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Photovoltaic Solar Technology: Economically sustainable self-consumption and Levelized Cost of Energy (LCOE) indicate its potential to generate energy at the same cost as non-renewable sources

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Introduction

Sufficient and secure energy is a fundamental need for welfare and economic development of a society. Since energy and energy-related industries have a strong environmental impact, it is vital to provide an energy system to overlay the needs of the economies and preserve the environment, hence the need of a sustainable energy system.

Energy sector give rise to a challenge in the context of sustainable growth because of its size, complexity, path dependency and dependence on long-lived assets.

Furthermore, the demand for two hydrocarbon supply sources, oil and coal, is expected to peak around 2030[1] (for oil as late as 2040[2]), to highlight the need of an energy system independent from fossil-fuels, which means based on renewable energy, in the long-term.

Thus, the need of an efficient and sustainable energy system is clear, from which the importance of renewable energy. From the market analysis within the renewable technologies the photovoltaic solar is the predominant, having achieved great results in terms of installed capacity and efficiency. The diffusion in Italy of this technology is entirely due to incentive policies, in that period the installed power grew by 3566% between 2008 and 2013. However, the true challenge, partially achieved, is to generate energy through photovoltaics without the need of incentives. For these reasons, the goal of this thesis is to demonstrate the competitiveness of the photovoltaic solar energy with respect to traditional non-renewable sources. To do so, a performance indicator called Levelized Cost of Energy (LCOE), which can be considered as the average generation cost, will be computed. It is worth noting that two different purposes of having a photovoltaic plant will be analyzed, the former relates to self-consumption while the latter is related to the sale of energy to the GSE or independent traders.

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[1] Accenture Strategy: Energy Company of the Future, 2017.
[2] Accenture Strategy: Energy Company of the Future, 2017.

Chapter 1

Solar Photovoltaic Technology

This chapter aims to illustrate the basic science behind photovoltaic technology, the main components of a PV[3] plant as well as the basic choices that are made while designing a PV plant. Hence, it will first illustrate the photoelectric effect, which was the main historical milestone in developing the technology. It will discuss the main components of a photovoltaic energy plant and the main technologies which are on the market. Furthermore, it will analyse the basic choices that must be done while designing a photovoltaic plant will be performed.

1.1 Photovoltaic Effect

The first milestone in the history of this technology is the discovery of the photovoltaic effect, the phenomenon behind the corresponding technology. The French scientist Edmond Becquerel discovered the photovoltaic effect when he was nineteen (1839), while performing an experiment placing an electrolytic cell made up of two metal electrodes into an electricity conducting solution. While performing the experiment, Becquerel noticed that a difference in potential (voltage) developed when light struck the electrodes.

[3] PV: abbreviation for photovoltaic;

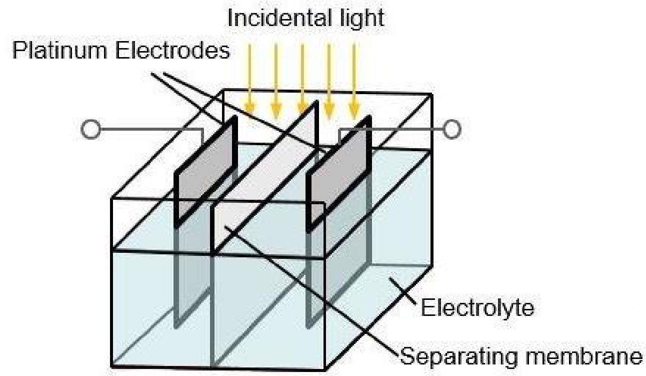

Figure 1.1: Experiment Performed by Edmond Becquerel

The second milestone in developing the modern technology was the 1883 realization of the first solar module. An American inventor named Charles Edgar Fritts achieved this by coating a plate of copper with selenium topped with a thin film of gold. The cell achieved an energy conversion rate of 1 to 2 percent. The inventor reported that the module produced a current *"that is continuous, constant and of considerable force"*.

Charles Fritts installed these first solar panels on a New York City rooftop in 1884 as shown in the figure below.

Figure 1.2: First solar array installed on a New York City rooftop by American inventor Charles Fritts

Therefore, the capability to get a voltage from the sunlight (with proper tools) was acknowledged from 1839 onwards, although the theoretical scientific reason behind it was still unknown.

The first person to postulate and explain the phenomenon was Albert Einstein, who stated that light contains packets of energy called "light quanta" (now called photons) in a famous paper published in 1905: *"Energy, during the propagation of a ray of light, is not continuously distributed over steadily increasing spaces, but it consists of a finite number of energy quanta localised at points in space, moving without dividing and capable of being absorbed or generated only as entities"*[4]. Furthermore, Einstein noted that the photoelectric effect depends on the wavelength, and thus on the frequency of the light. Only light above a certain frequency would have enough energy to liberate an electron.

To clarify, it is feasible to say that the slight difference between photoelectric effect and photovoltaic effect lies in the way electrons are emitted. Electrons are emitted in an open space in the former, whereas electrons directly enter a different material upon emission in the latter.

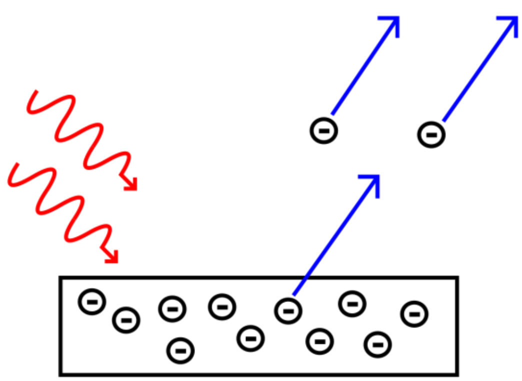

Figure 1.3: Photoelectric Effect

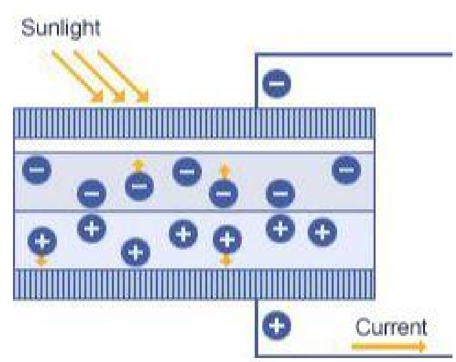

Figure 1.4: Photovoltaic Effect

[4] Citation taken by the first article of the *ANNUS MIRABILIS* papers, published by Albert Einstein in 1905.

It is therefore possible to say that photovoltaic effect may be considered as a sub-category of the photoelectric effect.

Early discoveries in this field failed to gain a good conversion rate, one that remained 1% or less, for almost the first fifty years of the twentieth century. In fact, the first practical solar cell was constructed in 1954 by Bell Laboratories in Murray Hill, New Jersey. It had an efficiency of 6%. The solar cell was constructed following the same principles of a transistor, which means that a junction is set in silicon crystal. The junction divides it into two zones, one of which contains a slight impurity that creates an excess of movable electrons while the other zone has that instead functions to absorb electrons instead of producing them.

1.2 Components of a photovoltaic plant

This second sub-chapter aims to illustrate the basic components of a photovoltaic plant. It will explain the following concepts in the order shown:

- Photovoltaic module;
- Mounting and Tracking system;
- Inverter;
- Meters;

1.2.1 Photovoltaic Module

The basic constituent of a photovoltaic module is the photovoltaic cell, which is an electrical device capable of converting light directly into electricity. A solar cell can be compared to a diode with a large section located within two electrodes. The diode consists of two different doped zones: one is called “P-type”, where there is an excess of electron holes; while the other, named “N-type”, has an excess of electrons. This excess either of electrons holes or electrons is obtained doping[5] the material.

[5] Doping of semi-conductors is the practice of adding small percentage of atoms which do not belong to it initially with the purpose of modifying its electronic properties.

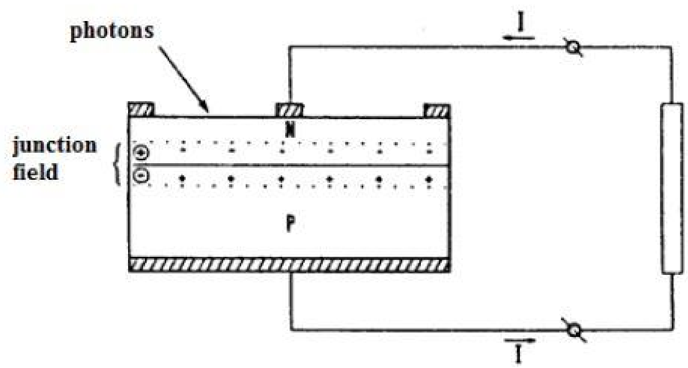

Figure 1.5: Structure of a crystalline silicon solar cell, image from the Photovoltaic Power System short handbook, F.Spertino

Electrons that flow from the N-type into the P-type form a distribution of positive charges in one zone, while a distribution of negative charges in the other (the junction region contains both but no mobile charges). Without going too deep in the "micro" operations of a solar cell, it can be said that only photons with enough energy are able to "push" an electron to jump from the valence band to the conduction band. To be better able to understand how photovoltaic cells function, have a look at the circuit shown below. A solar cell may be considered as a *de facto* current generator that, thanks to photovoltaic effect, can transduce in electricity the incident light.

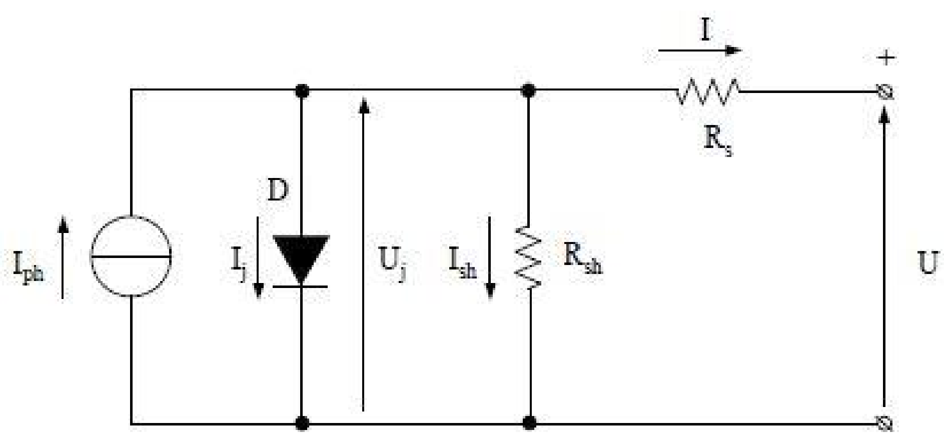

Figure 1.6: Equivalent circuit of a solar cell, figure taken from Solar Power System short handbook, F.Spertino

In this figure from the *Solar Power System handbook by F.Spertino* it is possible to describe the circuit as follows:

Iph: Current generator;

Rsh: Resistance given by the leakage paths along the lateral surfaces between the frontal grid and the plate of the solar cell;

Rs: Sum of volumetric resistance of the semiconductor, resistances of the electrodes and of their own contacts;

D: Diode connected in anti-parallel to let the current flow in one direction and block it in the other.

Applying Kirchhoff's law to the circuit and taking U as the voltage measured on the load, it is possible to find that:

$$I = Iph - Ij - \frac{Uj}{Rsh}$$

$$U = Uj - Rs * I$$

Hence, after having shown how a solar cell works, it is possible to illustrate how modules are built and which are the main families in the contemporary market.

The most common solar device is the photovoltaic module, which is a sandwich made of different layers put together. The most important part is the solar cell, as shown below. Since more than 90%[6] of solar device installations are silicon-based technology, no other technologies are going to be discussed.

[6] Data from the Renewable Energy Report, Energy Strategy Group (2019);

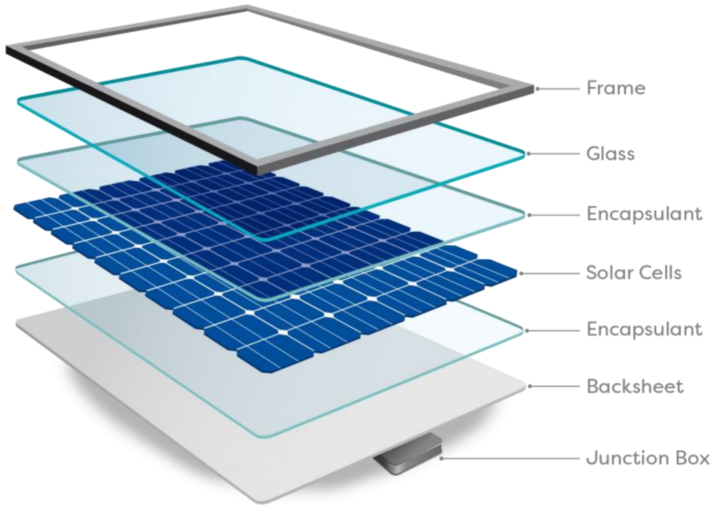

Figure 1.7: Photovoltaic Module Sandwich

The construction process of a solar cell starts with the production of the solar grade silicon, which is the core component of this technology. Although silicon is the second most abundant element on earth after oxygen, it is needed to fuse it with carbon powder to obtain pure silicon[7] of almost 98% of purity. Depending on the level of impurity it is possible to distinguish three different kinds of silicon: metallurgical silicon, solar grade silicon and electronic grade silicon.

Without discussing the production process of solar grade silicon extensively, it is possible to state that there are mainly three kinds of modules at the moment:

1. The p – Si Technology;
2. The m – Si Technology;
3. Thin film Technology.

First, before diving deep into the differences of the families listed above, it is better to explain what solar cell efficiency is. Solar cell efficiency refers to the percentage of energy contained in solar irradiance which is converted via photovoltaics

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[7] Silicon found in nature is the second element for abundance on earth after oxygen but it is not pure;

into electric energy. The efficiency of commercial photovoltaic modules gravitates between 13% and 20% at this moment (2020).

Concerning the first family, the Poly – Crystalline (p - Si) technology that is most commonly employed in the world, silicon is produced starting through a metallurgical purification process starting with the metallurgical grade silicon. Polycrystalline or multi-crystalline silicon (multi – Si) cells consist of little crystals giving the material its typical *metal flake effect* shown in the figure below. The *metal flake effect* is due to the misaligned crystals.

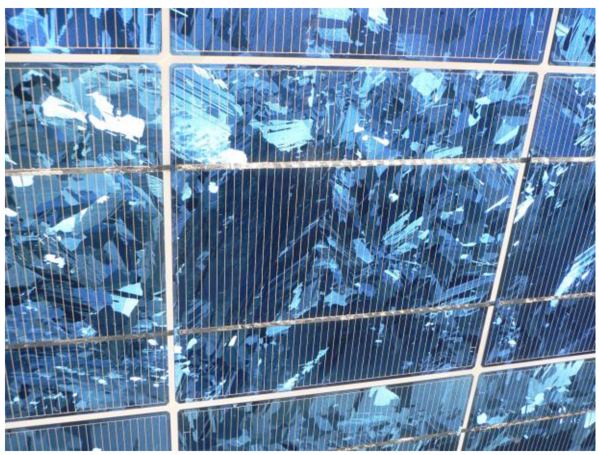

Figure 1.8: Polycrystalline solar cells

Regarding technical characteristics, the efficiency of commercial solar polycrystalline modules gravitates around 14% and 17%, which has a slightly lower average than that of monocrystalline modules (given the same production surface) but with slightly lower production costs as well.

Monocrystalline photovoltaic modules are the first developed in PV history, and they reach higher efficiency of around 18% and 22%, depending on the typology of modules, given the same production surface, with respect to polycrystalline ones.

