiency with a definitely better FF. Moreover, the panel with high efficiency are similarly shaped so the fill factor is almost the same in particular in big areas. That is also confirmed by the closeness of the two lines of the figure 3.2 due to the similar FF and technological efficiency. In addition, it is possible to assume that for low areas the difference in global efficiency is 1.5% and that is due to the fact that FF can compensate for the difference in technology. In big areas, the advantage of high-efficiency panel return is 2.5% and that is another proof that for large rooftops the geometry aspect is secondary.

3.1.2 Capacity of the plants

Some parameters have been investigated to individuate in which rooftops there are the biggest increases of capacity, and which are the type of ceilings that are more adaptable to each panel. The parameters are the number of obstacles placed and the area of the rooftop. So, the average capacity that is possible to install for each combination of obstacle and area has been calculated. These results are used to create the following three 3D graphs fig 3.3 fig 3.4 fig 3.5 in which for each technology is shown the capacity installable. The two most promising technologies are used for comparison with the reference panel.

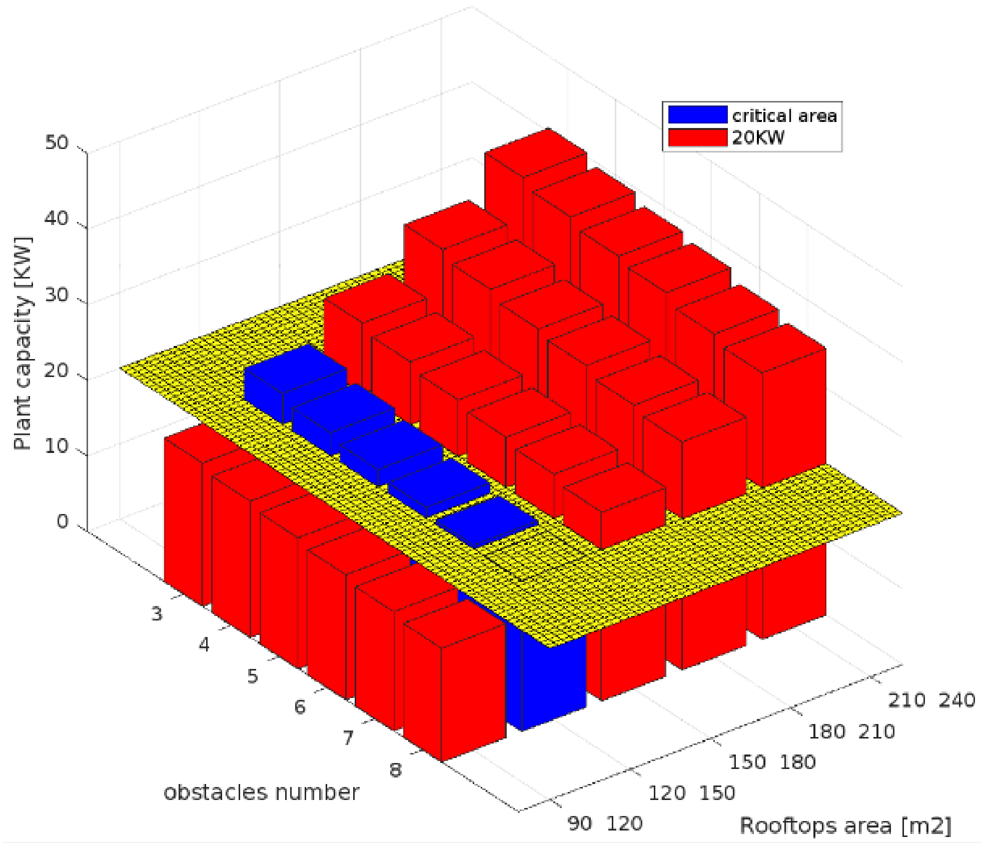

Figure 3.3: Installable capacity in function of the number of obstacles and available surface: Trienergia panel

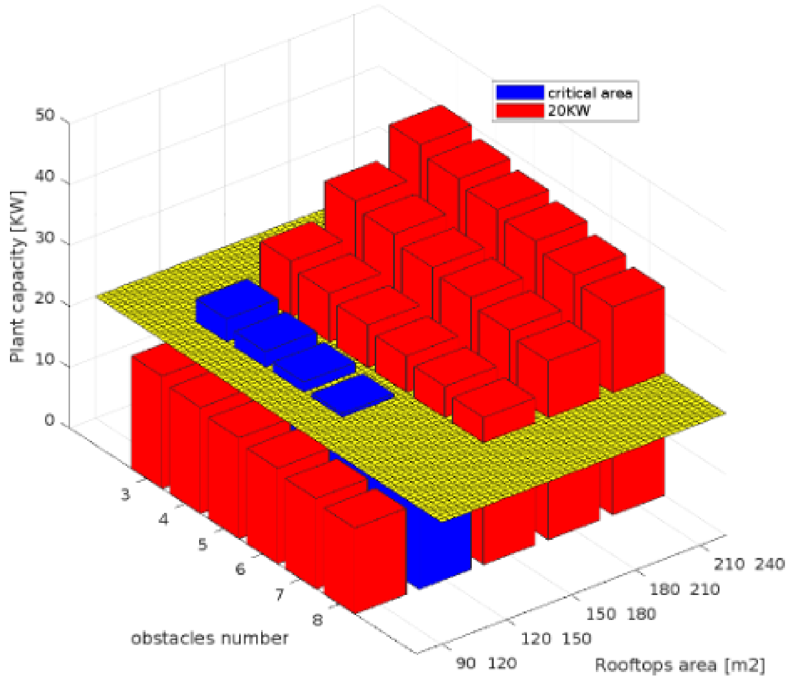

Figure 3.4: Installable capacity in function of the number of obstacles and available surface: Benchmark panel

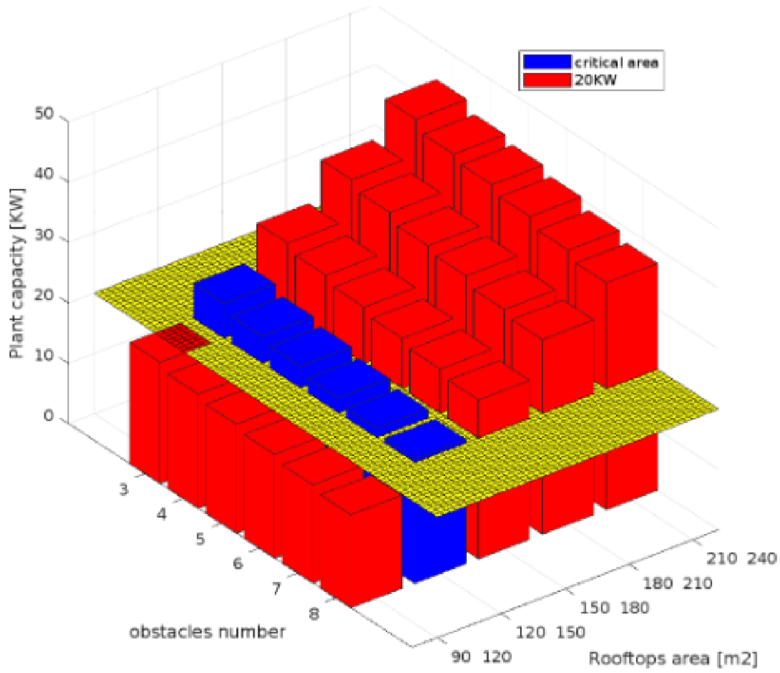

Figure 3.5: Installable capacity in function of the number of obstacles and available surface: Canadian panel

Seemingly, all three technologies are able to reach the 20 kW average capacity for any rooftop of at least 150 square metres. Canadian panel is the one that can install more capacity, and that reflects by its bigger capacity density. Trienergia panel is similar to the benchmark, at least on average, which is due to the fact that some rooftops present a combination of obstacles that benefit Trienergia panel and others that benefit the benchmark panel. Another important aspect is that for small rooftops (until 120 square metres), any technology is not in able to reach the set minimum. Consequentially, that allows establishing that the most important ceilings are the ones between 120 and 150 m^2, because they are the ones in which the increase of capacity due to the new technology allows to overcome the imposed limit. In particular, the graph shows that Canadian panel is able to install, on average, 20 kW for every obstacle combination. Trienergia panel installs less capacity than Canadian but more than the benchmark used. In order to give more numerical information about this section of the field, a boxplot 3.6 has been also done for this area, which is shown below