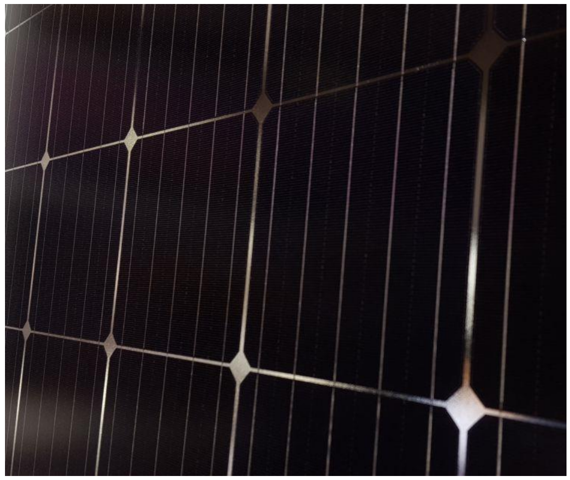

Figure 1.9: Monocrystalline photovoltaic module

Concern the last family of Thin film Technology, common characteristics[8] are:

- Lower processing temperature (300 – 500 °C);
- Integration of the cells simultaneously with their production (integrated or monolithic connection of cells which form the module);
- Reduced current 1-3 A and efficiency between 6-15%;

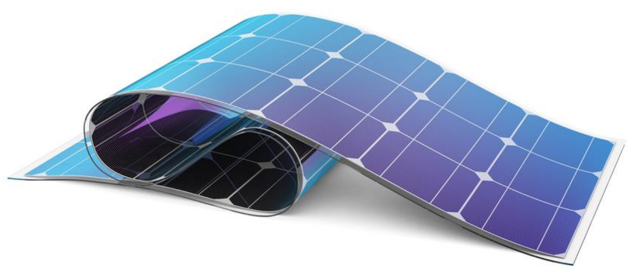

Figure 1.10: Thin film technology

1.2.2 Mounting and tracking system

Photovoltaic modules must be mounted on a structure in order to keep them oriented in the right direction. Furthermore, the mounting system provides them with structural support and protection. Mounting structures can be of two types: fixed or tracking. Fixed

[8] Characteristics taken from the Solar Power System short handbook by F.Spertino(2016).

mounting structures keep the module or a string of modules at a fixed tilt[9] and orientation (azimuth[10]) angle.

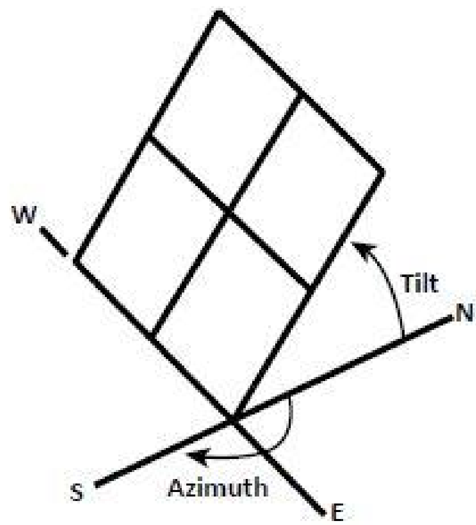

Figure 1.11: PV array Tilt and Azimuth

The mounting structures are usually made either of steel or aluminium, despite that there are examples of different materials such as wood also used. Purchasing a good quality mounting structure is often a low-risk and low-cost option. Furthermore, some producers provide soil testing qualification processes as well, to see if any special condition is present. Fixed mounting structures are therefore arguably simpler, cheaper and have lower maintenance necessity with respect to tracking systems.

In contrast, tracking systems are usually taken into consideration in location with a higher solar irradiation than the average, where single or dual-axis tracking systems can be used to increase the average total annual irradiation. As the name suggests, single axis tracking system change either the tilt or azimuth angle only, whereas dual axis

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[9] Tilt angle is the angle of PV modules from the horizontal plane;
[10] Azimuth angle is the angle of the PV modules with respect to south. The definition may vary but 0° indicate true south, -90° represents east, 180° represents north and 90° represents west.

tracking system can change both. Despite the obvious higher cost, tracking system may increase the yield up to 27[11]% for single axis trackers and 45[12]% for dual axis trackers.

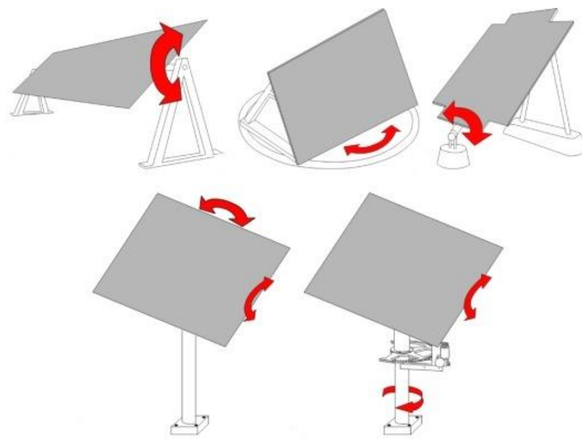


Figure 1.12: Some examples of different single axis and dual axis solar trackers

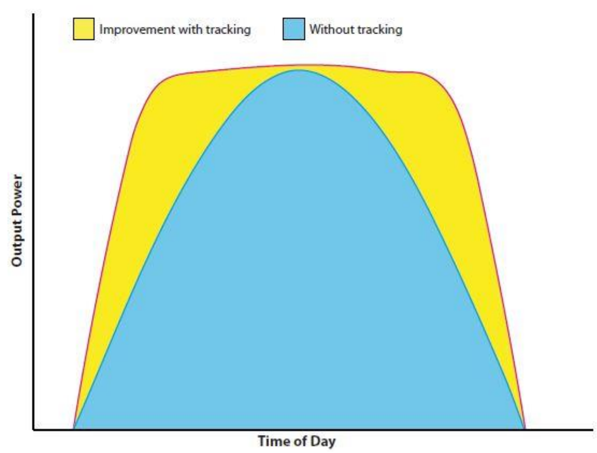


Figure 1.13: Comparison between dual axis tracking system and without tracking power output, image from Future Mechatronic Systems

Although there is a higher average yearly energy yield with a tracking system, there are other financial and operational aspects to consider.

Main financial aspects to consider are:

- Higher capital costs for the procurement and installation of the tracking system;

[11] Data taken from the IFC Solar Report – A project developer's guide;
[12] Data taken from the IFC Solar Report – A project developer's guide.

- Greater surface needed because of the shading problem with respect to fixed system.

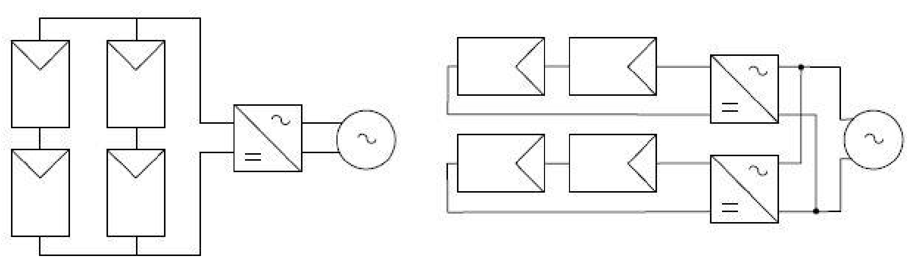
Whereas for the operational aspects, the following must be taken into consideration:

- The angle of tracking systems varies depending on the producer and performance therefore varies according to these parameters;
- Tracking systems need to be able to move into safety position in the case of strong wind and storm, reducing the energy yield and hence revenues in case of special location sites with high risks of this kind.

1.2.3 Inverters

The output of photovoltaic output is in direct current (DC), while the local grid and most of industrial or civil users need alternate current (AC) to function. Hence, the need of a device capable of transforming the direct current into alternate current is clear. This solid-state electronic device is called an inverter.

It is possible to distinguish two broad categories of inverters: central inverters and string inverters.



Figures 1.14 – 1.15: The first image represents a configuration with a central inverter, whereas the second one string inverters

The former (central inverters) is simple to install and provides high reliability, but a few disadvantages, such as:

- Mismatch losses, which represents the overall loss in power when modules are connected in a network, in comparison to the sum of their individual maximum power points (module mismatch is the variation of current-voltage characteristic of photovoltaic modules);
- Absence of maximum power point tracking[13] (MPPT) for each string;
  - In case of an inverter failure, a long lead time with significant yield loss before replacement may be needed.

Whereas concerning string inverters, as shown in figures 1.14 - 1.15, inverters are set up in each string (a group of modules connected in series). They have several advantages because:

- They are easier to manage even by non-specialist personnel;
- They provide MPPT on a string level;
- It is easier to keep spare string inverters on site and therefore handle unforeseen circumstances.

Inverter efficiency measures how much of the DC power input is transformed into AC power output.

$$\eta = \frac{AC\ power\ output}{DC\ power\ input}$$

Typical efficiency of inverters is between 95% and 98%.

1.2.4 Meters

Organizing meters is fundamental to ensuring that the photovoltaic plant owner is fully compensated for electricity generated. Meters, their configuration and arrangement are usually defined by the country's grid code while the installation is usually, but not

[13] Maximum Power Point Tracking (MPPT) is the capability of the inverter to adjust its impedance so that string is at an operating voltage which maximises the power output.

always, up to the project's developer. There are two common different metering arrangements for a PV system:

- Net metering: The photovoltaic plant provides energy to local loads and exports any excess energy to the grid. In the case of bad weather conditions or dormant night time (if no storage system is installed), the local grid provides energy. In this case, a bi-directional meter is used to measure and record the net result. From a public policy perspective, net metering scheme is arguably not a wise choice in countries where the grid operator does not have the option to charge for the benefits of transmission;
- Gross metering: The whole output is transmitted to the local grid. This is a common choice in countries where Feed-in-Tariff (FiT) is enforced. The loads are feed from the grid and metered separately on regular (non-FiT) rates.

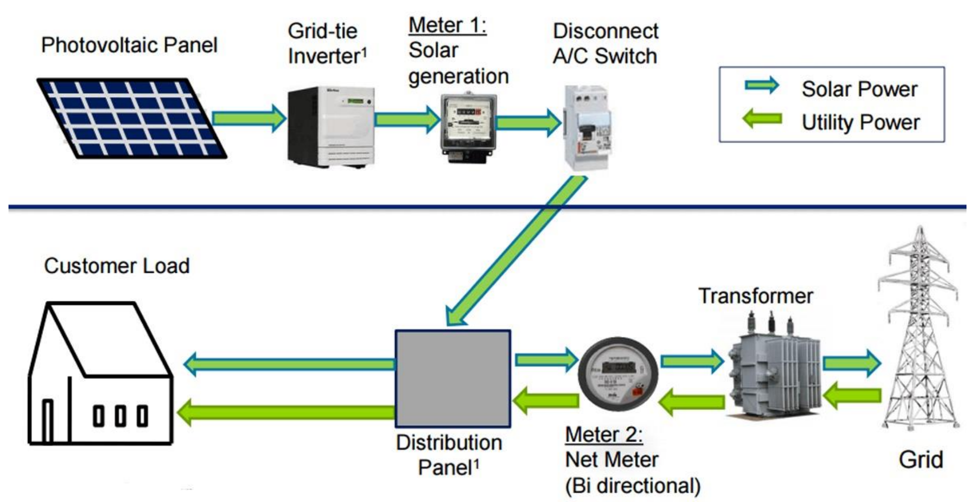


Figure 1.16: Example of net metering

1.3 Photovoltaic plant designing and financing: An overview

1.3.1 Optimization of plant design

Optimization of plant design involves several considerations, of which the most important ones are:

- Photovoltaic modules characteristics;
- Trade-offs between increased investment (e.g. for tracking) and energy yield;
- Shading;
- Performance degradation;

The fundamental part of a photovoltaic plant is, as already said, the module. As explained before, a module is a group of solar cells put together (e.g. 36 or 72). As it is the most basic and essential part of a photovoltaic plant, the choice of a good quality module plays an important part during the design process. Consequently, PV modules typically account for 40% - 60% of the cost of the plant. They have an expected functional life that exceeds 25 years, hence the abnormal degradation has a significant impact on project economics.

To ensure about the quality of PV modules, it is suggested to analyse the following points:

- Module technical characteristic;
- Quality of the manufacturing facility;
- Certification and testing procedure;
- Track record of the company and module;
- Warranty conditions;
- Company financial position.

In order to obtain a comprehensive view on module risks, a full assessment of these criteria should be undertaken. The failure curve typical for PV modules is the so called “bath-tube” shape shown below.

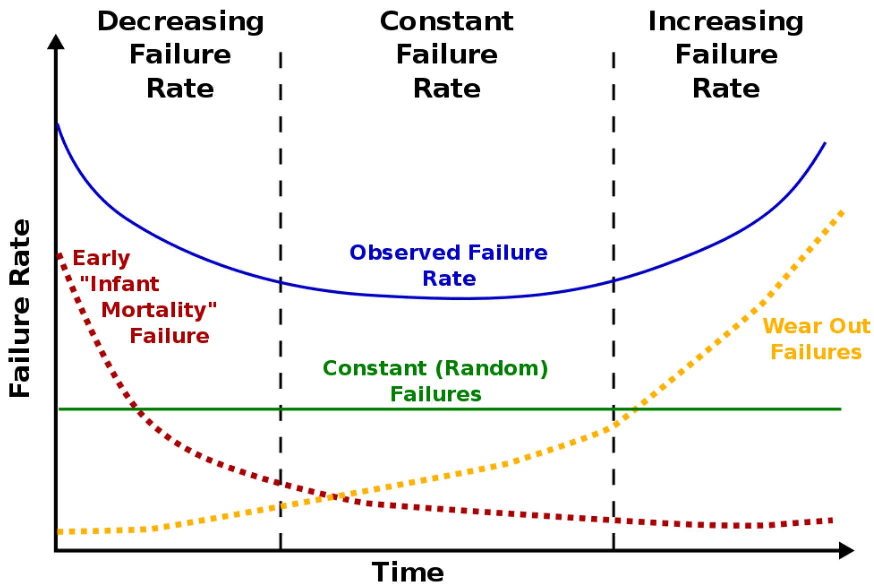


Figure 1.17: Bath tube curve

As shown in figure 1.17, there is a high risk of failure called infant failure during the early years, whereas the risk during the mid-term of the project is low (midlife-failures) but increases again at the end of the project lifetime as modules deteriorate (wear-out failures). Another valuable aspect to consider while choosing PV modules is the warranty period, which currently should be around 25 years from most of the manufacturers.

In summary, it is possible to state that:

- High efficiency modules require less land than low efficiency ones;
- The temperature coefficient of power plays an important role in hot climates;
- Degradation properties should be carefully analyzed;
- Manufacturer's warranty period must be looked upon.

It is worth noting that a study titled *Energy and Efficient Electric Power Systems* by Gil Masters from Stanford University demonstrates how shading just one of the 36 cells that compose a module can reduce power output by over 75%.

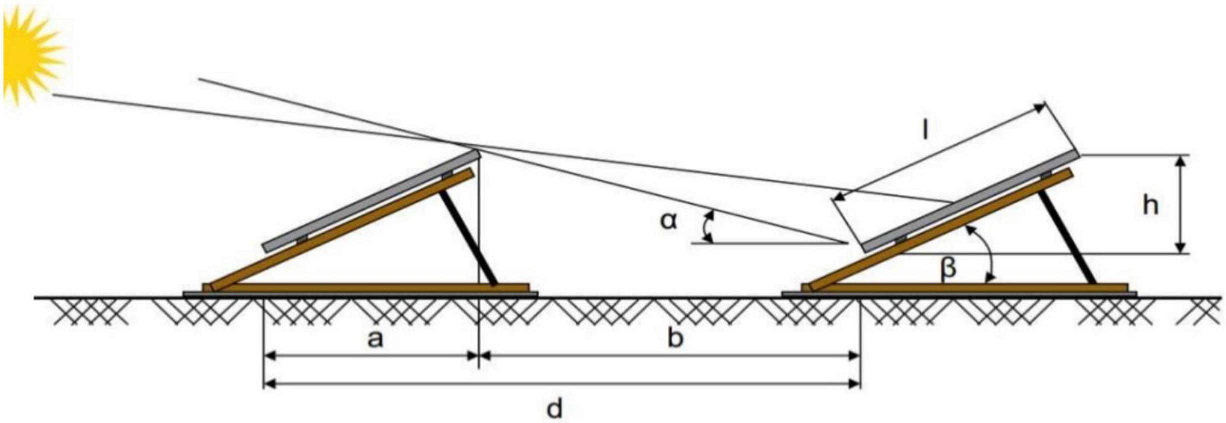


Figure 1.18: Distances of PV rows involved in PV plant when designing

where:

- α, the shading limit angle is the solar elevation angle beyond which there is no inter-row shading on the modules;
- The shading limit angle may be reduced either by reducing the tilt angle β or increasing the row distance d.

The problem of shading has previously been discussed in this paper but, it is useful to furthermore discuss how modules have *bypass diodes* connected in anti-parallel creating a dual effect. First, this protects the shaded cells from reverse voltages and secondly, thanks to its bypass function, allows the power delivered by the string to be reduced only by the contribution of the shadowed module so not to have the failure of the whole string.