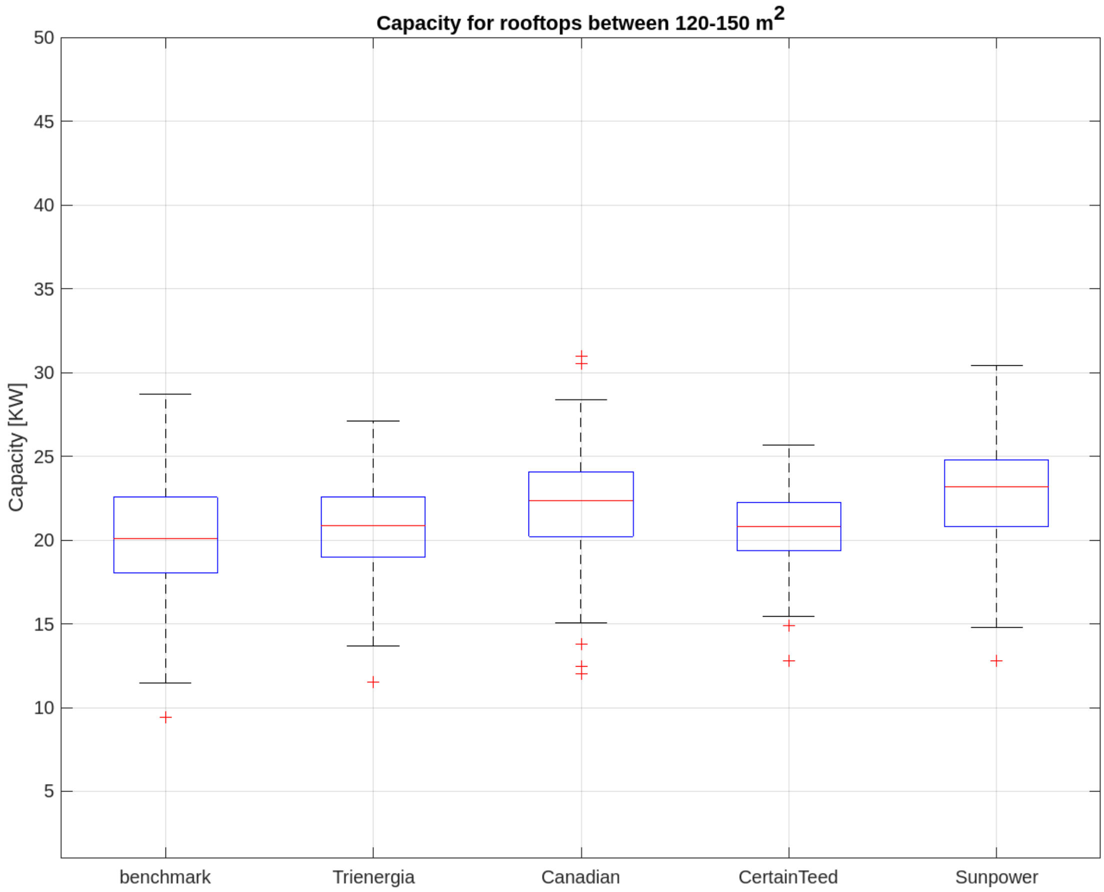

Figure 3.6: Statistical variation of the installable PV capacity

This figure summarizes the capacity that is possible to install by every technology. The red line represents the average, the same number from the previous bar graph. The box represents 50% of the simulated case while the line corresponds to the rest of the cases. In this graph, it is evident that in most of the cases for Canadian panel and also more for Sunpower panel, it is possible to install more capacity than the benchmark. It is also evident that CertainTeed panel does not allow to install sensibly more. Lastly, Trienergia is in the middle between high efficiency and the benchmark.

3.1.3 Relative capacity increase analysis

After defining which section is the most important, the best rooftop for each panel is selected by the calculation and the plots of the percentage difference between the capacity installed by the benchmark and the one installed by every technology. these plots are the figures 3.7 3.8.

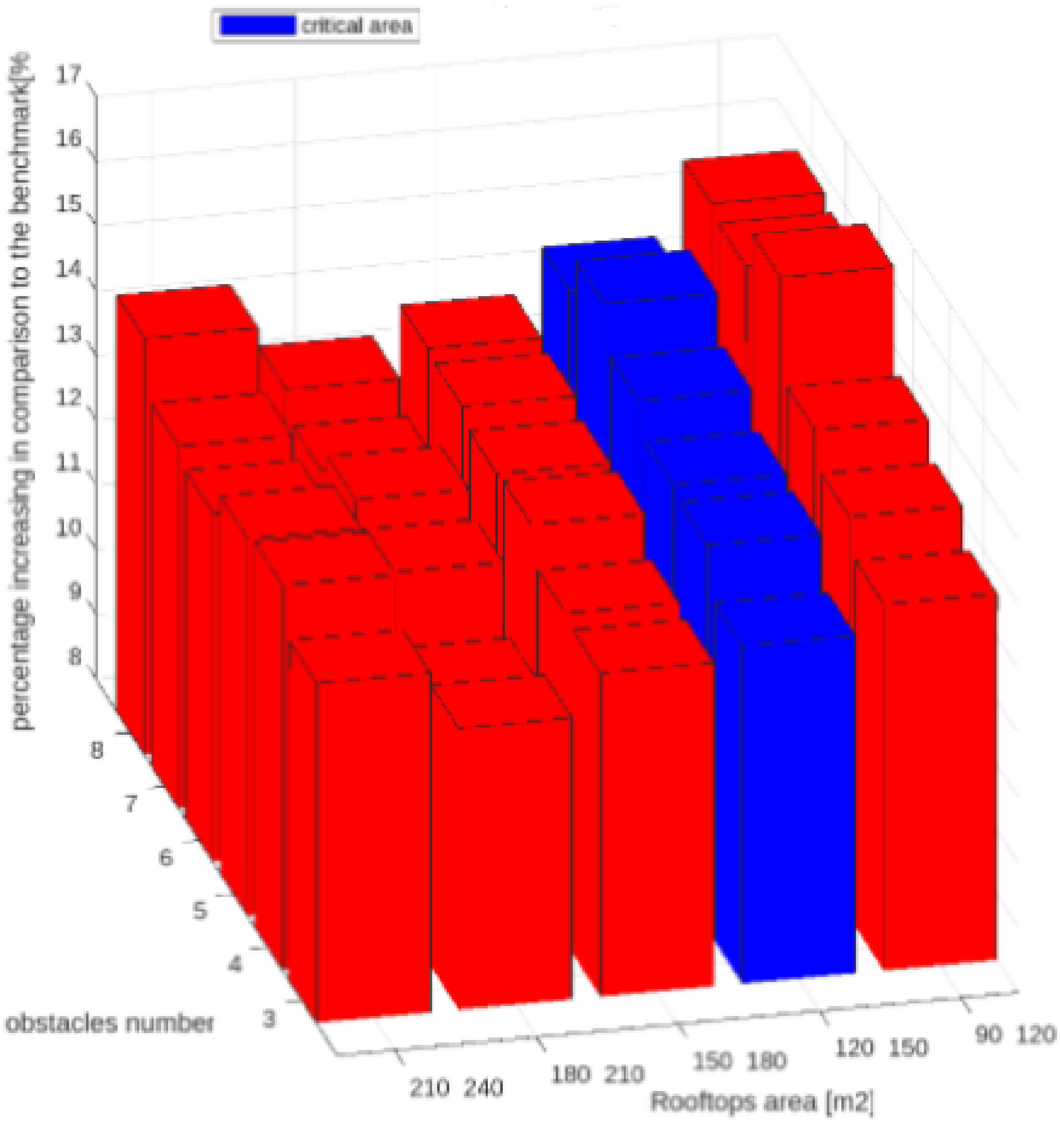

Figure 3.7: Capacity improvement in percentage in function of the number of obstacles and available surface: Sunpower panel

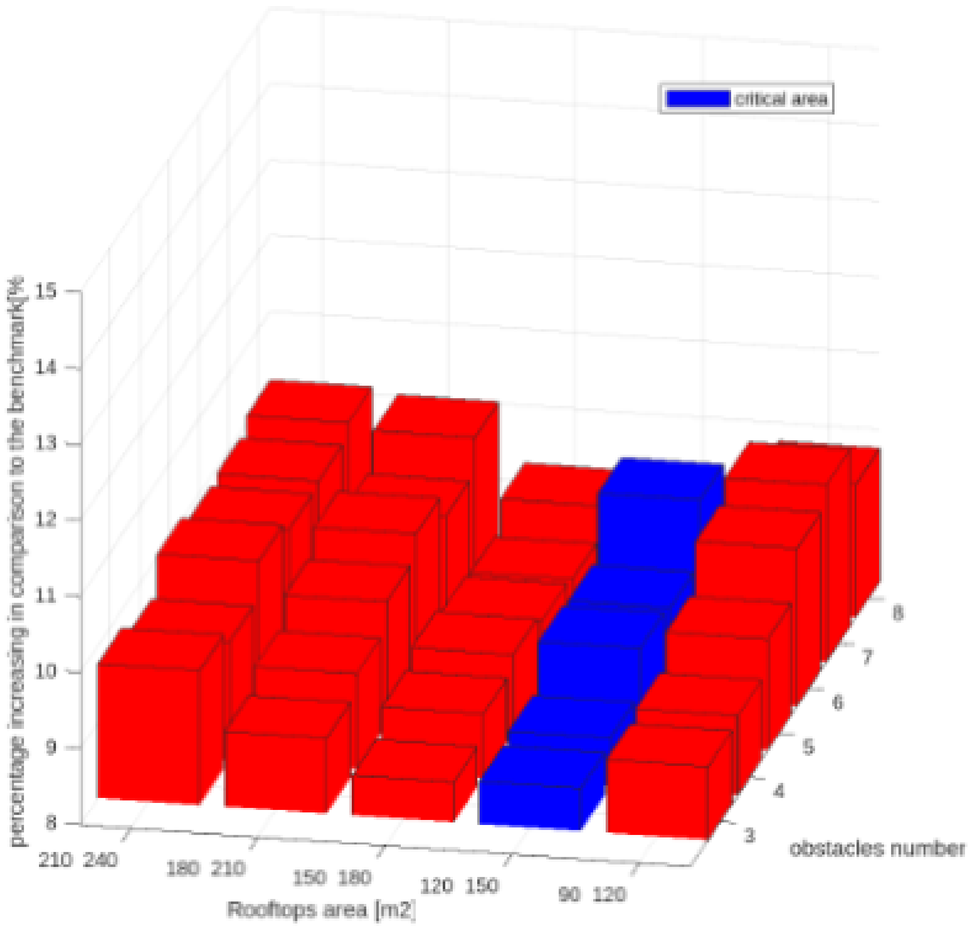

Figure 3.8: Capacity improvement in percentage in function of the number of obstacles and available surface: Canadian panel