The problem becomes more difficult if a tracking system is adopted, because of the moving parts. Since the projects that will be considered in this thesis have a fixed mounting system, shading problems associated with tracking systems will not be deeply discussed. That being said, tracking systems can potentially increase production up to 50% more that of fixed mounting systems. This percentage is, however, limited because of:

- Margin of error with the tracking system;
- Mutual shading between elements;
- Energy consumption of the tracking system.

Considering the limits listed above, it is still worth noting that, dual axis tracking systems currently increase the output by almost 30% while single axis systems increase output by around 20%.

Furthermore, when designing PV tracking systems other elements such as the following listed must be considered:

- Operational activity with strong wind;
- Automatic safety position in case of an installation site characterized by strong wind and snowstorm;
- Maintenance necessity for the moving parts;
- More space is needed for with respect to fixed systems.

Hence, fixed mounting structure systems are installed drastically more than w.r.t tracking systems because of the lower cost, risk and maintenance related to it.

Performance degradation is heavily dependent on the other points, since performance is highly related to a mixture of the points described. Realistically, even if the previous points are carefully managed, a natural degradation of performance is unavoidable. Developers often use the manufacturer's warranty as a loss reference when designing PV systems, which is usually a loss of efficiency of around 20% after 25 years.

1.3.2 Project financing

To obtain financing, the developer must prepare comprehensive documentation of the project so that a potential investor may be able to assess the risk of the investment.

Activities that relate to project financing are parallel with project design and permits. Initial actions for developing a project include securing land lease agreement and permits, as well as strategizing preliminary financing schemes.

The main tasks required to perform initial stages of the project are:

- Energy resource assessment;
- Site selection;
- Land lease agreement;

- Obtaining preliminary permits/license.

Project financing structures generally comprise of two key components:

- Equity from one or more investors, injected directly through a special purpose vehicle (SPV) with the project developer;
- Debt from one or more lenders, secured against the assets owned by the SPV.

1.3.2.1 Corporate Financing

Large companies could find solar plants on their balance sheet, supplying equity themselves. Since large companies with a solid financial position have access to low-cost debt, they must decide on a form of financing (equity, debt or a mix of the two).

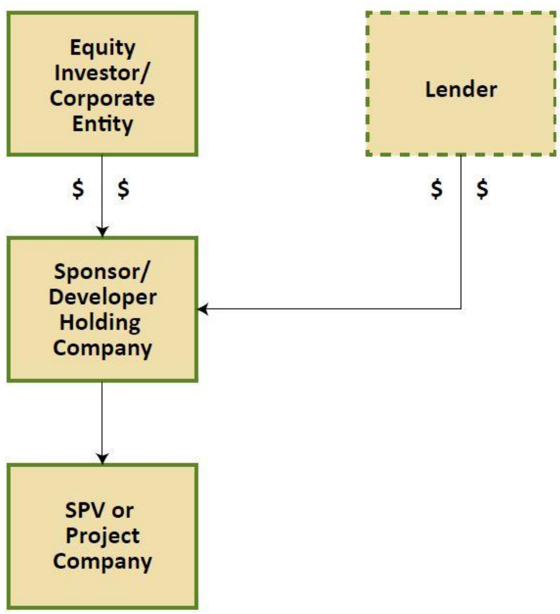


Figure 1.20: Corporate Financing

Corporate financing usually involves a single ownership structure; but, fully-ownership of the project, gives the owner the full-risk. This type of financing may be beneficial for both large firms and small projects.

1.3.2.2 Equity Financing

Usually, debt is cheaper than equity and therefore more attractive when financing projects.

Nevertheless, sometimes, solar PV plants are financed entirely with equity; This may be the case either for a high-cost debt or if there is a very small time frame available to procure investment (which would thus push the owner to use full equity in financing).

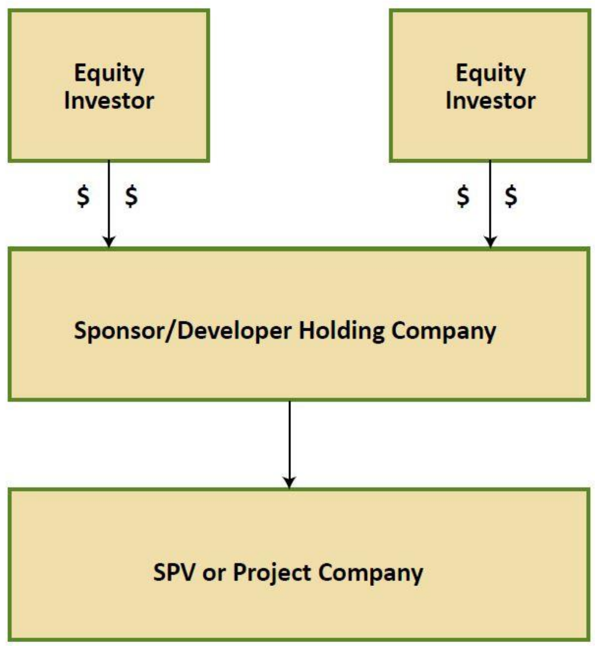


Figure 1.21: Usual Equity Financing Structure

Finally, funds can be secured internally or with a third equity partner in a shorter time period with an all-equity financing structure. This is also the case with developers who have experience and seek equity from new partners who have the capital but lack experience.

1.3.2.3 The role of the Special Purpose Vehicle (SPV)

Developers and equity partners generally start the development process by creating a project company or SPV; with the relevant criteria and rights of the project. The SPV owns the project and plant.

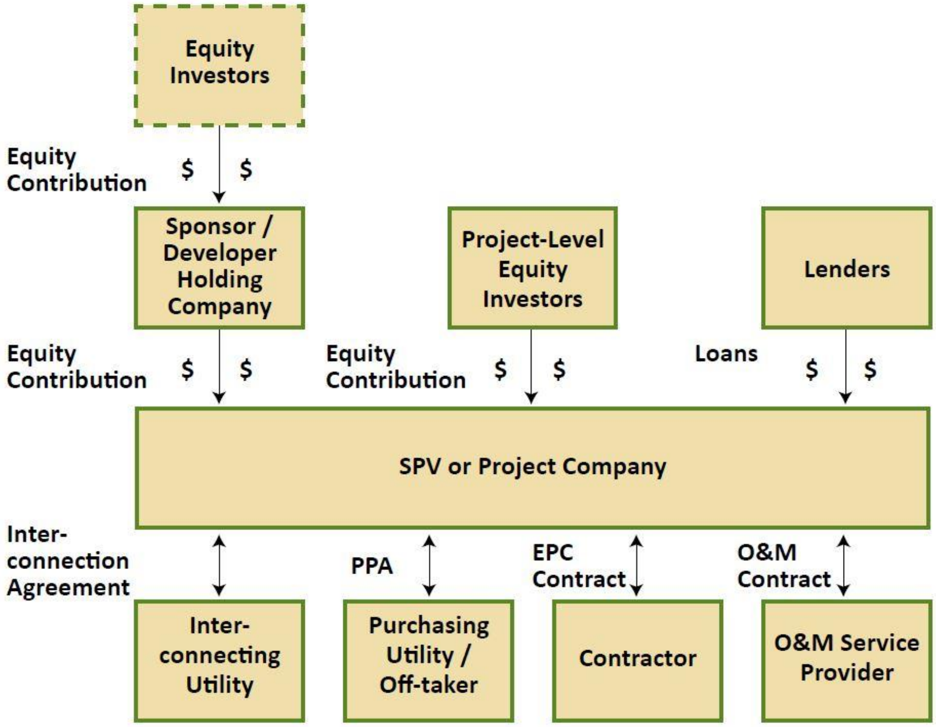


Figure 1.22: The role of SPV

In this kind of project financing:

- Lenders loan money for the development of the project based on projected cash flows of the project;
- In case of default, recourse is against SPV;
- Pricing and structuring of the debt based on the forecasted cash flows;
- Lenders usually require a very detailed plan to feel comfortable investing in the project.

1.4 Permits and timing for the connection of a PV plant to the national grid

The connection of a PV plant follows a bureaucratic procedure that is under the responsibility either of e-distribuzione S.p.A or Terna S.p.A; The first group manages medium-voltage national electric grid and meters installation, while the second one controls high-voltage connections. It is worth noting that, these kinds of procedures, apply to PV plants with the purpose of injecting the energy on the grid, whereas industrial

PV plants with the purpose of self-consumption are linked to the same connection point of the company, thus not increasing the costs of the project.

The procedural aspects of the connection to the grid are defined by ARERA which is the "Autorità di Regolazione per Energia Reti e Ambiente".

Costs for the connection to the grid are split into two tranches. The first tranche must be paid merely in order to receive a price quotation, and usually prices are as follows:

- 100€ for below 50 kW;
- 200€ between 50 kW and 100 kW;
- 500€ between 100 kW and 500 kW;
- 1500€ between 500 kW and 1000 kW;
- 2500€ beyond 1000 kW.

The second tranche is computed, by instead, measuring the power at the point of connection in addition to the distances between the connection point and the transformer stations. There are two formulas to compute the price to pay, the minimum between them is taken.

It is worth defining:

- P: Power at the point of connection (kW);
- DA: Distance (km) between the connection point and the medium-low voltage transformer cabin;
- DB: Distance (km) between the connection point and the high-medium voltage transformer cabin.

$$A = CP_A \times P + CM_A \times P \times D_A + 100$$

$$B = CP_B \times P + CM_B \times P \times D_B + 6000$$

where:

- CP_A= 35 €/kW;

- $CM_A = 90\,€/(kW \times km)$
- $CP_B = 4\,€/kW$
- $CM_B = 7.5\,€/(kW \times km)$

  The above formulas and coefficients are valid for overhead cables, whereas if a new connection with underground cables is needed, CM coefficients must be multiplied by 2.

The minimum between A and B is taken; 30% of that value must be paid before the work begins, and 70% once the job is completed, or before the start of the work in a unique tranche. Concerning the time needed to get the price quotation, it is usually as follow:

- 20 working days for power up to 100 kW;
- 45 working days for power up to 1000 kW;
- 60 working days for power beyond 1000 kW.

Once the quotation has been received, it stays valid for 45 days. Thus, the person responsible for the plant has 45 days to accept the price quotation by paying the initial 30% of the quotation, and then completing it at the end of the job. The actual time needed for the connection runs between 30 to 90 days, and possibly longer, depending on the complexity of the plant. The TICA (Testo Integrato delle Connessioni Attive) foresees the following timing starting from the date of the end of work:

- 30 working days for simple work;
- 90 working days for complex work; These days increase by 15 any exceeding km of medium voltage beyond the first kilometre.

If a deeper knowledge on connection procedures and related prices is needed, *Testo integrato delle connessioni attive (TICA)*, available on the ARERA website serves as a resource.

Chapter 2

Market Analysis

This chapter covers the basic topics related to the energy industry, the renewable energy and PV industry in particular. The purpose is to give the reader a basic overview of the energy industry and the different resources used to produce energy. It starts by illustrating the energy industry in general, then it focuses on renewable energy, while later concentrating only on the PV industry in Italy. The main source of data for this chapter has been the *BP Statistical Review 2019,* which is the most recently published review at this time.

2.1 Energy Industry Overview

Primary energy consumption grew by 2,9% in 2018 w.r.t 2017, according to *BP Statistical Review of World Energy (2019),* with the most growth represented by natural gas and renewables. Meanwhile, carbon emissions also increased by 2%, which is the highest growth recorded in the last seven years. This growth was led by China, US, and India; as shown in the figure below. An interesting point underlined in the *BP Statistical Review 2019,* is that this growth was mainly due to weather effects. As the report explains, there were an unusual number of hot and cold days across many of the world's major demand centers (US, China and Russia) in 2018, causing an increase in demand for cooling and heating services.

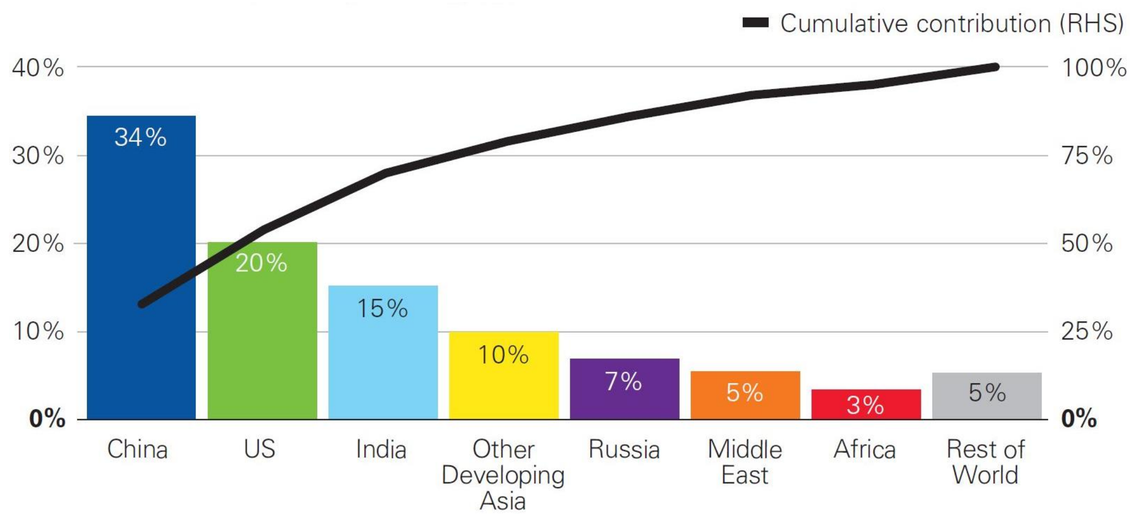


Figure 2.1: Contribution to primary energy growth in 2018, data from BP statistical review 2019

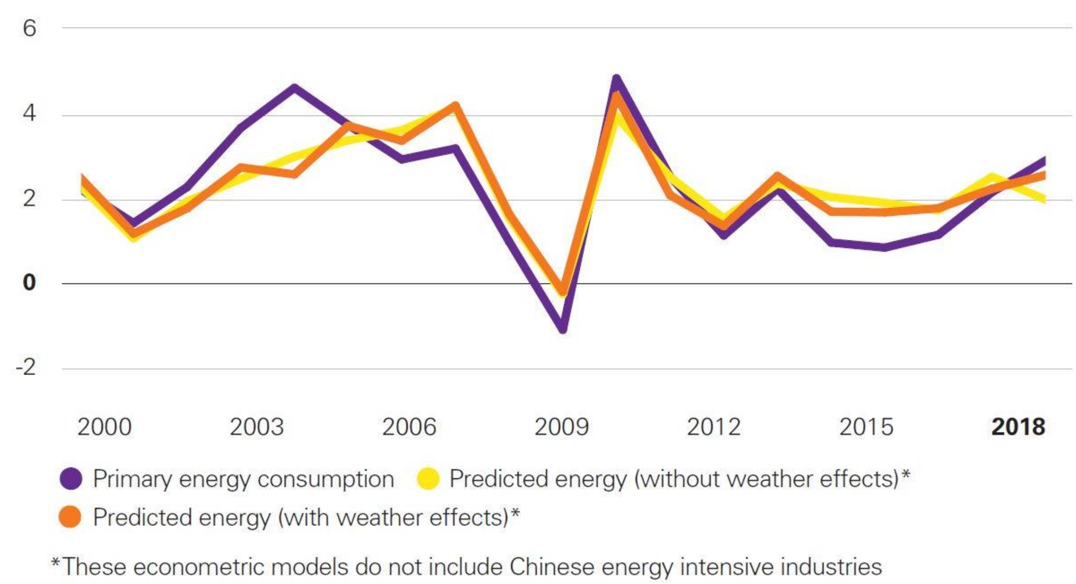


Figure 2.2: Global Energy Consumption Growth – annual change, from BP statistical review 2019

Million tonnes oil equivalent	2017 Oil	2017 Natural gas	2017 Coal	2017 Nuclear energy	2017 Hydro-electricity	2017 Renew-ables	2017 Total	2018 Oil	2018 Natural gas	2018 Coal	2018 Nuclear energy	2018 Hydro-electricity	2018 Renew-ables	2018 **Total**
Canada	108.8	94.3	18.6	22.7	89.7	9.5	343.7	110.0	99.5	14.4	22.6	87.6	10.3	**344.4**
Mexico	85.8	74.3	15.2	2.5	7.2	4.3	189.3	82.8	77.0	11.9	3.1	7.3	4.8	**186.9**
US	902.0	635.8	331.3	191.7	67.2	94.5	2222.5	919.7	702.6	317.0	192.2	65.3	103.8	**2300.6**
Total North America	1096.6	804.4	365.1	216.9	164.1	108.4	2755.5	1112.5	879.1	343.3	217.9	160.3	118.8	**2832.0**
Argentina	32.0	41.5	1.1	1.4	9.4	0.7	86.1	30.1	41.9	1.2	1.6	9.4	0.9	**85.1**
Brazil	136.1	32.4	16.6	3.6	83.9	21.4	293.9	135.9	30.9	15.9	3.5	87.7	23.6	**297.6**
Chile	17.7	4.8	7.7	–	4.8	3.3	38.3	18.1	5.5	7.7	–	5.2	3.5	**40.1**
Colombia	16.5	10.5	5.2	–	13.0	0.5	45.5	16.6	11.2	5.9	–	12.8	0.5	**46.9**
Ecuador	11.3	0.7	–	–	4.5	0.1	16.7	12.2	0.6	–	–	4.7	0.1	**17.6**
Peru	12.0	5.8	0.6	–	6.6	0.4	25.4	12.4	6.1	0.9	–	7.0	0.7	**27.0**
Trinidad & Tobago	2.1	13.1	–	–	–	†	15.2	2.1	13.2	–	–	–	†	**15.3**
Venezuela	22.1	33.4	0.1	–	18.0	†	73.6	19.5	28.7	0.1	–	16.3	†	**64.6**
Other S. & Cent. America	67.4	6.2	3.5	–	22.8	5.2	105.1	68.3	6.8	4.3	–	22.3	6.1	**107.8**
Total S. & Cent. America	317.2	148.4	34.8	4.9	163.0	31.5	699.8	315.3	144.8	36.0	5.1	165.5	35.4	**702.0**
Austria	13.1	7.8	3.1	–	8.7	2.8	35.5	13.4	7.5	2.9	–	8.5	2.8	**35.0**
Belgium	33.7	14.1	3.1	9.6	0.1	3.5	64.1	34.1	14.5	3.3	6.4	0.1	3.8	**62.2**
Czech Republic	10.4	7.2	15.6	6.4	0.4	1.8	41.8	10.6	6.9	15.7	6.8	0.4	1.7	**42.1**
Finland	10.3	1.6	4.0	5.1	3.3	3.8	28.1	10.7	1.8	4.3	5.2	3.0	4.3	**29.3**
France	79.1	38.5	9.3	90.1	11.1	9.4	237.5	78.9	36.7	8.4	93.5	14.5	10.6	**242.6**
Germany	119.0	77.2	71.5	17.3	4.6	44.4	333.9	113.2	75.9	66.4	17.2	3.8	47.3	**323.9**
Greece	16.0	4.1	4.8	–	0.9	2.2	28.0	16.0	4.1	4.7	–	1.3	2.4	**28.3**
Hungary	8.3	8.5	2.2	3.6	†	0.7	23.5	8.8	8.3	2.2	3.6	0.1	0.8	**23.7**
Italy	62.0	61.5	9.6	–	7.8	15.3	156.3	60.8	59.5	8.9	–	10.4	14.9	**154.5**
Netherlands	39.6	31.0	9.1	0.8	†	3.9	84.5	40.9	30.7	8.2	0.8	†	4.2	**84.8**
Norway	10.1	3.9	0.8	–	32.1	0.7	47.6	10.4	3.9	0.8	–	31.3	0.9	**47.4**
Poland	31.7	16.5	49.8	–	0.6	4.9	103.4	32.8	17.0	50.5	–	0.4	4.4	**105.2**
Portugal	12.0	5.5	3.2	–	1.3	3.8	25.8	11.5	5.0	2.7	–	2.8	3.9	**26.0**
Romania	10.3	9.6	5.4	2.6	3.3	2.2	33.4	10.2	9.3	5.3	2.6	4.0	2.0	**33.4**
Spain	65.0	27.3	13.4	13.1	4.2	15.7	138.8	66.6	27.1	11.1	12.6	8.0	16.0	**141.4**
Sweden	15.4	0.7	2.0	14.9	14.7	6.8	54.4	14.8	0.7	2.0	15.5	14.0	6.6	**53.6**
Switzerland	10.9	2.7	0.1	4.6	7.7	0.8	26.9	10.5	2.6	0.1	5.8	7.9	0.9	**27.8**
Turkey	49.2	44.3	39.5	–	13.2	6.6	152.7	48.6	40.7	42.3	–	13.5	8.5	**153.5**
Ukraine	9.9	26.0	25.7	19.4	2.0	0.4	83.4	9.6	26.3	26.2	19.1	2.2	0.6	**84.0**
United Kingdom	78.0	67.8	9.1	15.9	1.3	21.1	193.2	77.0	67.8	7.6	14.7	1.2	23.9	**192.3**
Other Europe	62.5	26.1	34.1	8.4	14.9	11.4	157.3	62.4	25.9	33.6	8.3	17.9	11.7	**159.8**
Total Europe	746.2	481.9	315.5	211.8	132.3	162.3	2050.0	742.0	472.0	307.1	212.1	145.3	172.2	**2050.7**
Azerbaijan	4.7	9.1	†	–	0.4	†	14.3	4.6	9.3	†	–	0.4	†	**14.4**
Belarus	6.7	15.7	0.8	–	0.1	0.1	23.4	6.8	16.6	1.0	–	0.1	0.1	**24.6**
Kazakhstan	15.0	13.7	36.4	–	2.5	0.1	67.6	16.4	16.7	40.8	–	2.3	0.1	**76.4**
Russian Federation	151.5	370.7	83.9	46.0	41.9	0.3	694.3	152.3	390.8	88.0	46.3	43.0	0.3	**720.7**
Turkmenistan	6.9	21.8	–	–	–	†	28.7	7.1	24.4	–	–	–	†	**31.5**
Uzbekistan	2.7	37.1	3.5	–	1.7	–	45.0	2.6	36.6	3.1	–	1.6	–	**43.9**
Other CIS	3.6	4.3	1.8	0.6	7.7	†	18.0	3.7	4.9	2.0	0.5	8.0	†	**19.0**
Total CIS	191.1	472.3	126.4	46.6	54.3	0.5	891.2	193.5	499.4	134.9	46.7	55.4	0.6	**930.5**
Iran	84.5	180.5	1.4	1.6	3.9	0.1	272.0	86.2	193.9	1.5	1.6	2.4	0.1	**285.7**
Iraq	35.6	11.0	–	–	0.5	†	47.1	38.4	14.7	–	–	0.7	†	**53.7**
Israel	11.7	8.5	5.0	–	†	0.4	25.6	11.5	9.0	4.7	–	†	0.5	**25.6**
Kuwait	20.4	18.1	0.2	–	–	†	38.7	20.0	18.7	0.2	–	–	†	**39.0**
Oman	9.2	20.0	0.1	–	–	†	29.3	9.2	21.4	0.1	–	–	†	**30.7**
Qatar	11.8	37.0	–	–	–	†	48.9	12.2	36.0	–	–	–	†	**48.3**
Saudi Arabia	168.8	93.9	0.1	–	–	†	262.8	162.6	96.4	0.1	–	–	†	**259.2**
United Arab Emirates	43.8	64.0	1.0	–	–	0.1	109.0	45.1	65.8	1.1	–	–	0.2	**112.2**
Other Middle East	26.6	20.1	0.4	–	0.3	0.5	48.0	26.8	19.5	0.4	–	0.3	0.8	**47.9**
Total Middle East	412.5	453.2	8.2	1.6	4.7	1.3	881.4	412.1	475.6	7.9	1.6	3.4	1.7	**902.3**
Algeria	19.4	33.4	0.2	–	†	0.1	53.1	19.6	36.7	0.2	–	†	0.1	**56.7**
Egypt	39.2	48.1	1.6	–	3.0	0.6	92.6	36.7	51.2	2.8	–	3.1	0.8	**94.5**
Morocco	13.5	1.0	4.5	–	0.3	0.8	20.0	13.2	0.9	5.4	–	0.4	1.1	**21.0**
South Africa	27.5	3.8	84.3	3.6	0.2	2.4	121.8	26.3	3.7	86.0	2.5	0.2	2.8	**121.5**
Other Africa	92.4	34.7	7.0	–	24.7	2.2	161.0	95.5	36.4	7.0	–	26.4	2.4	**167.8**
Total Africa	192.1	121.0	97.6	3.6	28.2	6.1	448.6	191.3	129.0	101.4	2.5	30.1	7.2	**461.5**
Australia	51.1	35.5	45.1	–	3.1	5.8	140.5	53.3	35.6	44.3	–	3.9	7.2	**144.3**
Bangladesh	7.9	22.9	1.9	–	0.2	0.1	33.0	9.0	24.4	2.1	–	0.2	0.1	**35.8**
China	610.7	206.7	1890.4	56.1	263.6	111.4	3139.0	641.2	243.3	1906.7	66.6	272.1	143.5	**3273.5**
China Hong Kong SAR	21.9	2.7	6.3	–	–	†	30.9	22.2	2.6	6.3	–	–	†	**31.1**
India	227.1	46.2	415.9	8.5	30.7	21.7	750.1	239.1	49.9	452.2	8.8	31.6	27.5	**809.2**
Indonesia	79.3	33.1	57.2	–	4.2	3.0	176.9	83.4	33.5	61.6	–	3.7	3.3	**185.5**
Japan	187.8	100.6	119.9	6.6	17.9	22.4	455.2	182.4	99.5	117.5	11.1	18.3	25.4	**454.1**
Malaysia	36.0	35.9	19.3	–	5.2	0.3	96.7	36.9	35.5	21.1	–	5.5	0.3	**99.3**
New Zealand	8.5	4.3	1.2	–	5.7	2.4	22.2	8.4	3.7	1.3	–	6.0	2.4	**21.7**
Pakistan	29.2	35.0	7.1	1.9	6.9	0.9	81.0	24.3	37.5	11.6	2.2	8.1	1.2	**85.0**
Philippines	21.7	3.2	15.5	–	2.2	3.1	45.7	22.0	3.5	16.3	–	2.1	3.2	**47.0**
Singapore	74.8	10.6	0.9	–	–	0.2	86.5	75.8	10.6	0.9	–	–	0.3	**87.6**
South Korea	130.0	42.8	86.2	33.6	0.6	4.0	297.1	128.9	48.1	88.2	30.2	0.7	5.0	**301.0**
Sri Lanka	5.4	–	1.4	–	0.9	0.1	7.8	5.3	–	1.2	–	1.4	0.1	**8.1**
Taiwan	50.1	20.0	39.4	5.1	1.2	1.2	117.0	50.0	20.3	39.3	6.3	1.0	1.5	**118.4**
Thailand	64.4	43.1	18.3	–	1.1	3.4	130.2	65.8	42.9	18.5	–	1.7	4.0	**133.0**
Vietnam	23.6	8.2	27.9	–	16.0	0.1	75.8	24.9	8.3	34.3	–	18.3	0.1	**85.8**
Other Asia Pacific	21.9	9.8	16.9	–	13.6	0.2	62.4	22.5	10.3	18.0	–	14.2	0.3	**65.4**
Total Asia Pacific	1651.3	660.6	2770.8	111.7	373.2	180.2	5748.0	1695.4	709.6	2841.3	125.3	388.9	225.4	**5985.8**
Total World	**4607.0**	**3141.9**	**3718.4**	**597.1**	**919.9**	**490.2**	**13474.6**	**4662.1**	**3309.4**	**3772.1**	**611.3**	**948.8**	**561.3**	**13864.9**
of which: OECD	2196.5	1435.2	892.9	443.4	314.6	304.3	5586.9	2204.8	1505.2	861.3	446.1	321.3	330.4	**5669.0**
Non-OECD	2410.5	1706.7	2825.6	153.7	605.3	185.9	7887.7	2457.3	1804.2	2910.8	165.2	627.5	230.8	**8195.9**
European Union	649.5	400.4	234.2	187.8	67.4	152.4	1691.8	646.8	394.2	222.4	187.2	78.0	159.6	**1688.2**

*In this review, primary energy comprises commercially-traded fuels, including modern renewables used to generate electricity.
†Less than 0.05.

Table 2.1: Primary Energy Consumption by fuel, data from BP Statistical Review (2019)

The data in the previous table are illustrated in million tonnes of oil equivalent (Mtoe). The tonne of oil equivalent (toe) is a unit of energy defined as the amount of energy released by burning one tonne (1000 kgs) of crude oil. It is approximately 42 gigajoules or 11,63 megawatt hours (MWh).

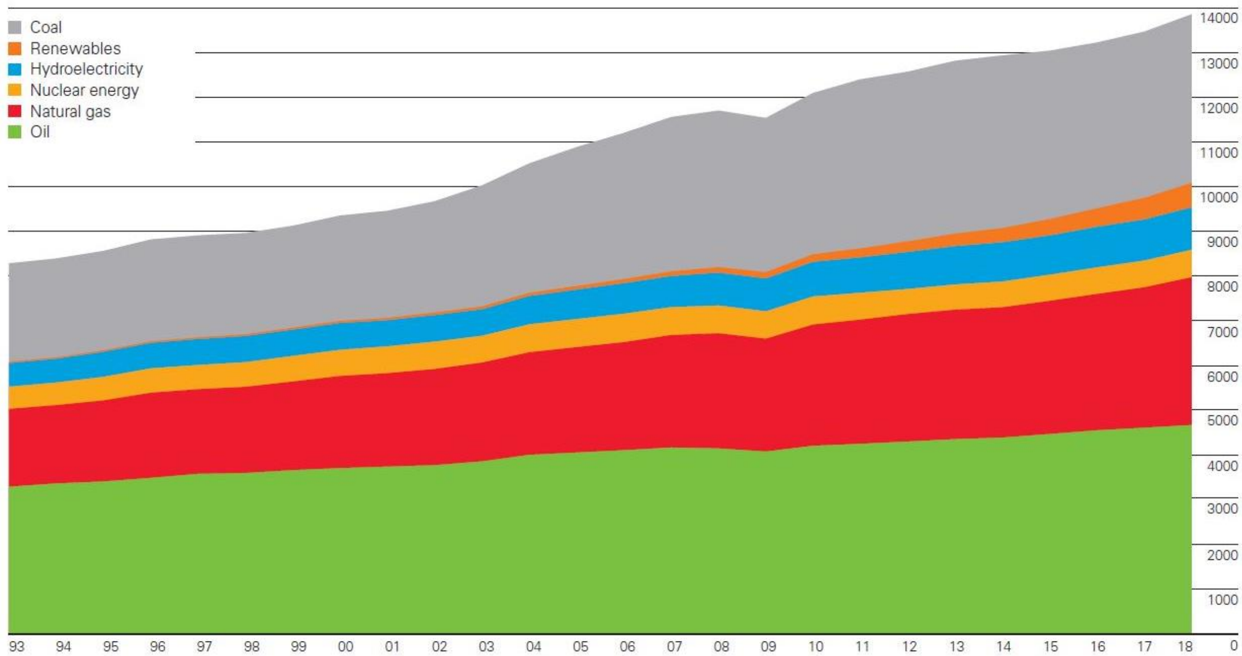


Figure 2.3: World Consumption, by BP statistical review, data in toe (2019)

Analysing the data from table 2.1, there is noticeable growth in power generated by renewable energy, which grew by 14,5%, followed by coal (3,0%) and natural gas (3,9%). It is worth noting that, even here, renewables growth is driven by China. The country accounts for almost 45% of the global growth of renewable energy, more than the all OECD countries, combined. Figure 2.3 demonstrates that coal and oil still dominate with respect to other resources. Plotting data from table 1, chart below demonstrates the variation in regional fuel consumption.