From the figures 3.8 and 3.7, it is evident that Sunpower's shape allows it to get a small advantage, in particular for small rooftops. While Canadian's shape does not give a particular advantage. In fact, the percentage increase of this technology is practically flat and so it is possible to suppose that its FF is almost the same as the benchmark, unlike Sunpower which has both the advantages, technological and geometrical. The figures 3.9 3.10 show the improvment of those technology

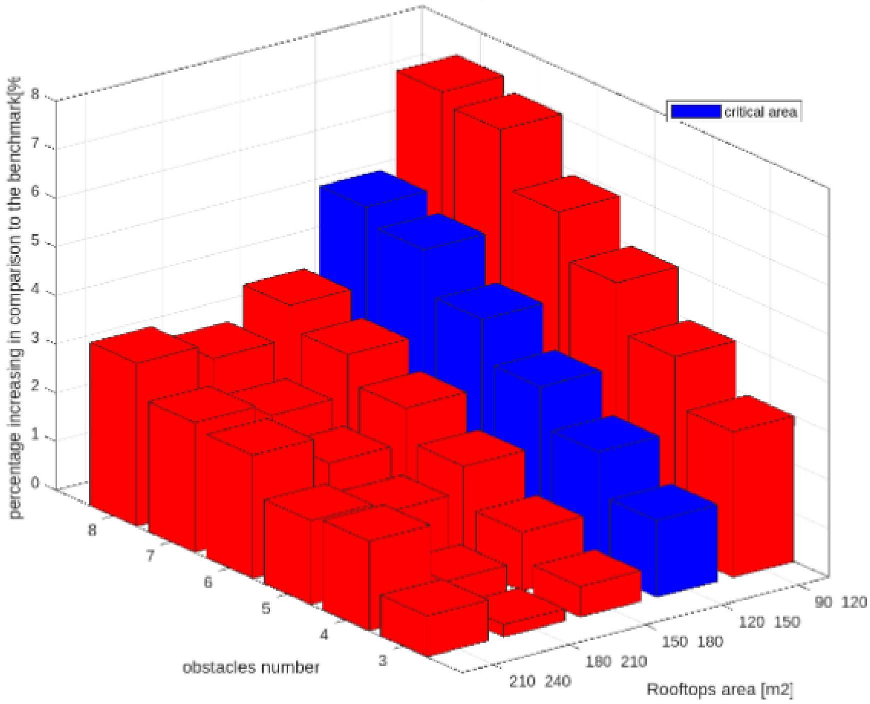

Figure 3.9: Capacity improvement in percentage in function of the number of obstacles and available surface: Trinergia panel

In these graphs, it is possible to understand how important the shape of the rooftop is by looking at the distribution of the dimension of the bars. Trienergia has the average increase lower, in particular for extremely small ceilings, and for a high number of obstacles. In fact, CertainTeed's capacity depends strongly on the number of obstacles. It is evident for example that for a low number of obstacles, CertainTeed product definitely worst than the benchmark panel. Unlike Trienergia which can install more capacity with few obstacles but also when they are a higher number, Trienergia's capacity installable is higher at areas larger than 120 m^2 for every obstacle. In conclusion, Trienergia definitely installs more capacity than the shingle also in critical areas.

3.1.4 PV technology with the highest capacity

The technical analysis has two different scopes: defining which panel can, on average, install more capacity and at the same time, figuring out which is the best technology to surpass the target of 20 kW where the benchmark panel can not. To visualize this aspect the graph 3.11 is useful :

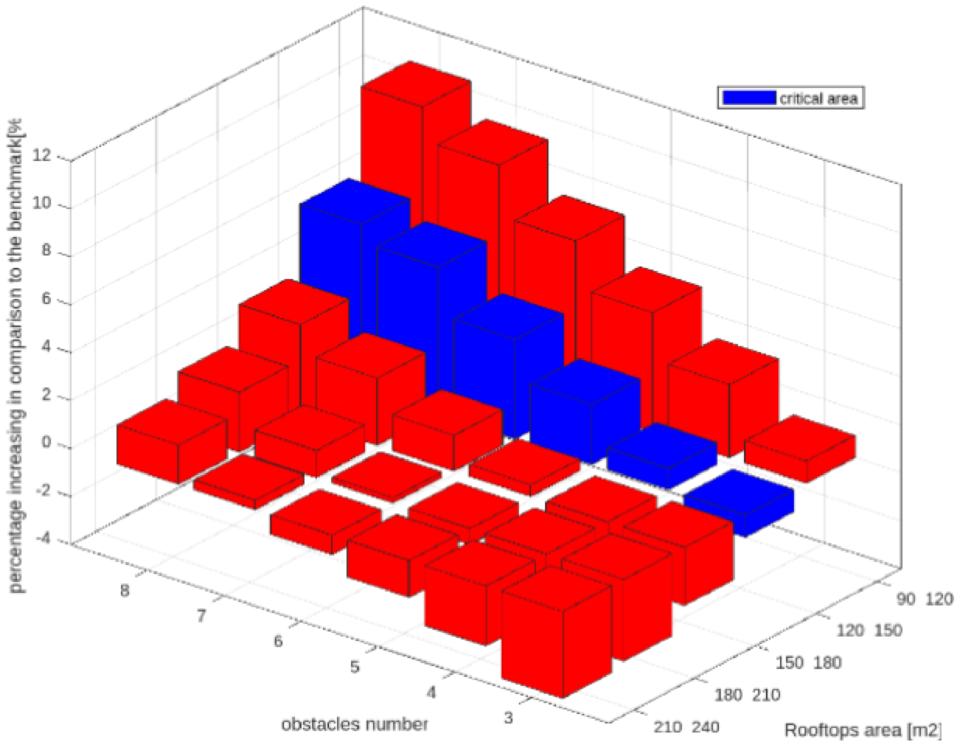

Figure 3.10: Capacity improvement in percentage in function of the number of obstacles and available surface: Certainteed panel

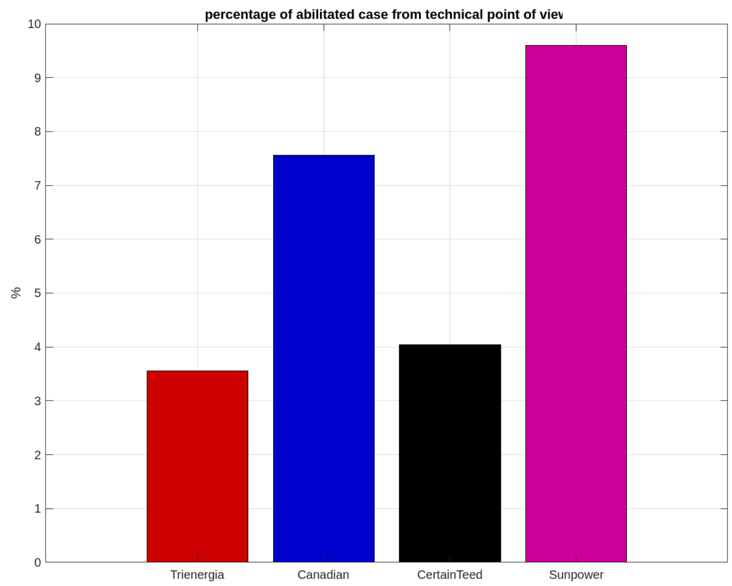

Figure 3.11: Percentage of cases that overcome the required technical performance

According to figure 3.11, the best PV panel from this point of view is Sunpower which allows surpassing the 20 kW limit, with 12% more of the rooftops. Custom-shaped panels (Trienergia and CertainTeed) are almost the same and they allow to increase by a 5% percentage of rooftops in which it is possible to install more than 20kW. It is also important to analyze the increase that is possible to obtain by installing the other panel from the capacity point of view. In particular, in the critical area, graph 3.12 delves into this topic.

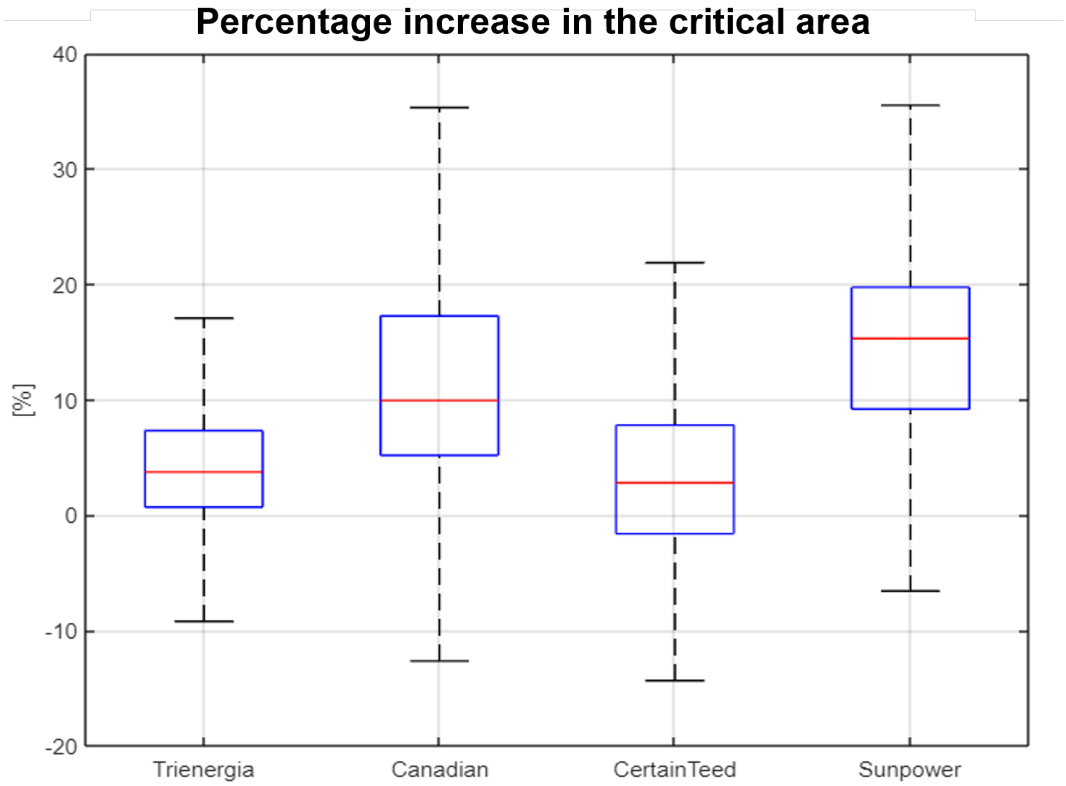

Figure 3.12: Capacity increase in percentage for rooftops with area 120-150 m^2

Therefore, it is possible by looking at this graph to understand that even if the maximum increase due to the high-efficiency panel is almost the same, Sunpower has most of the cases with a higher capacity installed, with a peak of 35% of increase in a few cases. Concerning the custom PV panel, it is possible to say that CertainTeed has the same cases with better performance, but on average, Trienergia allows it to install more capacity. Hence, the best panel from a technical point of view is the Maxeon 3 by Sunpower.

3.2 Financial results

In this chapter, the financial comparison between the different panels that are been analyzed is explained in order to establish which is the best panel from the economical point of view and to quantify the market share that is possible to reach using each technology. The beginning of the study is to calculate the financial KPI such as the IRR and LCOE in function with the technology used and the dimension of the rooftops. Afterward, by comparing each of the IRR of the investments, it is possible to establish which is currently the best panel. This section ends with a sensitivity analysis of the panel cost to find out which is the maximum cost that allows having the same IRR of the benchmark technology. The analysis is made on 2500 random rooftops and is divided into 2 sections:

- the first comparison is between the benchmark technology with the highest possible price with the other technology that does not have a cost that takes advantage of the scale benefit. So imagining to buy a small number of panels

- The second comparison is between the benchmark with a cost of 320 €/kW and the Canadian solar with a cost of 360 €/kW. The reduction of price is under the hypothesis to buy a large number of panels and obtain in this way a reduction in prices.

3.2.1 IRR analysis for high-cost devices

The results obtained using the formula 1.2 for the first case are resumed in figure 3.13. Using this graph, it is also possible to validate the model. In fact, comparing the average data with the BU in this condition, they get similar results. From this graph, the first conclusion that is possible to arrive at is that there is no technology that is better than the benchmark but the best one seems to be Trienergia. Certainteed has been excluded from the analysis since its performance is too low. This is confirmed by using the LCOE, in fact as is possible to see in the graph 3.14, CertainTeed has low performances also in terms of this KPI. Another detail is that the Benchmark also from this point of view results in a better investment in this case of the initial price.

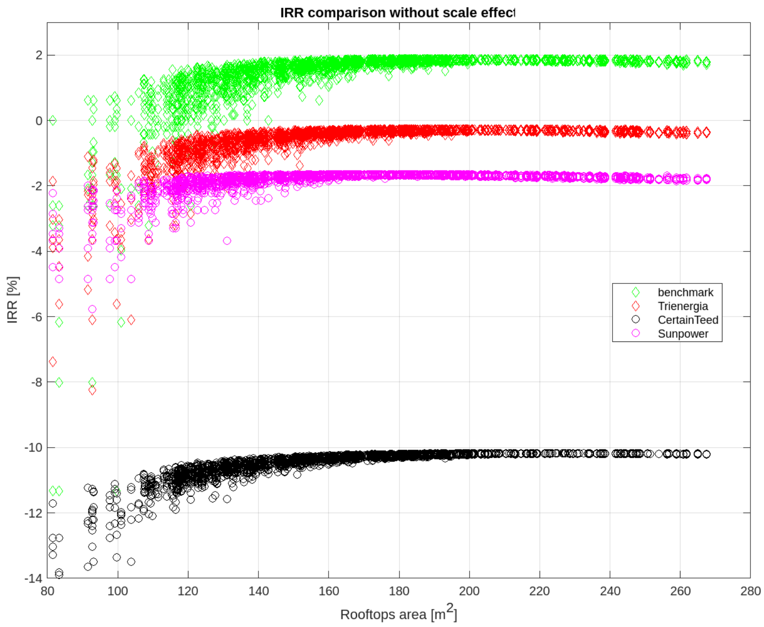

Figure 3.13: IRR in function of rooftops' area per technologies

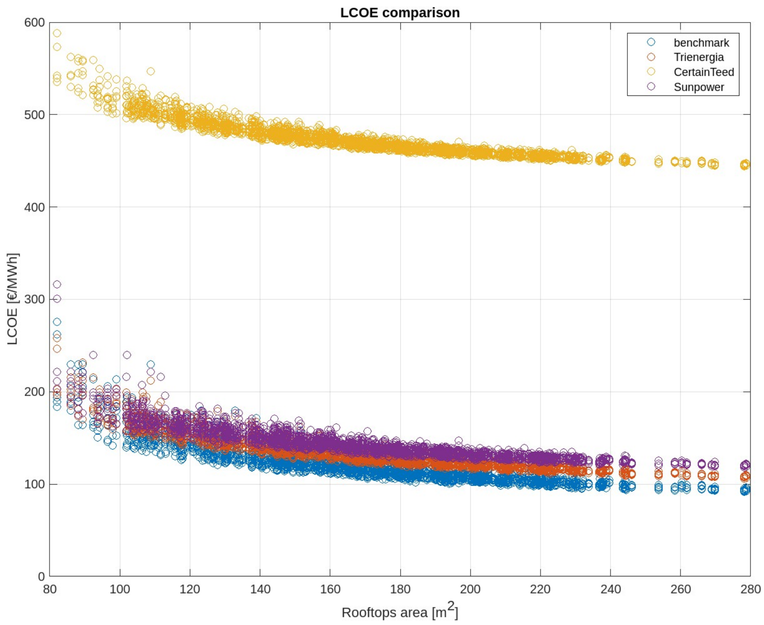

Figure 3.14: LCOE in function of the rooftops' area per technology

Since Certainteed can be excluded, a focus on the other three technology has been performed and shown in figure 3.15:

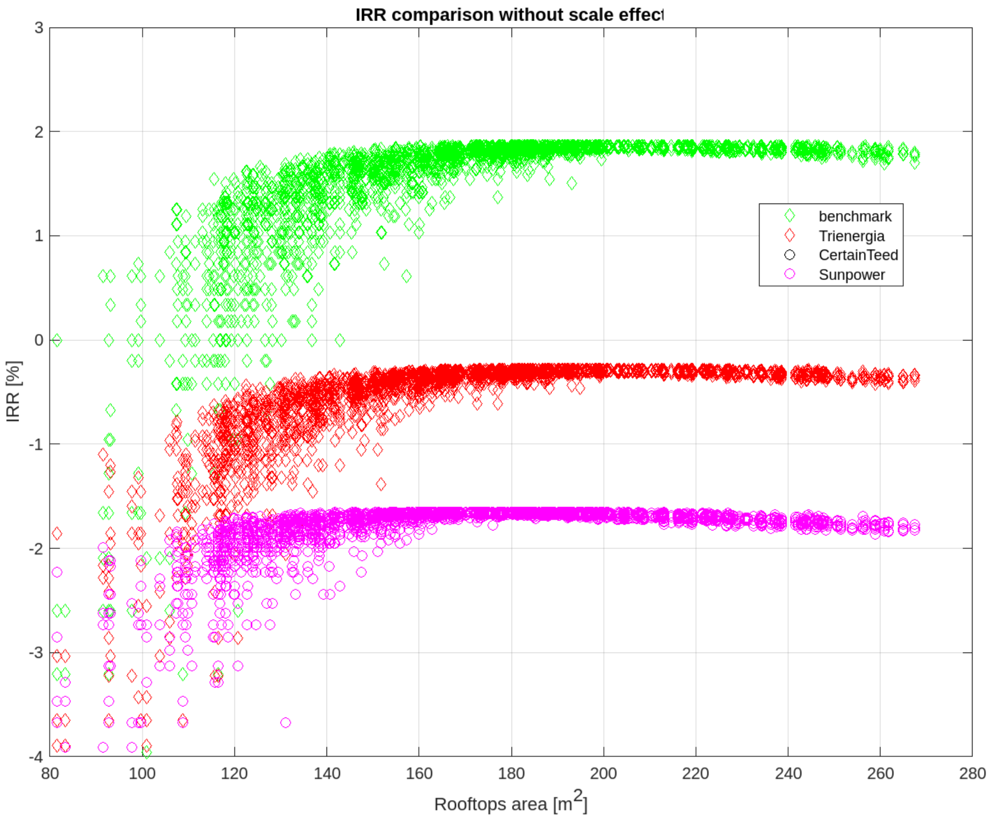

Figure 3.15: IRR calculated in function of the rooftops' area: zoom on the best 2 technologies

Now it is easier to recognize that by increasing the global efficiency of each panel (in order: Trienergia panel, Benchmark panel, Sunpower panel), the maximum of the curve moves towards the left. This is due to the fact that since they are able to install more capacity in less space, they can meet the energy load with smaller rooftops and gain the maximum benefits from the GSE incentive. Another piece of evidence is that there is a maximum and a range of values enclosing the maximum reached for the rooftop of dimensions around 120 150 m^2, which is also the critical area individuated in the technical analysis. In the same way, in the graph 3.16 the LCOE has been zoomed to try to discover a trend.