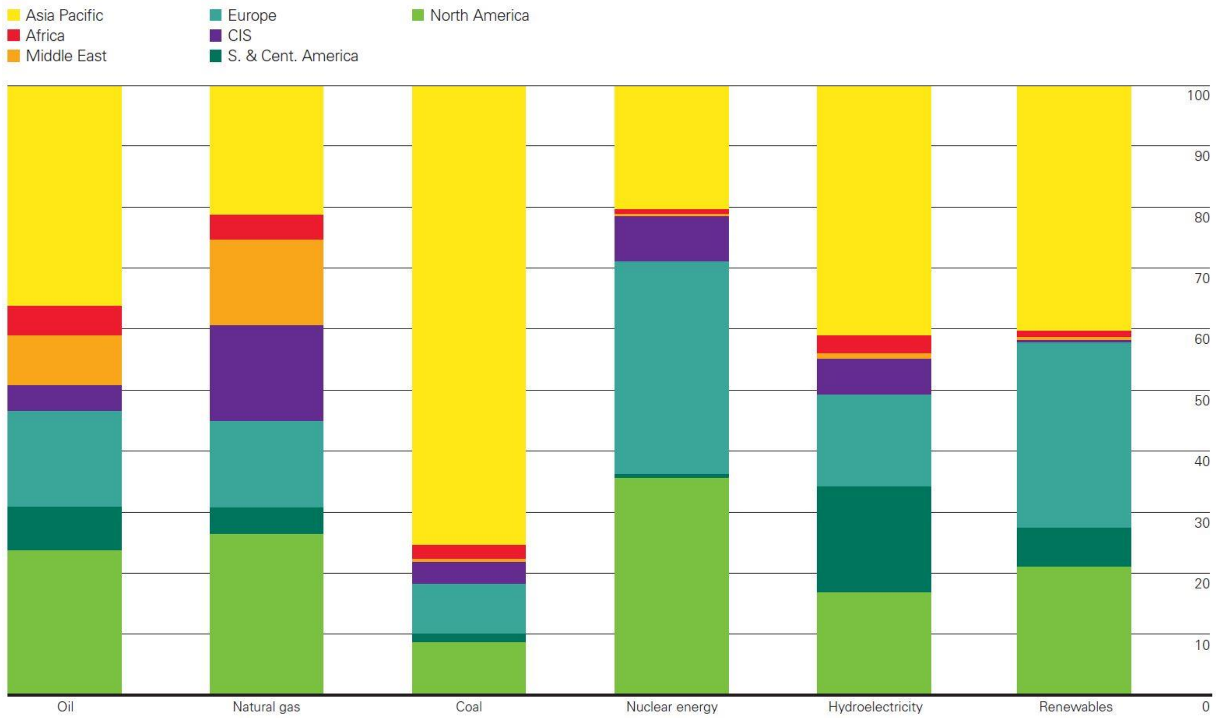


Figure 2.4: Fuel consumption by region (percentage), by BP statistical review (2019)

As is evident in figure 2.4, oil is mainly consumed in the Asia Pacific region and North America accounting for almost 60% of the world consumption. Coal is mostly consumed in the Asia Pacific region while for nuclear energy is largely consumed by North America and Europe. For renewable energy, more than 90% of production is represented by the same regions: Asia Pacific, Europe and North America.

Since this thesis is focused on a specific kind of renewable energy (photovoltaic solar energy), the next sub-chapters focus on this kind of technology.

2.2 Renewable Energy Overview

After outlining the main indicators of the energy industry in general in the previous chapter, the following will focus on renewable energy. It is worth repeating that renewable energy has the highest growing percentage of all the resources utilization analyzed, leading the percentage growth in 2018.

Terawatt-hours	Wind	Solar	Other renewables‡	2017 Total	Wind	Solar	Other renewables‡	2018 Total	2018 Growth rate			
									Wind	Solar	Other renewables‡	Total
Canada	29.1	3.3	9.7	42.1	32.2	3.5	9.6	**45.3**	10.7%	7.7%	-1.4%	**7.7%**
Mexico	10.6	1.2	7.3	19.1	12.6	2.2	6.5	**21.4**	18.9%	89.0%	-11.5%	**11.6%**
US	256.9	78.1	82.8	417.8	277.7	97.1	83.7	**458.5**	8.1%	24.4%	1.0%	**9.8%**
Total North America	296.6	82.5	99.9	479.0	322.5	102.9	99.7	**525.2**	8.8%	24.7%	-0.1%	**9.6%**
Argentina	0.6	†	2.4	3.0	1.4	0.1	2.3	**3.8**	131.0%	558.6%	-3.6%	**26.8%**
Brazil	42.4	0.8	51.3	94.5	48.5	3.1	52.9	**104.5**	14.4%	277.1%	3.2%	**10.6%**
Chile	3.6	3.9	6.9	14.5	3.7	5.1	6.7	**15.5**	1.7%	31.4%	-2.8%	**7.6%**
Colombia	†	–	2.0	2.0	†	†	2.1	**2.1**	1314.2%	–	4.9%	**7.5%**
Ecuador	0.1	†	0.4	0.5	0.1	†	0.4	**0.5**	9.3%	1.4%	-0.7%	**0.8%**
Peru	1.1	0.3	0.6	1.9	1.5	0.7	0.7	**2.9**	39.1%	159.5%	16.8%	**50.3%**
Trinidad & Tobago	–	†	–	†	–	†	–	**†**	–	–	–	**–**
Venezuela	–	†	–	†	–	†	–	**†**	–	–	–	**–**
Other S. & Cent. America	8.4	2.4	12.2	22.9	10.7	3.3	12.9	**26.8**	27.4%	37.3%	5.9%	**17.0%**
Total S. & Cent. America	56.1	7.5	75.8	139.4	65.9	12.4	78.0	**156.3**	17.3%	66.7%	3.0%	**12.2%**
Austria	6.6	1.3	4.6	12.5	5.9	1.6	4.8	**12.2**	-10.3%	24.4%	2.6%	**-1.9%**
Belgium	6.5	3.3	5.8	15.6	7.5	4.0	5.4	**16.9**	14.7%	20.8%	-5.8%	**8.4%**
Czech Republic	0.6	2.2	5.0	7.7	0.6	2.3	4.7	**7.7**	3.1%	6.6%	-4.8%	**-0.9%**
Finland	4.8	†	11.8	16.7	5.9	0.2	12.9	**18.9**	22.1%	272.0%	8.6%	**13.2%**
France	24.3	9.2	8.0	41.5	28.2	10.2	8.5	**46.8**	15.8%	10.9%	6.6%	**13.0%**
Germany	105.7	39.4	51.1	196.2	111.6	46.2	51.4	**209.2**	5.6%	17.2%	0.7%	**6.6%**
Greece	5.5	4.0	0.3	9.8	6.3	3.8	0.3	**10.4**	13.8%	-5.0%	-3.8%	**5.6%**
Hungary	0.8	0.3	2.1	3.2	0.6	0.6	2.4	**3.6**	-19.8%	68.7%	10.8%	**9.9%**
Italy	17.7	24.4	25.6	67.7	17.5	23.2	25.3	**66.0**	-1.5%	-4.7%	-1.0%	**-2.5%**
Netherlands	10.6	2.2	4.6	17.4	10.5	3.2	4.9	**18.6**	-0.2%	45.2%	6.0%	**7.2%**
Norway	2.9	†	0.2	3.1	3.9	0.1	0.2	**4.1**	35.8%	58.2%	-15.1%	**32.7%**
Poland	14.9	0.2	6.5	21.6	12.8	0.3	6.3	**19.5**	-13.8%	81.2%	-2.4%	**-9.7%**
Portugal	12.2	1.0	3.4	16.7	12.7	1.0	3.4	**17.1**	3.3%	2.8%	0.1%	**2.6%**
Romania	7.4	1.9	0.5	9.8	6.5	1.7	0.5	**8.6**	-12.3%	-9.8%	-12.1%	**-11.8%**
Spain	49.1	14.3	6.1	69.5	50.8	12.5	7.4	**70.7**	3.5%	-12.6%	21.4%	**1.7%**
Sweden	17.6	0.2	12.1	29.9	16.8	0.4	11.9	**29.0**	-4.5%	62.2%	-1.8%	**-2.9%**
Switzerland	0.1	1.7	1.8	3.7	0.1	2.0	2.0	**4.1**	–	16.3%	7.4%	**11.2%**
Turkey	17.9	2.9	8.3	29.0	19.8	7.9	10.0	**37.7**	10.7%	173.1%	21.0%	**29.8%**
Ukraine	1.0	0.8	0.2	1.9	1.1	1.3	0.2	**2.6**	15.7%	69.7%	33.7%	**38.8%**
United Kingdom	50.0	11.5	31.9	93.4	57.1	12.9	35.6	**105.6**	14.2%	12.1%	11.7%	**13.1%**
Other Europe	0.3	0.4	0.2	0.9	0.5	0.4	0.2	**1.2**	80.8%	14.8%	18.3%	**37.8%**
Total Europe	384.3	124.5	208.2	717.1	404.4	139.1	217.6	**761.1**	5.2%	11.7%	4.5%	**6.1%**
Azerbaijan	†	†	0.1	0.1	0.1	†	0.1	**0.2**	271.9%	5.5%	-4.8%	**40.2%**
Belarus	0.1	0.1	0.1	0.3	0.1	0.1	0.1	**0.4**	21.6%	51.1%	3.0%	**23.8%**
Kazakhstan	0.3	0.1	–	0.4	0.5	0.1	†	**0.7**	64.0%	27.9%	–	**56.8%**
Russian Federation	0.1	0.5	0.5	1.1	0.2	0.6	0.5	**1.3**	62.4%	6.9%	-0.9%	**10.5%**
Turkmenistan	–	†	–	†	–	†	–	**†**	–	–	–	**–**
Uzbekistan	–	–	–	–	–	–	–	**–**	–	–	–	**–**
Other CIS	†	†	†	†	†	†	†	**†**	-2.5%	46.3%	–	**11.2%**
Total CIS	0.6	0.8	0.7	2.0	1.0	0.9	0.7	**2.5**	63.5%	14.9%	-0.4%	**24.0%**
Iran	0.3	†	†	0.3	0.4	†	†	**0.4**	23.8%	157.5%	–	**28.2%**
Iraq	–	0.1	–	0.1	–	0.1	–	**0.1**	–	–	–	**–**
Israel	0.1	1.6	0.1	1.8	0.1	1.8	0.1	**2.0**	–	12.4%	–	**10.9%**
Kuwait	†	0.1	–	0.1	†	0.1	–	**0.1**	–	–	–	**–**
Oman	–	†	–	†	–	†	–	**†**	–	57.5%	–	**57.5%**
Qatar	–	†	0.1	0.1	–	†	0.1	**0.1**	–	–	–	**–**
Saudi Arabia	–	0.1	–	0.1	–	0.2	–	**0.2**	–	9.2%	–	**9.2%**
United Arab Emirates	†	0.5	†	0.5	†	0.9	†	**1.0**	◆	77.9%	–	**76.9%**
Other Middle East	0.5	2.0	†	2.4	0.6	3.0	†	**3.6**	25.7%	53.9%	–	**48.5%**
Total Middle East	0.9	4.4	0.3	5.5	1.1	6.1	0.3	**7.4**	21.4%	38.8%	–	**34.2%**
Algeria	†	0.5	–	0.5	†	0.6	–	**0.6**	-47.4%	19.6%	–	**17.2%**
Egypt	2.4	0.3	–	2.7	2.4	1.0	–	**3.5**	-0.4%	294.2%	–	**28.1%**
Morocco	3.0	0.4	–	3.5	3.8	1.0	–	**4.8**	26.6%	128.8%	–	**38.9%**
South Africa	5.9	4.3	0.5	10.6	6.9	4.9	0.5	**12.4**	17.5%	15.4%	9.8%	**16.3%**
Other Africa	1.4	1.2	7.0	9.6	1.5	1.5	7.6	**10.6**	5.3%	30.6%	8.9%	**11.0%**
Total Africa	12.8	6.6	7.5	26.9	14.7	9.0	8.2	**31.9**	14.8%	36.6%	8.9%	**18.5%**
Australia	13.2	9.0	3.5	25.7	16.3	12.1	3.5	**31.9**	23.3%	34.9%	-0.1%	**24.1%**
Bangladesh	†	0.3	†	0.3	†	0.3	†	**0.3**	–	12.9%	–	**12.3%**
China	295.0	117.8	79.6	492.4	366.0	177.5	90.7	**634.2**	24.1%	50.7%	14.0%	**28.8%**
China Hong Kong SAR	†	†	0.1	0.1	†	†	0.1	**0.1**	–	-9.3%	–	**-0.1%**
India	52.6	21.5	21.6	95.8	60.3	30.7	30.5	**121.5**	14.6%	42.8%	40.9%	**26.9%**
Indonesia	–	†	13.4	13.4	0.2	†	14.5	**14.8**	–	-36.8%	8.9%	**10.2%**
Japan	6.1	61.8	30.9	98.8	6.8	71.7	33.7	**112.1**	11.1%	15.9%	9.0%	**13.5%**
Malaysia	–	0.4	1.0	1.3	–	0.5	1.0	**1.5**	–	26.7%	4.9%	**10.9%**
New Zealand	2.1	0.1	8.4	10.6	2.0	0.1	8.3	**10.5**	-4.4%	30.3%	-1.3%	**-1.7%**
Pakistan	1.2	1.1	1.6	3.9	1.7	2.1	1.7	**5.5**	43.1%	100.5%	2.8%	**41.9%**
Philippines	1.1	1.2	11.3	13.6	1.2	1.2	11.5	**13.9**	5.4%	4.0%	2.3%	**2.7%**
Singapore	–	0.2	0.8	1.1	–	0.3	0.9	**1.2**	–	25.0%	8.2%	**11.8%**
South Korea	2.2	7.1	8.3	17.6	2.4	9.3	10.2	**21.9**	10.8%	32.5%	21.9%	**24.8%**
Sri Lanka	0.4	0.1	0.1	0.6	0.3	0.2	0.1	**0.6**	-17.4%	38.1%	57.2%	**5.6%**
Taiwan	1.7	1.7	1.9	5.3	1.7	2.7	2.0	**6.4**	-2.5%	61.6%	8.2%	**21.8%**
Thailand	0.5	4.5	9.9	14.9	0.8	4.7	12.3	**17.8**	45.0%	5.3%	24.0%	**19.1%**
Vietnam	0.3	†	0.1	0.3	0.3	0.1	0.1	**0.5**	23.4%	803.3%	–	**39.8%**
Other Asia Pacific	0.3	0.5	0.2	0.9	0.5	0.6	0.2	**1.2**	58.0%	22.8%	8.3%	**32.2%**
Total Asia Pacific	376.7	227.2	192.6	796.6	460.5	314.2	221.3	**996.0**	22.2%	38.3%	14.9%	**25.0%**
Total World	**1128.0**	**453.5**	**585.0**	**2166.5**	**1270.0**	**584.6**	**625.8**	**2480.4**	**12.6%**	**28.9%**	**7.0%**	**14.5%**
of which: OECD	695.1	285.7	363.9	1344.8	745.8	337.2	377.3	**1460.3**	7.3%	18.0%	3.7%	**8.6%**
Non–OECD	432.9	167.8	221.0	821.7	524.1	247.4	248.6	**1020.1**	21.1%	47.5%	12.4%	**24.1%**
European Union	362.0	119.1	192.4	673.5	378.8	127.8	199.0	**705.5**	4.6%	7.3%	3.4%	**4.8%**

*Based on gross generation and not accounting for cross–border electricity supply.
‡Includes electricity generated from: geothermal, biomass and other sources of renewable energy (not already itemized).
†Less than 0.05.
◆Less than 0.05%.

Table 2.2: Renewable energy: generation by source, BP Statistical Review (2019)

Table 2.2 indicates that main contributors of renewable energy are wind and solar, with solar in the lead with the highest percentage growth with respect to the previous year, 2017. Examining specific countries where solar energy grew, Vietnam lead with a percentage growth of 803,3% between 2017 and 2018, followed by Argentina and Brazil respectively. Looking at the data from a geographical point of view, South and Central America drive the growth with 66% in 2018, followed by Middle East and Asia Pacific. According to a study performed by *Allied Market Research*, the overall market for renewable energy reached almost $928 billion in 2017, and is expected to reach $1.512,3 billion by 2025, with a CAGR[14] of almost 6%.

The photovoltaic solar energy market, was valued at almost $53 billion in 2018 with an expected growth of up to $224 billion by 2026, showing a projected CAGR of 20,5% from 2019 to 2026.

2.3 Focus: Italian Market

The Italian PV market had an installed capacity that reached 20.107,6[15] MW at the end of 2018, thus being the fifth countries in the world for installed capacity after China, Germany, Japan and United states respectively. According to *Gestore Servizi Energetici (GSE)* and *Ricerca Sistema Energetico (RSE),* Italy installed 48225 PV plants in 2018 adding almost 440 MW to its already existing capacity. The industrial sector represents most of the installed capacity, almost 9 GW, where the usual size of an industrial plant is between 200 kW and 1 MW.