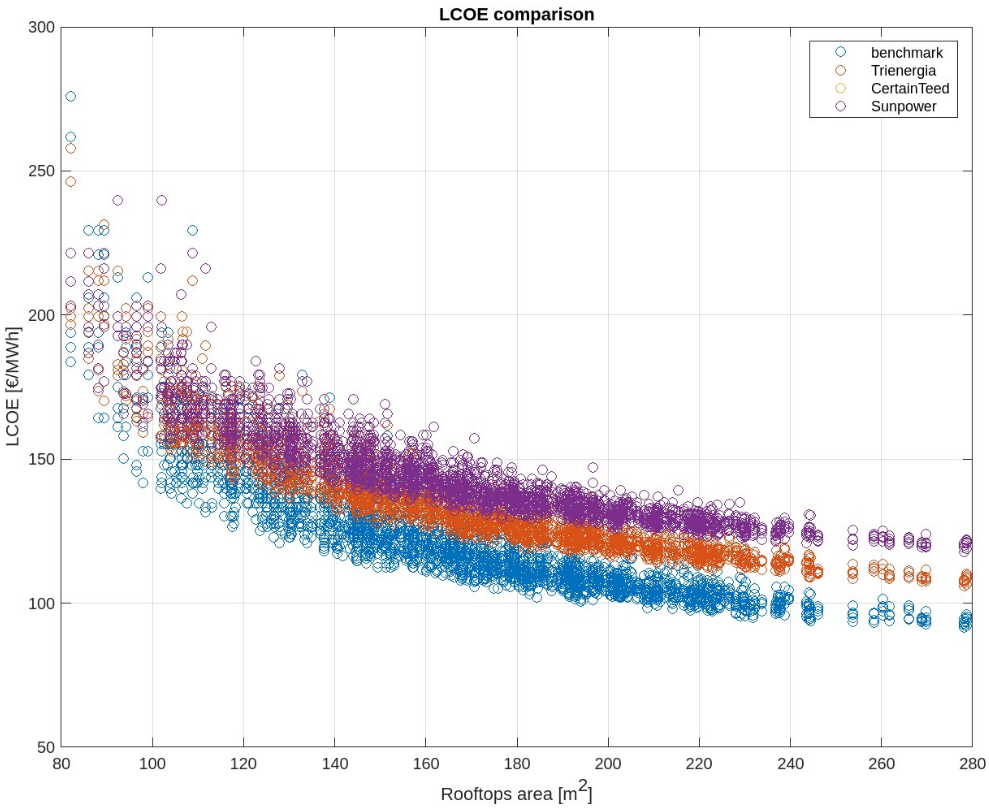

Figure 3.16: LCOE in function of the rooftops' area: zoom on the three best 2 technologies

In this case, the trend is descending, and is impossible individuate a suitable area to use. As was predictable the LCOE decrees with the increase of the area since the energy produced compensate for the increase in price. This graph shows also as the LCOE is not a good indicator since don't take into account self-consumption.

3.2.2 Focus on "Canadian" PV type

For Canadian, the performance is certainly better, which is mostly due to the low price that can be found taking into account the scale economy. The results are encapsulated in the graph 3.17. According to this graph, Canadian, at this price, perform considerably better than the benchmark reaching an IRR of around 3.2%. Also in this graph, the maximum is reached between 120 and 150 m^2 for the same reason as the other cases. And exactly, in the same way, there is a plateau that lasts until 220 m^2. To explain this last aspect, figure 3.18 is necessary.

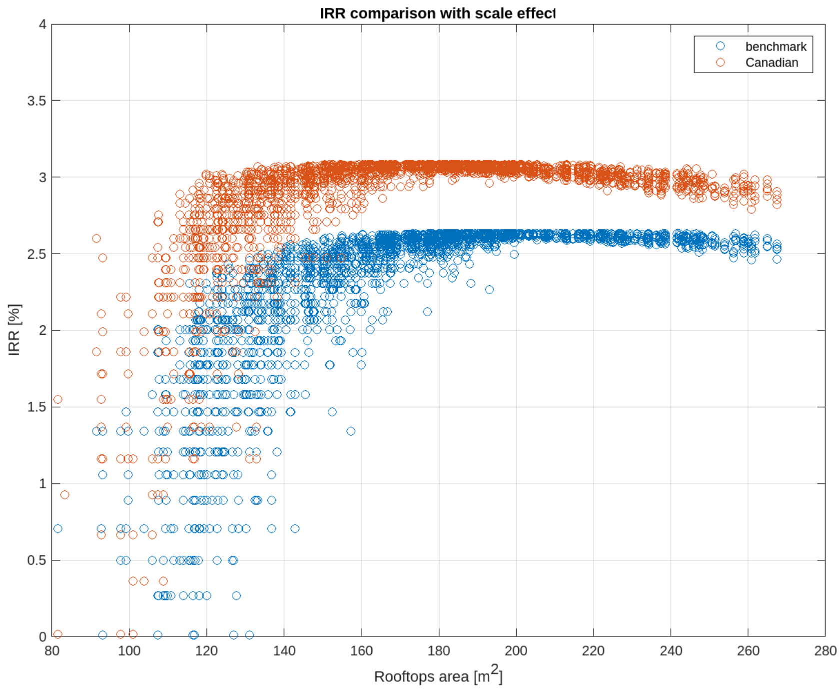

Figure 3.17: IRR in function of the rooftops' area: Canadian panel

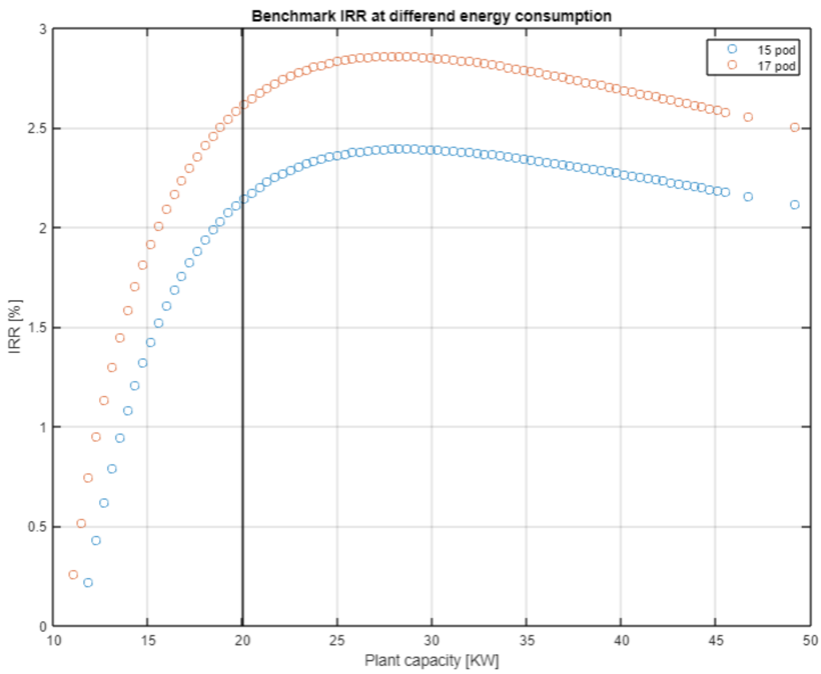

Figure 3.18: IRR of the reference panel for different energy loads in function of the power installed

As it is possible to get from this last graph, around the maximum of the curve, the IRR barely does not change. This effect creates the plateau of the previous graph. In fact, a big number of different rooftops exist with different areas that allow installation close to the maximum. From this graph, another possible conclusion is that after a certain capacity, it is not useful anymore to install. Undoubtedly, this amount will change if the load has a different shape. However, by fixing that, it is possible to obtain easily which capacity allows reaching the maximum IRR. In this case, it is around 27 kW. Another detail is that the limit of 20 kW is not suitable limit from the IRR point of view because in cases with a high load, it is possible to also reach a good IRR (around 2.5%) but with less capacity.

Regarding the LCOE the result is similar, Canadian produce more energy, and that compensates at all the higher cost, as is shown in figure 3.19.

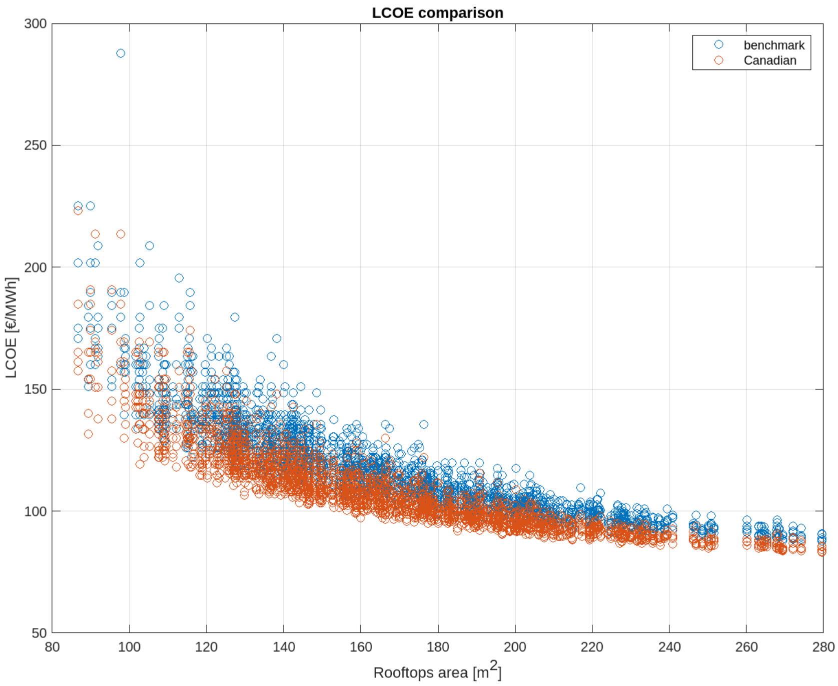

Figure 3.19: LCOE in function of the rooftops' area: Canadian panel

The higher amount of energy is due to higher efficiency but also to a better degradation coefficient. The LCOE is a bit lower around 100 $\frac{€}{MWh}$ and the trend is similar to others technologies. In fact, when the capacity increase the LCOE increase with an important reduction and a plateau explained by the not linear reduction of cost in the function of capacity installable. This concludes the economic analysis of the technology in the present state. Now the section about the sensitivity and the scenario analysis is explained.

3.2.3 Sensitivity analysis

The sensitivity is divided into two sections. The one for Trienergia with the goal to individuate the price that a similar device should have to reach the same IRR of the benchmark technology. The second sensitivity is made increasing the starting price of Canadian panel, to discover which is the maximum price that is possible to pay, in order to keep the advantages in terms of IRR that the high-efficiency technology has on the benchmark.

Sensitivy on Trienergia

The simulation has always been made with 2500 cases, in particular, 500 different rooftops with 5 combinations of obstacles in each one. For each simulation, the price of the panel was changed in a parametric way of 5%. Afterward, the simulation was repeated to find out exactly which is the price that allows, on average, to reach the same IRR. At the same time, a parametric variation on the load is made by modifying the number of floors of the building and so adding 2 PODs for each simulation. As it is shown by the graphs 3.20 3.21 , the reduction needed is around 45%, so the simulation was made between 50 and 60% of the initial price.

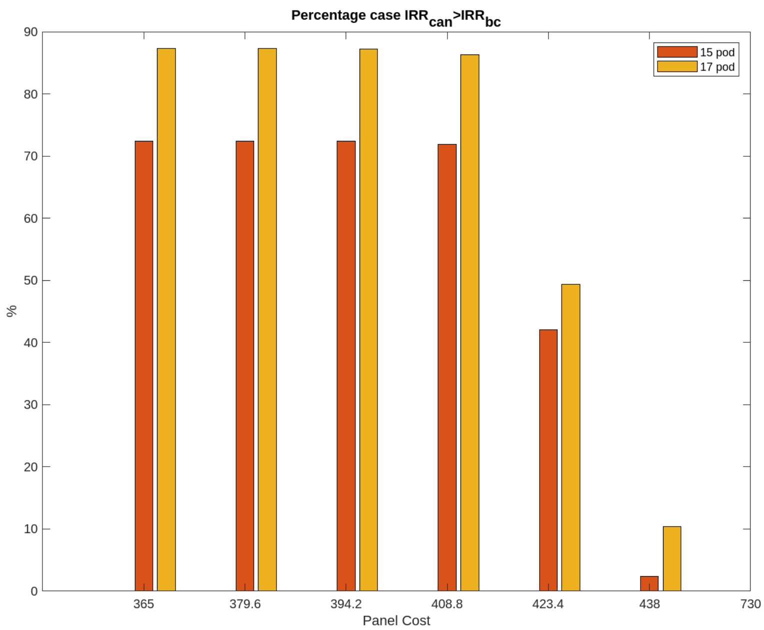

Figure 3.20: Percentage of cases in which Trienergia panel's IRR is greater or equal to the reference panel

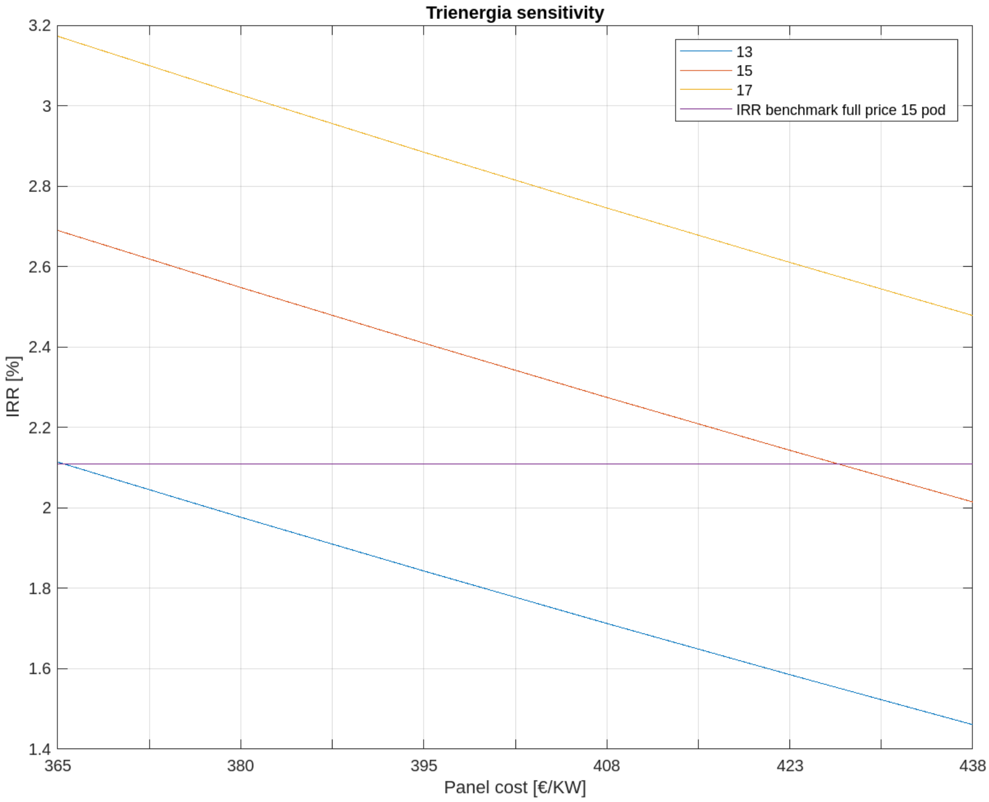

Figure 3.21: Average IRR in function of the Trienergia panel price

Feasibly, from the graph, when the cost of the panel is 27 €/kW higher than the benchmark, on average, the same IRR for a high energy load is reached. This number is increased for higher consumption and reduced for lower since the load increases the self-consumption and so increases the incentive obtained. That is evident from the first graph since the yellow bar is always higher than the red one. The reason that a blue bar is pointless is that to be counted as a good case, the minimum IRR should be 2%. As it is easy to derive from the graph (3.13), the benchmark is never higher than this limit. In conclusion, it is possible to establish that the price that allows reaching, on average, the same financial performance as the benchmark is 427 €/kW. While only in the case of consumption around 4000 kWh/year each PODs for 13 PODs, there are only 10% of the rooftop that guarantees a financial advantage. In order to establish which is the best possible rooftop, the difference between the IRR of the benchmark and the one of Trienergia in the case of 24 €/kW has been plotted in function of the rooftop area. The graph 3.22 showcases those results.

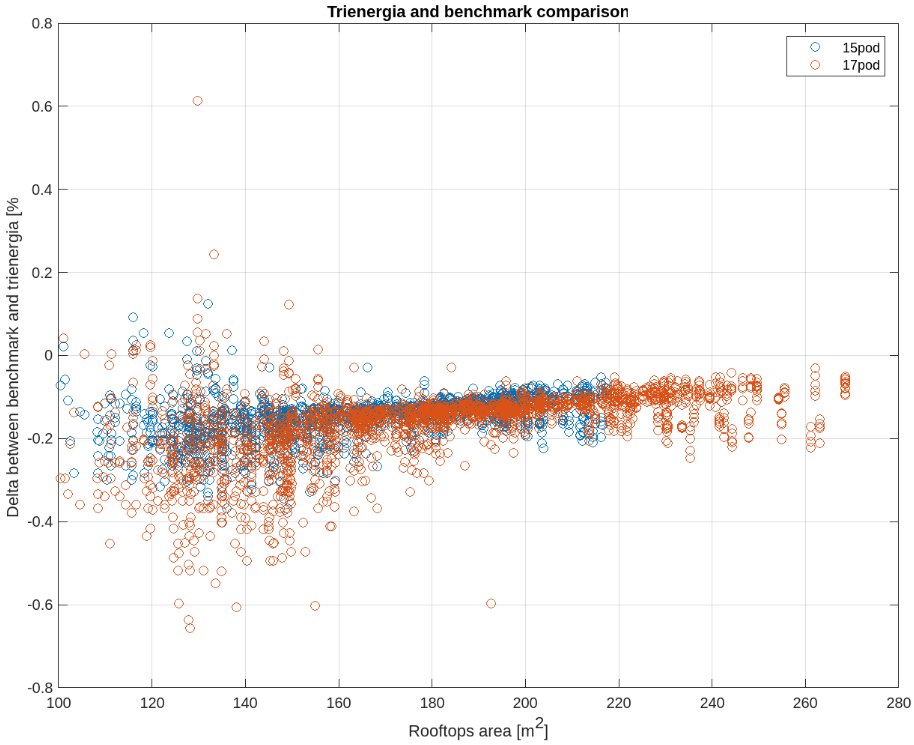

Figure 3.22: Difference between Trienergia panel IRR and the reference ones in function of the rooftops area for different energy loads

the graph shows that between 100 and 160 m^2, there is an advantage that also remains for a lower energy load. The maximum advantage is between 120 and 150 m^2 and that is due to the fact that the product of the technical increase and the IRR increase for capacity installed is maximum in this section. It is also possible to discover the starting of an increasing reduction, which is due to the different reduction slopes of the IRR curve after the maximum. However, this information is useless since even if the rooftop allows to install of more capacity, it is inefficient to install a higher capacity than the one that maximizes the IRR. In fact, in this way, the investments will be less profitable.