[14] Compounded annual growth rate;
[15] Data from the National Survey Report of PV Power Applications in Italy, 2018 by IEA Energy technology network.

		Installed PV capacity in 2018 [MW]	AC or DC
PV capacity	Off-grid		
	Decentralized[(2)]	434,3	DC
	Centralized[(3)]	5,5	DC
	Total	439,8	DC

[1] Blank box stands for not available data

[2] Any PV installation which is embedded into a customer's premises (self-consumption)

[3] Any PV installation which only injects electricity and is not associated with a consumer (no self-consumption)

Table 2.3: Annual PV power installed during 2018, from NSR of PV power application in Italy (2018)

			Installed PV capacity in 2018 [MW]	Installed PV capacity in 2018 [MW]	AC or DC
Grid-connected	BAPV[(2)]	Residential	410,5	178,1	DC
		Commercial		99,5	DC
		Industrial		132,9	DC
	BIPV[(3)]	Residential			
		Commercial			
		Industrial			
	Utility-scale	Ground-mounted	29,3	29,3	DC
		Floating		0	DC
		Agricultural		0	DC
Off-grid		Residential			
		Other			
		Hybrid systems			
Total			439,8		DC

[1] Blank box stands for not available data

[2] Building Applied PhotoVoltaic

[3] Building Integrated PhotoVoltaic

Table 2.4: PV power installed during year 2018, from NSR of PV power application in Italy (2018)

It is worth underscoring that around 98% of PV plants in Italy are linked to the low voltage distribution grid, while the remaining 2% are linked to medium voltage grid but represent 57% of the total installed capacity.

Year	Off-grid[3] [MW]	Grid-connected distributed [MW]	Grid-connected centralized [MW]	Total [MW]
1992	7,8	0,1	0,7	8,6
1993	8,6	0,1	3,5	12,2
1994	9,4	0,2	4,6	14,2
1995	9,6	0,3	5,9	15,8
1996	9,8	0,4	5,9	16,1
1997	9,9	0,7	6,2	16,8
1998	10,3	0,8	6,6	17,7
1999	10,8	0,9	6,7	18,4
2000	11,1	1,2	6,7	19,0
2001	11,7	1,6	6,7	20,0
2002	11,7	3,6	6,7	22,0
2003	11,7	7,6	6,7	26,0
2004	12,0	12,0	6,7	30,7
2005	12,3	18,5	6,7	37,5
2006	12,8	30,5	6,7	50,0
2007	13,1	68,7	18,3	100,1
2008	13,3	309,1	173,9	496,3
2009	13,0	682,6	581,4	1277,0
2010	13,0	1.544,6	2.047,5	3.605,1
2011	10,0	4.333,3	8.797,7	13.141,0
2012	11,0	6.042,6	10.742,4	16.796,0
2013	12,0	7.010,0	11.175,5	18.197,5
2014	12,0	7.236,4	11.358,0	18.606,4
2015	14,0	7.493,5	11.407,2	18.914,7
2016[4]	14,0	7.809,9	11.473,2	19.297,2
2017		8.105,5	11.576,7	19.682,3[5]
2018		8.449,1	11.658,5	20.107,6[5]

[1] Blank box stands for not available data
[2] The classification for grid-connected distributed and grid-connected centralized PV plants, applied since 1992, is below or over 200 kW
[3] Best estimate
[4] Grid connected data updated with GSE statistics 2018
[5] Differences between two values are due also to decommissioning and statistical update

Table 2.5: Cumulative installed PV in Italy by typology, from NSR of PV power application in Italy (2018)

Table 2.5 demonstrates how the PV market boomed between 2008 and 2013. This was completely due to the incentives program which have been provided by the Italian government. The program was known under the name "Conto Energia" of which there have been five different programs during the period 2005-2013. Hence, the Italian PV market grew a stunning 3566% between 2008 and 2013, when the Feed-in-Tariff program ended. In order to not completely stop investments in this sector, the Italian government decided to provide tax credit (only for small size plants up to 20 kW and for storage devices), which is minuscule compared to FiT previously supplied. Finally, the market after the incentives period (which is responsible for the installation of almost 18 GW out of 20 GW of the overall capacity), moved mainly towards small and industrial size plants based on other mechanisms.

Currently, the PV landscape is rapidly changing thanks to the reduced costs of the technology and the higher consciousness of environmental problems.

2.3.1 Average dimension of PV plant and geographical location in Italy

At the end of 2018, according to *GSE*, the first Italian regions by number of plants are Lombardy and Veneto with 125.250 and 114.264 units respectively; This represents almost 30% of the plants throughout the whole country. However, in terms of installed power, Puglia ranks first with 2.652 MW and the highest average plant size (54,8 kW).

Inversely, the regions with the lowest presence of PV capacity are Basilicata, Molise and Valle D'Aosta. The incremental variation of 2018 did not change the territorial distribution, which remains almost the same with respect to the previous year.

The highest number of PV plants is in northern Italy (55% of the total), while 17% are located in central Italy 28% in the south.

The figures below respectively represent:

- Figure 2.5: Regional Distribution of installed power (end of 2018);
- Figure 2.6: Regional Distribution of number of plants (end of 2018);
- Figure 2.7: Regional Distribution of number of plants (installed in 2018).

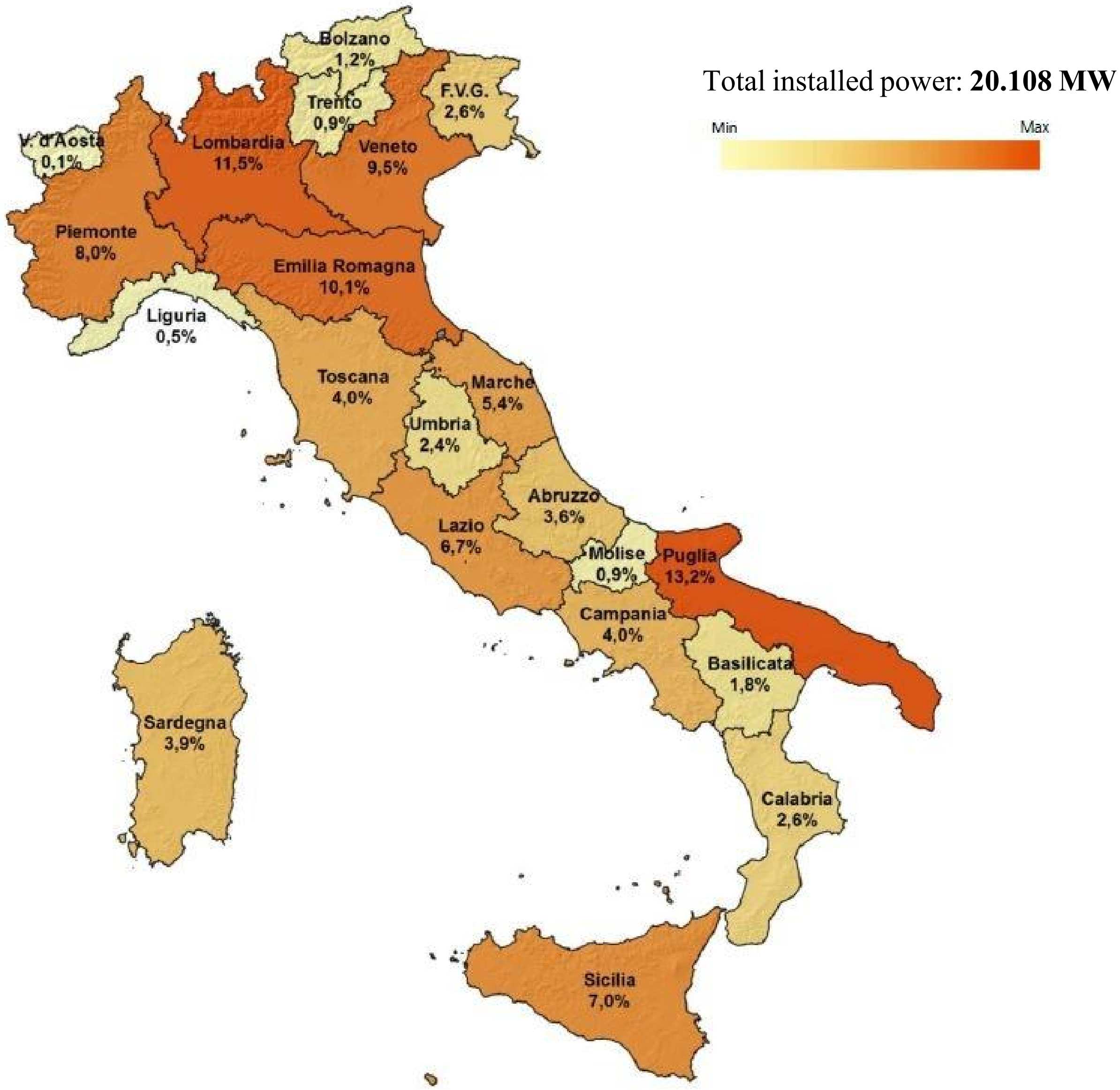


Figure 2.5: Regional Distribution of the installed power (end 2018), picture from GSE statistical review

The installed power is mainly in northern Italy (44%), followed by the south (37%) and the central region (19%). Puglia region is the first for regional contribution to the national total with 13.2%, followed by Lombardy with 11.5%. In the centre region Lazio ranks first with 6.7% of installed power.

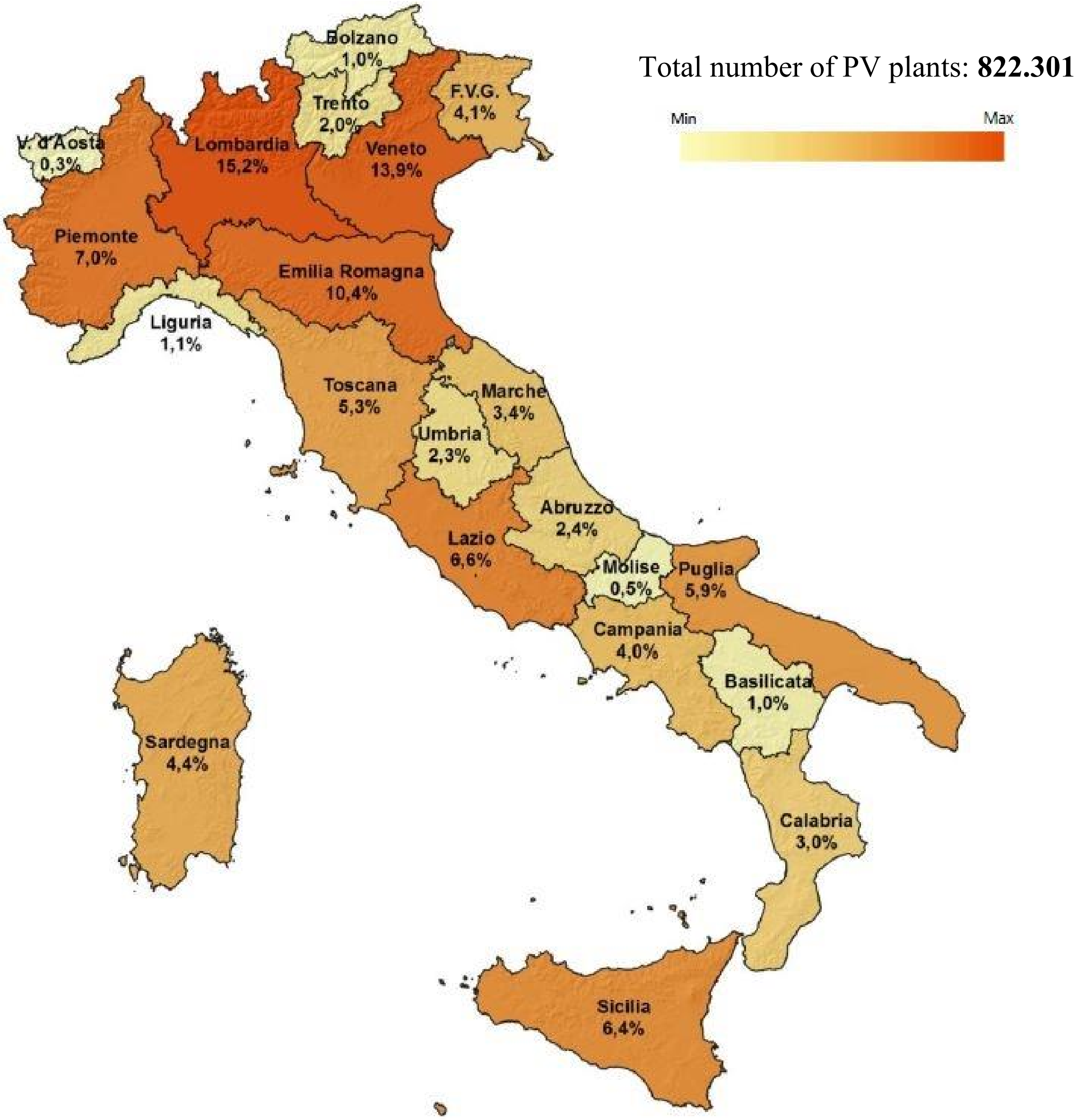


Figure 2.6: Regional distribution of number of plants throughout Italy, picture from GSE statistical review

For regional distribution of PV plants, Lombardy leads with 15,2%, followed by Veneto with 13,9% and Emilia-Romagna with 10,4% as illustrated in Figure 2.6 above. For the south, Sicily leads with 6% of new plants.

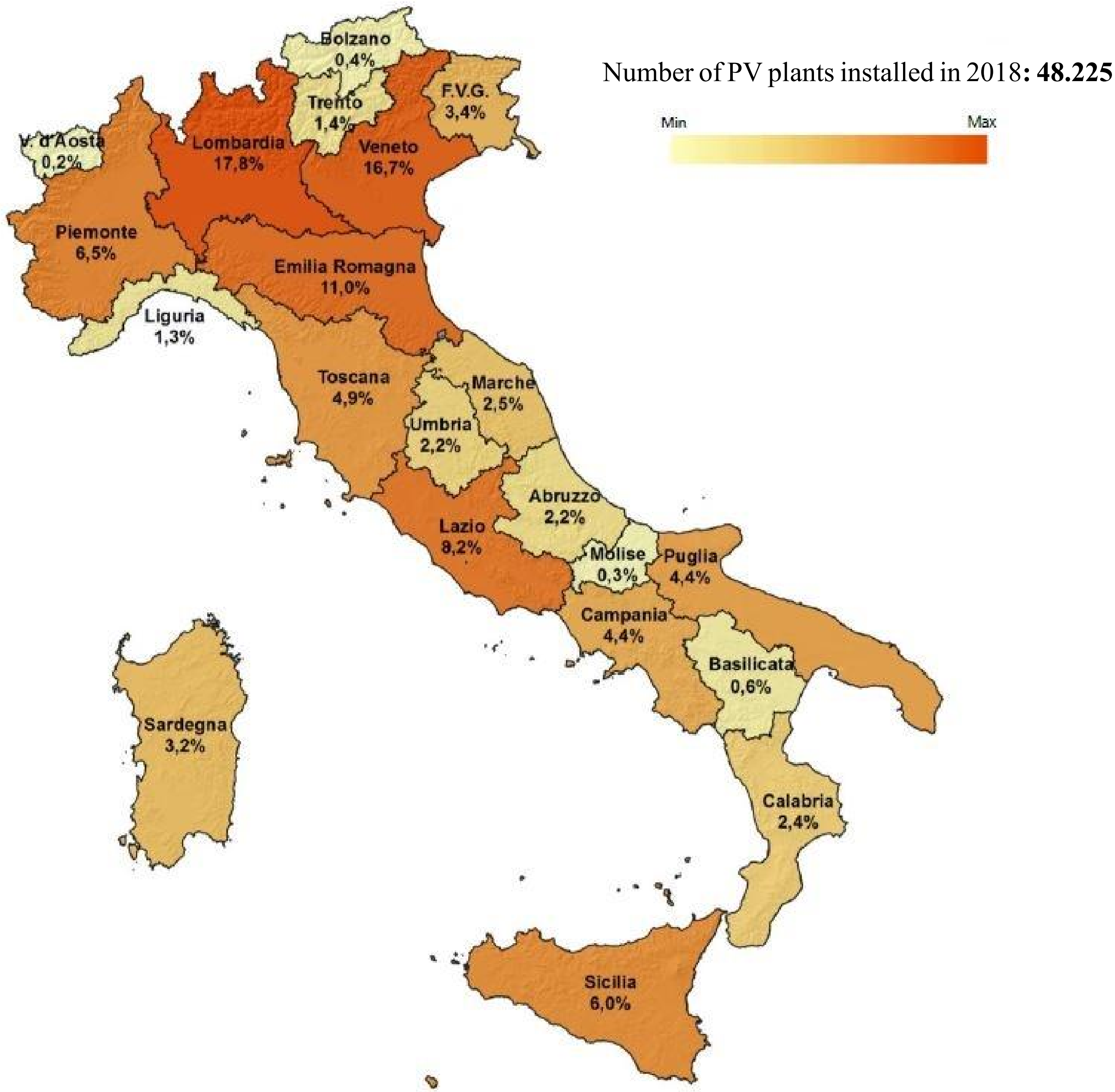


Figure 2.7: Regional Distribution of the number of plants installed in 2018, picture from GSE statistical review

Even for what concern the regional distribution of new plants installed in 2018, the same results emerge. Lombardy led the ranks with 17,8%, followed by Veneto with 16,7% and Emilia-Romagna with 11%. For the south, Sicily led with 6% of new plants installed in 2018.

The main conclusions that emerge from the analysis shown above is that for what concerns both power and the number of plants installed every year northern Italy leads the whole country.

However, on a regional level, Puglia ranks first both for power installed and average plant size (54,8 kW), this is probably due to factors such as lower density of population with respect to other regions, which means higher land availability. While for northern Italy the higher population density and heavy presence of firms makes it easier to have a higher number of investments and number of PV plants, but with an average plant size smaller than that of Puglia.

Chapter 3

Levelized Cost of Energy (LCOE)

PV energy, as pointed out by Green[16], is the technology with the steepest and fastest cost decrease due to Chinese manufacturing excellence and US investment. A vital element in this decrease in cost is the strong increase in demand, mainly due to European policies at the beginning of the 21st century (the German and Italian Feed-In-Tariff (FiT) for example).

Since the purpose of this thesis is to demonstrate that there are already some economically attractive PV plants that may compete with traditional methods, this short chapter focuses on to introducing the *levelized cost of energy (LCOE)*, which may be defined in different ways such as:

- "A convenient summary measure of the overall competitiveness of different generating technologies";
- "The per-kWh cost of building and operating a generating plant over an assumed financial life and duty cycle";
- "Ratio of the net present value of total capital and operating costs of a generic plant to the net present value of the net electricity generated by the plant over its operating life";
- "Average minimum price at which the electricity generated by the asset is required to be sold for in order to offset the total costs of production over its lifetime".

In summary, it is possible to say that LCOE is the average generation cost.

[16] Green MA. How did solar cells get so cheap? *Joule*. 2019;3(3):631-640.

In order to begin discussing LCOE, it is necessary to define the term utility-scale as it appears frequently. There is no real threshold after which it possible to define the plant utility-scale. Some people say that utility-scale refer to plant with a size that exceeds 1MW, other say that the term refers to much larger ones. Since the plants that will be considered in this work are close to 1 MW, the term utility-scale will be considered applicable to projects that will be discussed.

There are different formulas to compute LCOE value, and some of them embody a few assumptions that neglect the effect of taxes or, for example, the true cost of capital.

However, it is possible to say that it is accurate enough to compare different generating technologies, and therefore provide a good starting point for developing, designing, and most importantly, looking for investors.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{It + Mt + (Ft)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Et}{(1+r)^t}}$$

Where:

- It = Initial cost of the investment in the year t;
- Mt = Maintenance and operations expenditures in the year t;
- Ft = Fuel expenditures (if applicable) in the year t, not applicable to PV plants;
- n = expected lifetime of system or power station;
- r = discount rate;
- Et = Electrical energy generated in the year t.

A second formula which is more precise, includes all the costs involved in supplying PV electricity at the point of connection to the grid. According to *PV Parity: Grid Integration Cost of Photovoltaic Power Generation, project report. 2013,* the grid integration costs for most European countries are projected to be around 0,01 – 0,02 €/kWh by 2030. The grid integration costs will not be considered in the following comparison analysis, however, because also traditional technologies like coal and nuclear power do not have to pay grid integration costs.

Typically, LCOE is calculated using the lifetime of a plant. For a PV plant, LCOE usually takes 20 years as the life (even if a PV plant can last up to 30-35 years). The unit of measure is currency per kilowatt-hour or per megawatt-hour, €/kWh or €/MWh. The formula[17] is shown below:

$$LCOE = \frac{(CAPEX_{PV,total} + \sum[\frac{OPEX\ (t)}{(1+WACC_{nom})^{t}}] + \frac{InvRepl}{(1+WACC_{nom})^{\frac{N}{2}}} - \frac{ResValue}{(1+WACC_{nom})^{N}})}{\sum[\frac{Yield\ (0)\ \times\ (1-\ Degr)^{t}}{(1+WACC_{real})^{t}}]}$$

Where:

- N is the economic lifetime of the system;
- t is the year number ranging from 1 to N;
- $CAPEX_{PV,total}$ is the total capital expenditure of the system, made at t = 0 in €/kWp;
- OPEX(t) is operation and maintenance expenditure in year t in €/kWp;
- InvRepl is the cost of inverter replacement, made at t = N/2 in €/kWp;
- ResValue is the residual value of the system at t = N in €/kWp, which can be either positive or negative;
- Yield (0) is initial annual yield in year 0 in kWh/kWp without degradation;
- Degr is annual degradation of the nominal power of the system;
- $WACC_{nom}$ is the nominal weighted average cost of capital per annum;
- $WACC_{real}$ is the real weighted average cost of capital per annum.

The formula below clarifies the relationship between $WACC_{nom}$ and $WACC_{real}$:

$$WACC_{real} = [\frac{(1+\ WACC_{nom})}{(1+Infl)}] - 1$$

[17] This formula is taken from the *Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelized cost of electricity, EU PVSEC PAPER – 5 august 2019*

where Infl is the annual inflation rate.

As the article *Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelized cost of electricity* states, discounting the expenditures with nominal WACC and electricity generation with real WACC ensures that the net present value for the investment with nominal WACC is zero when valuing generated electricity for the real LCOE. An alternative method is to assume that the inflation rate is zero in the equation and to use real WACC for discounting both the expenditures and the generation. Both methods give the same value for LCOE.

Nominal WACC can be defined as:

$$WACC_{nom} = \frac{[D \times Kd \times (1 - CT) + E \times Ke]}{(D + E)}$$

where:

- D is debt financing;
- Kd is the interest rate of debt financing;
- CT is corporate tax rate;
- E is equity financing;
- Ke is the interest rate of equity financing.

As the above-mentioned article explains, "*a 4% interest on debt and 14% on equity with a 70/30 debt to equity ratio would give a 7% nominal WACC assuming corporate tax is zero. With green bond financing for utility-scale renewable projects, debt rates as low as 1,5% can been achieved. A 1,5% interest on debt and 10% on equity would give about 4% nominal WACC with a 70/30 debt to equity ratio. Inflation rate is set at 2%, which is the recent historical average inflation of the Euro zone. This means that 2% nominal WACC corresponds to 0% real WACC*".

CAPEX is estimated with the help of learning rate (LR), which can be split into modules, inverters, and other balance of the system (BoS) components (for instance mounting structures, cabling, inverters, transformers, as divided by Martin Junginger and

Atse Louwen in the *Technological Learning in the Transition to a Low – Carbon Energy System)*. For modules, the price follows a learning curve. Historically, each time the global volume of produced modules has doubled, the average price of modules has reduced by 23 to 24%[18].

Solar inverters prices follow a learning curve as well, but slower with respect to solar modules. Finally, the other BoS components include but are not limited to:

- Mounting Structures;
- Cabling;
- Inverters;
- Transformer;
- Electrical components;
- Grid connection;
- Infrastructure;
- Installation work;
- Planning;
- Documentation;
- Other work.

Analysing all the components above may become very difficult. Furthermore, some of the components listed above follow a learning curve, while others depend on the area of the PV array or the power. The results of the article *Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelized cost of electricity*[19], seen in Figures 30 and 31, give a general overview.

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[18] [ITRPV] – International Technology Roadmap Photovoltaic. International Technology Roadmap Photovoltaic (ITRPV) 2018 Results, 10th edition, ITRPV, Frankfurt a.M. www.itrpv.net/publications, March.

[19] *Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelized cost of electricity, EU PVSEC PAPER – 5 august 2019*

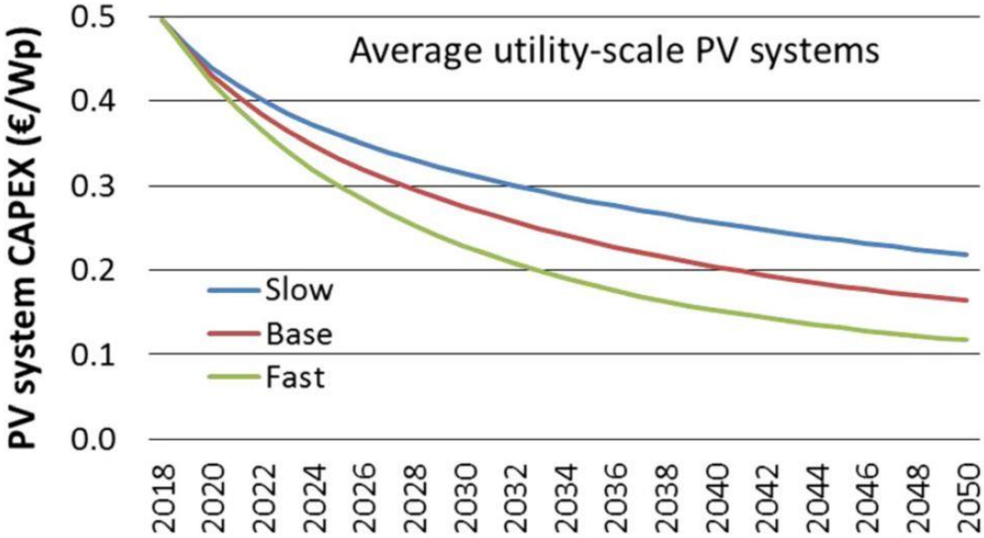

Figure 3.1: Projected CAPEX

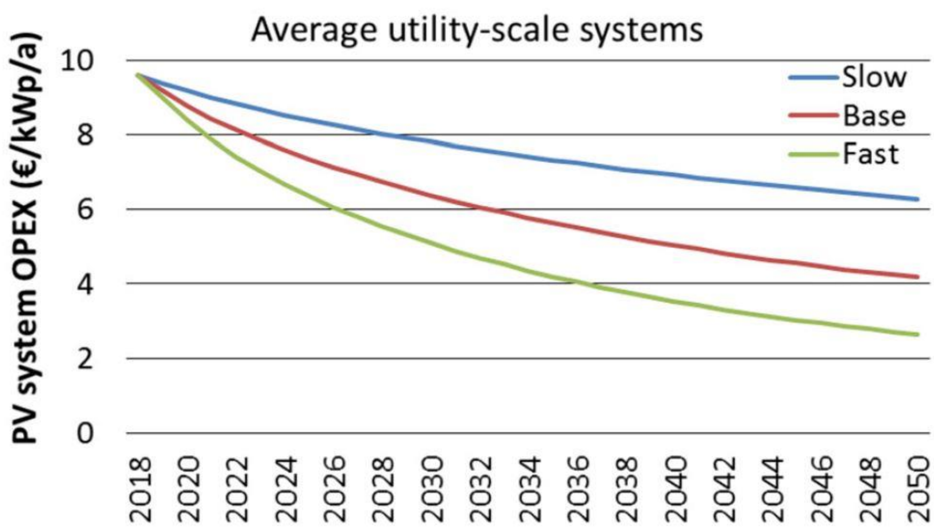

Figure 3.2: Projected OPEX

Chapter 4

LCOE of a ground mounted PV plant

In order to make a comparison of the Levelized Cost of Energy of the rooftop PV plant illustrated in Chapter5 with a reliable benchmark, this chapter analyzes a ground-mounted PV plant. The data taken do not come from a real operative PV plant like the one in the next chapter, but the data are as valid.

The PV plant data taken are for a system which is:

- Same size (≈1 MW);
- Same location (in order to have the same values of irradiation, thus, same energy yield).

Although the likely slightly higher energy yield is due to freedom of decisions on angles and structures to use for the designing of a ground-mounted PV plant, it involves significantly higher costs due to:

- Surface Rights;
- Higher cost for grid connection;
- Longer and more expensive bureaucratic procedures;
- Transformer cabin installation.
- Mounting structures

On the other hand, rooftop PV plants sizes are constrained by the surface and shape of the rooftop itself, which makes it harder to design angles and eventually mount tracking systems. It is also worth noting that with a ground mounted PV plant, self-consumption is not as easy to implement as, of course, for rooftop PV plants. It is possible to describe CAPEX and OPEX as follows:

CAPEX BREAKDOWN	
Description	**Amount**
ROOFTOP CAPEX	656.726,00 €
MOUNTING STRUCTURE AND CONSTRUCTION WORKS	112.581,60 €
COST FOR PRICE QUOTATION	1.500,00 €
COST FOR CONNECTION	59.007,17 €
TOTAL CAPEX	**829.814,77 €**

Table 4.1: CAPEX for a ground-mounted PV plant

The table above shows the CAPEX breakdown for a ground mounted plant. Capital expenditure differs depending on the type of project. The mounting structures of a rooftop are completely different with respect to this project.

In contrast, OPEX is estimated as follow

OPEX BREAKDOWN			
Description	**Length (Year)**	**% of the costs of the work**	**€/year**
O & M	20	10%	3.283,63 €
INSURANCE	20	5%	1.641,82 €
SURFACE RIGHTS	20	almost 3000€/hectare/year - for 1 MW almost 2 hectares are needed	6.000,00 €
SAFETY TOLERANCE	20	5%	1.641,82 €
TOTAL (WITHOUT DISCOUNTING)	20	---	251.345,20 €
TOTAL (EACH YEAR)	1		**12.567,26 €**

Table 4.2: OPEX for a ground mounted PV plant

Operational expenditure (OPEX) is computed using an average of different projects. For this analysis, operation and maintenance (O&M) are estimated to worth 10% of the capex divided into 20 years of duty cycle.

That said, it is possible to show the summary of the parameters taken for the calculation of the LCOE.

DESCRIPTION	**AMOUNT**	
CAPEX	857.960 €	914,49 €/kWp
OPEX (without discounting)	251.345,2	13,40 €/kWp
InvRepl (warranty)	0	-
ResValue	0	-
Yield (from PVGIS)	1.146.084,97	1.221,6 kWh / kWp
Degradation	0,60%	0,60%
WACCnom	2,50%	-
WACCreal	0,490%	-
Inflation	2,0%	

Table 4.3: Summary of the parameters for the calculation of the LCOE

$$LCOE = \frac{(CAPEX_{PV,total} + \sum[\frac{OPEX\ (t)}{(1+WACC_{nom})^t}] + \frac{InvRepl}{(1+WACC_{nom})^{\frac{N}{2}}} - \frac{ResValue}{(1+WACC_{nom})^N})}{\sum[\frac{Yield\ (0) \times (1-Degr)^t}{(1+WACC_{real})^t}]}$$

The formula above is used for the LCOE calculation.

LCOE	0,079	**€/ kWh**

The result shows that, currently, given the parameters above and the irradiation level in NAVE (BS) in northern Italy, it is possible to have an LCOE of 0,079 €/kWh, or 79 €/MWh. This number indicates the average generation cost for a ground-mounted PV plant with these characteristics. The first takeaway is that, as in the case with the rooftop plant later illustrated, self-consumption is economically very attractive, since a SME in Italy pays almost 150 €/MWh or 0,15 €/kWh. On the other hand, if the selling price is considered, the minimum price guaranteed for selling the energy to GSE is 40 €/MWh when it costs 79 €/MWh to generate it, making it less attractive.

This means that even though big steps have been made in PV technology, grid-parity has not yet been reached at this latitude, but it is getting very close. As soon as this is achieved for locations with this level of irradiation, it will be possible to generate energy at the same costs of traditional non-renewable sources

Chapter 5

Real case study of an industrial rooftop plant

This chapter aims to illustrate a real case study of an industrial rooftop plant located near Brescia, Lombardy. Due to privacy reasons, the company will not be mentioned, but the data used for the analysis are real. The chapter starts illustrating the technical features of aforementioned plant, and then demonstrates an economic analysis. Finally, the levelized cost of energy is computed.