Sensitivity of Canadian

The goal for Canadian is different, the analysis is made by increasing the starting price to reduce the IRR until it is the same as the benchmark. That is useful to figure out which is the maximum price that an entity should pay for a panel with similar energy performance. That is advantageous since for the price obtained for this technology, transportation, and storage costs are already taken into account. The sensitivity on the load is not performed since an increase in energy consumption will increase the price of Canadian. The sensitivity is performed by increasing the price by 5% each step until the average IRR performance of the benchmark is reached. The percentage of cases in which, for each price, Canadian is better than the benchmark is also calculated with the same rules as before. The results are summarized in the graphs 3.23 3.24.

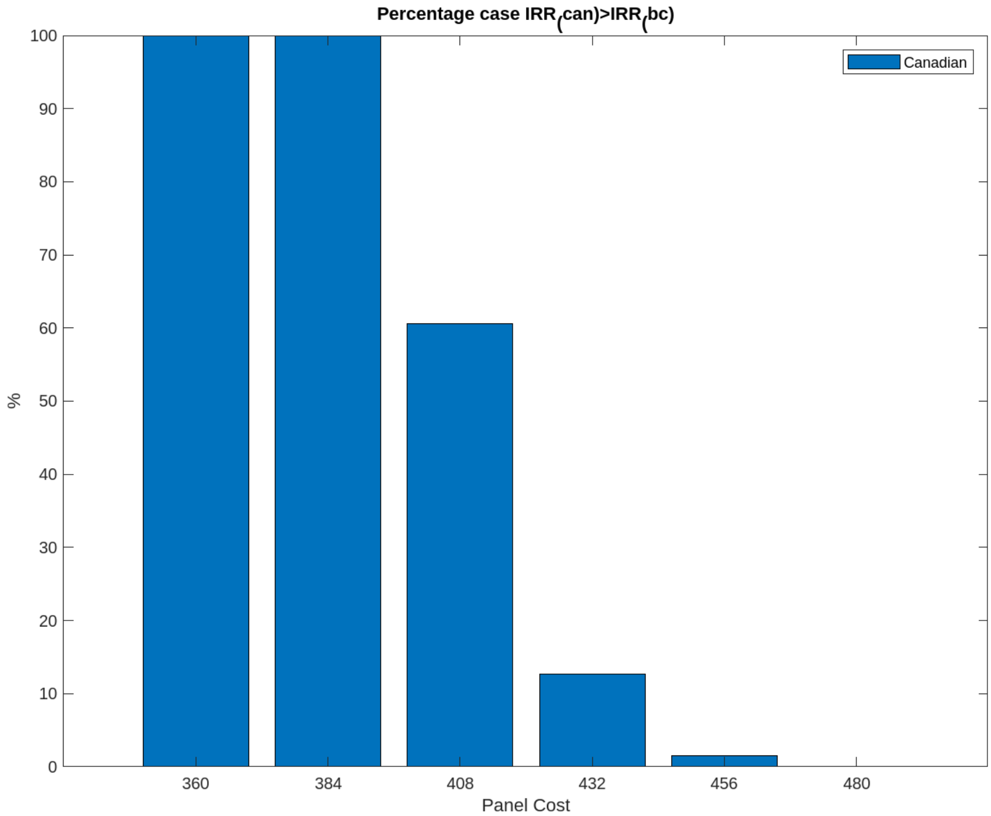

Figure 3.23: Percentage of cases in which Canadian panel IRR is greater or equal to the benchmark

In accordance with the graph, the cost that makes the IRR of the HTJ technology equal to the benchmark's is 415 €/kW, so around 30 % more than the price of the benchmark technology. Also, in this case, the simulation has been performed

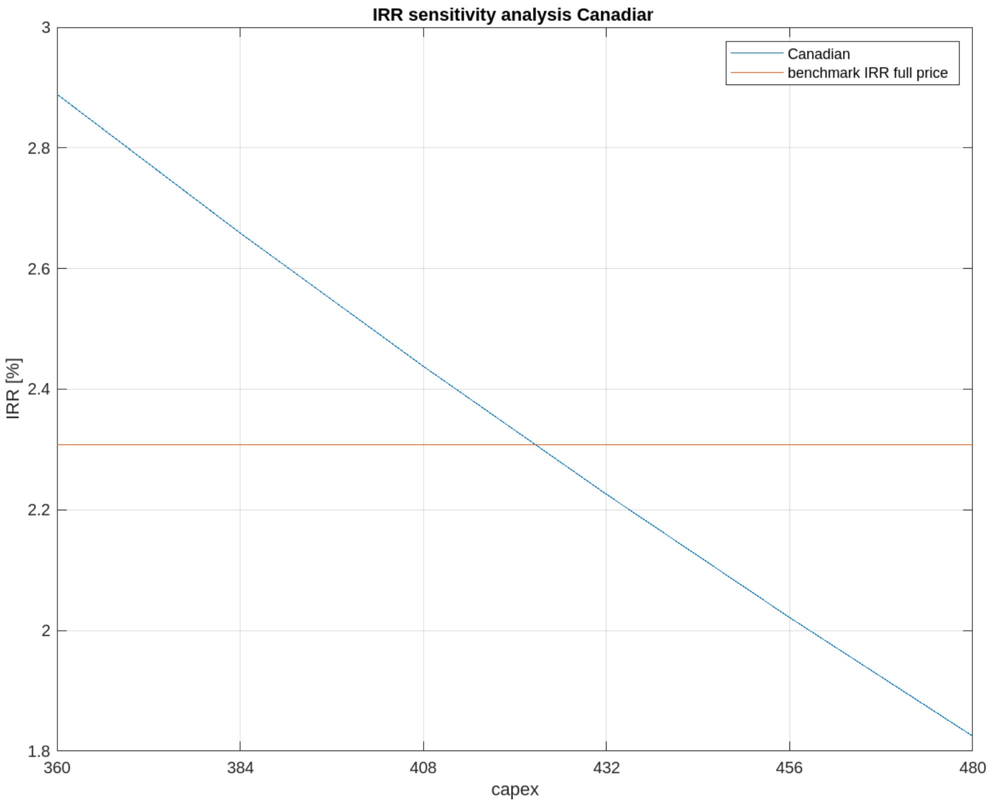

Figure 3.24: Average IRR of Canadian panel in function of its cost

with 2500 rooftops. The last price obtained, which allows cases in which changing technology is profitable, is 480 €/kW. Similarly, it is important to discover which rooftops that fit better with this technology. The same analysis of Trienergia was made, so a difference between benchmark and Canadian has been calculated, signified by a Δ. As previously, the more negative the difference, the more advantages there are for Canadian. The results are expressed in figure 3.25.

From the figure 3.25, the maximum advantages can again be found between 120 and 150 m^2. As previously, due to the product of the slope of the curve IRR vs capacity and the increase of capacity in this section of the graph. It is also evident that for ceilings reaching 180 m^2, picking Canadian is always an advantage, at least with this energy load. Exactly as before, to take into account what happens after 220 m^2 is futile since the maximum profitability is already reached with a lower capacity.

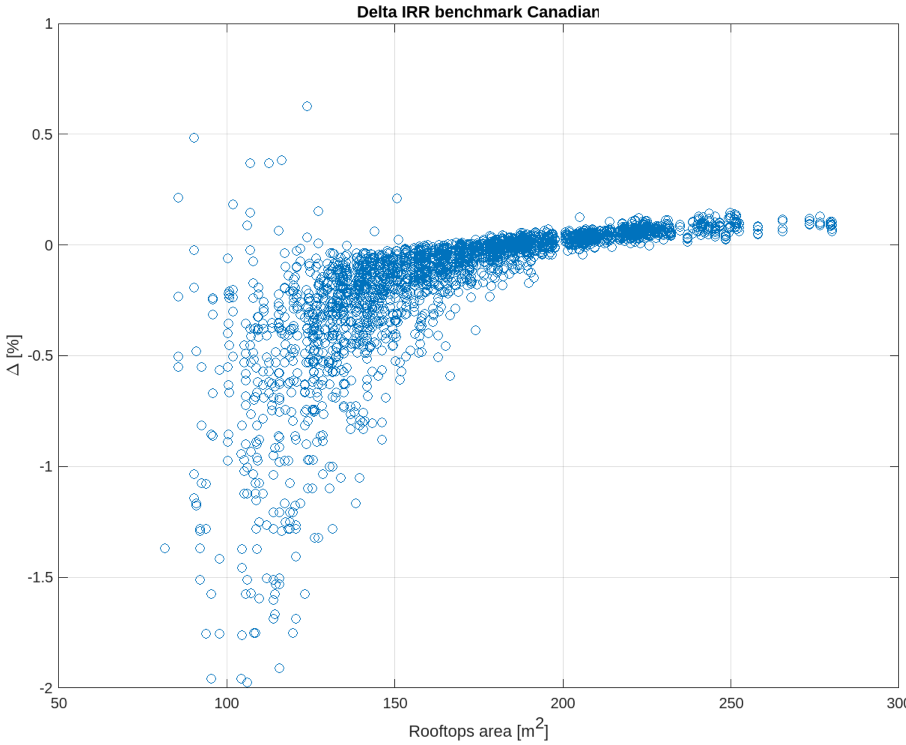

Figure 3.25: Difference between the IRR of Canadian panel with a cost of 420 €/kW and reference ones

3.2.4 Final consideration

It is possible to conclude that in the actual market, the high efficiency is the best purchase if its panel price is under 420 €/kW as shown in the graph 3.26: According to this graph, Canadian is considerably better at the price of 360€/kW and keeps this advantage until the price of 420€/kW. Keeping this margin on the benchmark is significantly higher than the manufacturing cost difference. For this reason, it is possible to forecast that now is the best choice to purchase but it will probably remain the best among the panels taken into account, also in the future. Another important conclusion is that the maximum purchase cost for a device like the Trienergia one is 427 €/kW. So in this case, the margin is not large enough, making it more difficult imagining a future in which similar devices are produced at this price. The rooftops between 120 and 150 m^2 are the most suitable for both of the devices. In fact, the best improvement in both cases is obtained in this category of the ceiling. That observation is also confirmed by the graph 3.27:

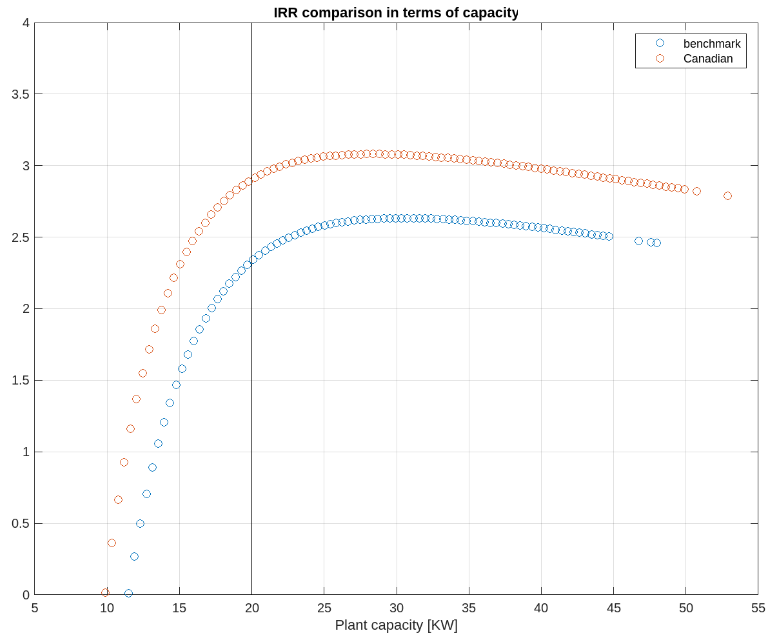

Figure 3.26: IRR comparison between Canadian and reference panel in function on the capacity installed

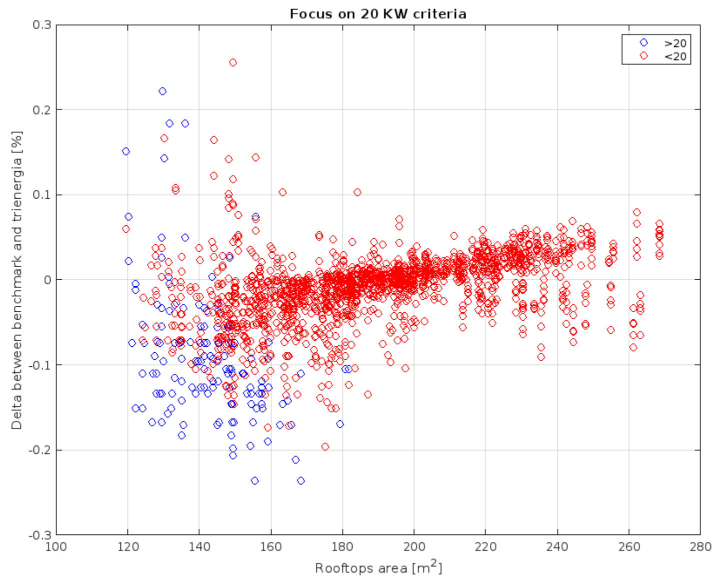

Figure 3.27: Difference between IRR of Trienergia panel with a discounted price and the reference ones: Different color in case the plant capacity is lower than 20 kW

From this graph, it is also possible to figure out that the criteria of 20kW are pretty accurate for the benchmark technology in the average energy load. However, it should be adjusted in case of different consumption or other devices. Particularly, as seen in (4.14), for Canadian a good set point would be 17 kW.

Chapter 4

Conclusions

The work started with a literature review to determine the market trend in PV technology in order to determine which technology can become the golden standard in the near future. Furthermore, market research that identifies panel models was conducted in response to a suggestion found in the literature. As a result of this section, four panels have been identified as promising devices, taking into account their technology and their specifications. Later, a number of real-application case studies have been evaluated. These devices were tested on PV design software, Aurora solar, to compare the benefits with the actual standards. Because the results of these simulations were not coherent, identifying a unique trend was difficult. As a result, a numerical simulation tool has been created in order to obtain results that can statistically quantify the benefits of new possible solutions compared currently commercially used PV panels. The model evaluates the capacity of these devices on rooftops of various sizes and obstacle dispositions in order to find the one that maximizes investment revenue. Indeed, the model allows for a comparison of the financial performance of the various plants as well as for the calculation of key performance indicators (KPI) to determine which is the best investment for each type of rooftop. The conclusion of this study is that in the present market condition, the choice that maximizes the IRR and minimizes the LCOE is the "hihero" panel produced by Canadian Solar. This panel reaches an IRR that can be in some cases around 30% higher than the benchmark panel used in this analysis. Following that, a sensitivity analysis on some of the models' inputs, such as energy prices and building energy loads, was performed in order to complement the forecast analysis performed. Also in this case, the Canadian model still proved to be the most promising technology among the ones considered, but the Trienergia ones can become a good alternative in the near future with performance slightly better with an improvement of around 10% in case of a reduction of the panel price or for high energy loads. Finally, an analysis of actual Italian residential constructions was performed in order to quantify the possible market share that the technologies can achieve and thus the potential revenue due to the increased market coverage. The result of this analysis highlights that the average Italian building has between 120 and 150 square metres of available area for PV applications. Those are the dimensions that maximize the revenue of both Canadian and Trienergia products, reaching an improvement of 30% in the economical KPI in spot case in this area. To conclude the work, a graphical interface has also been developed for the tool designed. Receiving as input: the economical model, the energy load, the geographical position, and the data of the panel, the application can perform the same analysis as the one presented in this manuscript and provide the user with the most relevant graphs. This application has been distributed internally in Edison S.p.A.

4.1 Next step

The next steps of this work can be in different directions: the most important improvement on this work is to implement an image recognition system that allows calculating from a gis image the rooftops suitable to install PV panels. This allows the removal of the random construction of the rooftop and it gives more reliability to the software. Another useful improvement is implementing a better displacement algorithm for the filling of the rooftops. In fact, the best substitute for the actual algorithm can be one based on artificial intelligence that is able to maximize the IRR of the investments or the energy produced. Another possible improvement is to implement in the work other KPIs that give information on other aspects of the investments. Another possibility is to implement in the calculation also the battery and verify the best investments taking into account also the possibility of energy storage.

Appendix A

Production model

The formulas used to Calculate I_p are the following ones

$$\delta_s = (23.45 \cdot \sin(360 \cdot (284 + numday))/365) \tag{A.1}$$

$$h_s = (15 \cdot (LST - 12)) \tag{A.2}$$

$$\alpha = \arcsin(\sin(L) \cdot \sin(\delta_s) + \cos(L) \cdot \cos(\delta_s) \cdot \cos(h_s) \tag{A.3}$$

$$\theta = \arcsin((\cos(\delta_s) \cdot \sin(hs)) \cdot \cos(\alpha)) \tag{A.4}$$

$$cos_i = \cos(\alpha) \cdot \cos(\alpha_s - \alpha_W) \cdot \sin(\beta) + \sin(\alpha) \cdot \cos(\beta) \tag{A.5}$$

$$I_p = I_d \cdot cos_i \tag{A.6}$$

where:

- $alpha_W$ = panel azimuth angle
- L= latitude
- h_s= solar hour angle
- LST =local standard time
- θ = Azimuth angle
- β = Tilt angle
- I_d = global irradiance

The formulas to calculate η_p are the following ones

$$\eta_p = \eta_{std} \cdot \eta_{deg} \cdot \eta_T \tag{A.7}$$

where η_{std} is the efficiency in standard condition, η_{deg} is the efficiency due to the time degradation of the panel calculated as:

$$\eta_{deg} = 1 - coef_d \cdot age \tag{A.8}$$

while η_T is calculated as:

$$\eta_T = 1 - \beta_T \cdot T_{cell} \tag{A.9}$$

$$T_{cell} = T_{env} + \frac{(T_{env} - 20) \cdot I_p}{800} \tag{A.10}$$

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