5.1 Technical characteristics of the plant

5.1.1 Modules

The selection of the specific photovoltaic modules used in the rooftop PV plant was made through a careful market analysis regarding energy efficiency and economic quotation.

The modules chosen consists of monocrystalline silicon cells that have the following characteristics:

- Light frame made with anodized aluminium profile, resistant to rust and corrosion (used to give greater strength to the modules);
- Terminal junctions on the back with pre-wired cables with quick waterproof connection;
- Solar cells electrically connected to each other and placed between a multi-layer support of Ethylene Vinyl Acetate (EVA) which guarantees protection from the external environment, resistance to humidity, stability to UV rays and electrical insulation;

- Construction features that comply with EEC regulations, qualified by the tests carried out by the ISPRA Joint Research Center according to specifications 1215/CEC503 and certified by TUV to class Il in compliance with IEC 61215 law;
- Guaranteed continuous operating conditions under temperatures ranging from - 40°C to +90°C; pressure up to 2400 N/m^2; hail up to a diameter of 25mm with an impact speed of 23 m/sec; humidity 85% at 85°C;
- Power of a single module with a max tolerance of +10 measured in accordance with EEC 503 Standards.

Brand: Heckert Solar	***Model: NeMo 60M (305W – Monocristalline)***
Electrical Characteristic	
Maximum Power	*305 Wp*
Current at the maximum point of power	*9,54 A*
Voltage at the maximum point of power	*32,22 V*
Short-circuit current	*9,95 A*
Open circuit voltage	*39,96 V*
Maximum voltage of the system	*1000 V*
Modules Efficiency	*18,2%*

Table 5.1: Technical characteristic of the module

5.1.2 Inverters

Inverters are suitable for transferring power generated from the PV generator to the grid, in compliance with the applicable technical and safety regulatory requirements. Values of the input voltage and current are compatible with those of the PV generator while values of the output voltage and frequency are compatible with that of the network to which the system is connected to.

Brand: SMA Solar Technology AG	*Model: Sunny Tripower CORE 1*
Electrical data - input	
Maximum power of PV plant	*75000 Wp*
Max input voltage	*1000 V*
Minimum input voltage	*150 V*
Maximum input current	*120 A*
Short-circuit current	*30 A*
Short – circuit current per string	*30 A*
Electrical data – output	
Nominal Power (at 230 V; 50 Hz)	*50000 W*
Apparent power	*50000 VA*
Nominal voltage	*230 V / 400 V*
Grid frequency / range	*50 Hz / from 44 Hz to 55 Hz*
Maximum output current	*72,5 A*
Power factor at nominal power	*1*
Max efficiency	*98,1%*

Table 5.2: Inverter Technical Characteristics

5.1.3 Nominal power of the generating plant

The size of the photovoltaic generator was based on the characteristics of the electricity supply, the potential of the installation site, and the characteristics of both the module and the conversion units (inverters). It was essential to evaluate the available surface and consequently designate the surface size of the modules to be laid, determining their inclination to optimize energy yields. The technical data relating to sizing are shown in the following table:

Modules	***Heckert Solar Model NeMo 60 M (305 W Monocrystalline)***
Module power	*305 Wp*
Module surface	*1,67 m^2*
Total number of modules	*3076*
Total module surface	*≈ 5.137 m^2*
Inverter	*SMA Solar Technologhy Model Sunny Tripower CORE 1 (STP 50-40)*
Total number of inverters	*15*
Power peak of the plant	*938,180 kWp*
Specific energy yield	*≈ 1.221,6 kWh/kW (PVGIS)*
Annual energy yield	*≈ 1.146.080,688 kWh*

Table 5.3: Annual energy yield of the plant

5.2 Economic Analysis

The PV plant was designed to allow both the supply of energy to industrial loads and, when the loads do not run, the "injection" of the energy into the national grid.

The remuneration mechanism that functions for cases in which the plant fails is called "Ritiro Dedicato". "Ritiro Dedicato" is a simplified modality for the commercialization of electric energy that is "injected" into the national grid. It consists in the cession either to GSE[20] or other traders of the energy produced by the plant, receiving a remuneration based on the quantity of energy injected. Under the "Ritiro Dedicato" mechanism the energy is valued by the "Prezzo medio zonale orario", at the average monthly time slot's price, relatively to the location of the plant.

[20] GSE: Gestore dei Servizi Energetici

CAPEX		
Description (CAPEX)	**Amount [€]**	**Amount [€/kWp]**
TOTAL COST	656.726,00 €	700,00

Table 5.4: Capital expenditure for a rooftop plant

While, on the other hand, OPEX is estimated as follow:

OPEX			
Description (OPEX)	**Lenght (Year)**	**% of the costs of the work**	**Amount [€ / year]**
O & M	20	10%	3.283,63
INSURANCE	20	5%	1.641,82
SAFETY TOLERANCE	20	5%	1.641,82
TOTAL (WITHOUT DISCOUNTING)	20		131.345,20
TOTAL (EACH YEAR)	1		**6.567,26**

Table 5.5: Operational expenditure for a rooftop plant

Thus, in summary, the plant is grid-connected, with a total power of 938,180 kW and an energy annual yield, of almost 1.146.080 kWh (equivalent to ≈ 1.221,6 kWh/kW) in its first year, thanks to 3.076 PV modules that make up 5137 m^2 of surface, with a total CAPEX of almost 656.726 €.

Annual Energy Yield was computed with the Photovoltaic Geographical Information System (PVGIS); PVGIS is an interactive tool through which it is possible to compute the annual energy yield of PV plants by incorporating geographical location, peak power, modules technology and inclination angles. The tool has been made available by the European Commission. It is estimated that the database error is under 5%.

The figure and charts below, respectively represent:

- Geographical area of the PV plant;

- Monthly energy output of the PV plant computed from the PVGIS tool;
- Monthly consumption of the client company;
- Consumption of the industrial plant (in blue) versus PV plant output on its rooftop.

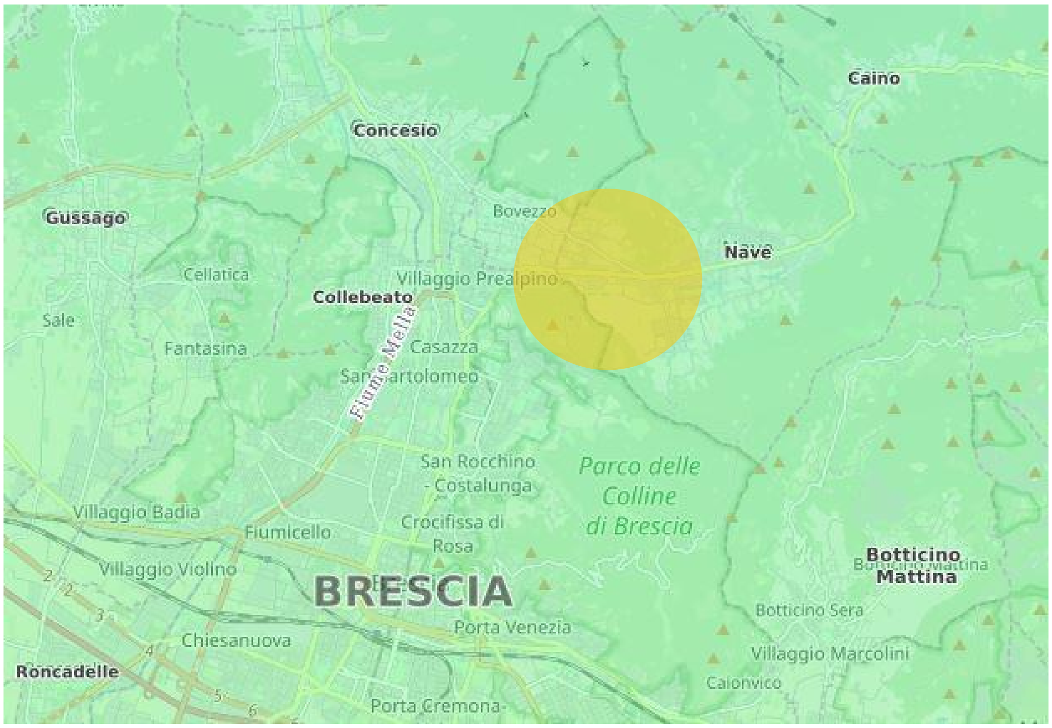

Figure 5.1: PV plant is in the yellow area

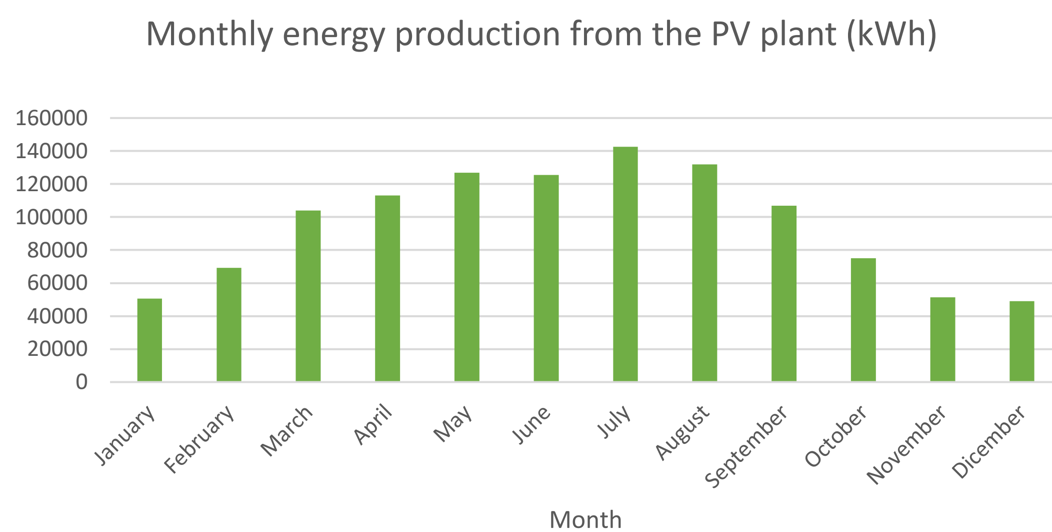

Figure 5.2: Monthly energy yield obtained from PVGIS for the location mentioned above

In contrast, the values of the company industrial consumption have been asked directly to the company. The values are shown in the chart below.

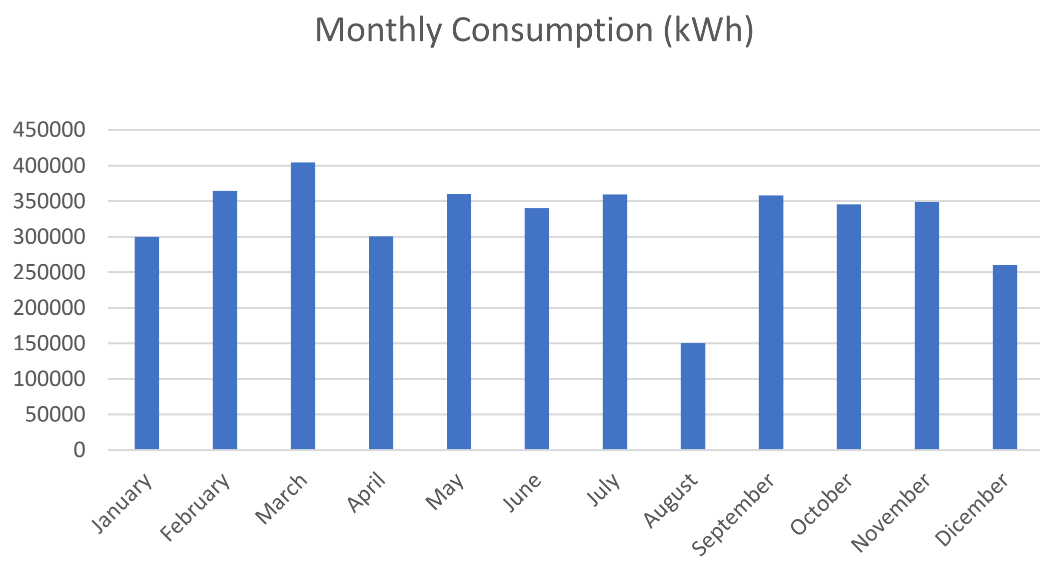

Figure 5.3: Consumption of the firm by month

Total consumption of the firm in year (0) is 3.894.026,91 kWh.

That being said, the chart below shows consumption versus production.

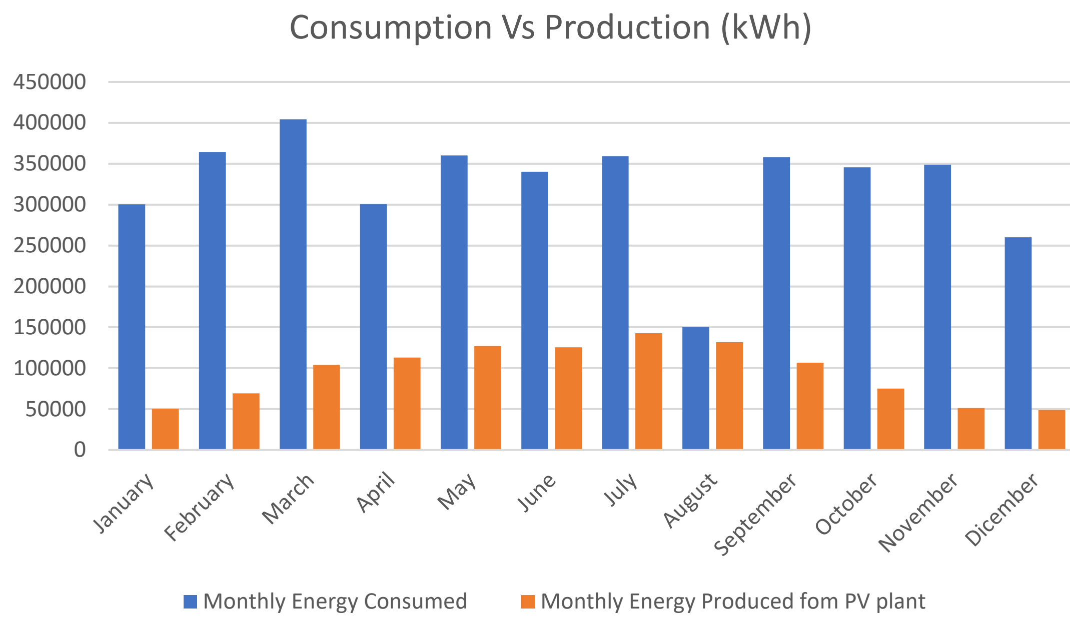

Figure 5.4: Consumption Vs Production

All charts above represent values at year (0). The project's economics derive from calculations that use the following parameters:

Degradation energy annual yield	0.6%
Tilt angle	35°
Cost per MWh from the grid	150 €/MWh
Selling price to the grid (minimum guaranteed – ARERA 2020)	40 €/MWh
System loss	14%
Annual increase in consumption	1%
Period considered	20 years

Table 5.6: Parameters used in the calculation of project economics

	0 (Time of the Investment)	1	2	3	4	5
ENERGY (kWh)						
Produced Energy		1146084,97	1139208,46	1132373,209	1125578,97	1118825,496
Grid - Injected Energy		54435	53056,74	51678,48	50300,22	48921,96
Self - Consumption Energy		1091649,97	1086151,72	1080694,729	1075278,75	1069903,536
Energy from the grid		2802376,94	2846815,459	2891602,121	2936741,069	2982236,481
CONSUMPTION (kWh)						
Total consumption		3894026,91	3932967,179	3972296,851	4012019,819	4052140,018
Self - Consumption (from PV plant)		1091649,97	1086151,72	1080694,729	1075278,75	1069903,536
From the Grid		2802376,94	2846815,459	2891602,121	2936741,069	2982236,481
PROJECT ECONOMICS (€)						
Revenues from the "Ritiro Dedicato" mechanism		2177,4	2122,2696	2067,1392	2012,0088	1956,8784
Saving in energy bills		163747,5	162922,8	162104,2	161291,8	160485,5
Exercise Cost		14644,4	14785,1	14927,2	15070,7	15215,7
Periodic Cost		14071,2	14211,9	14354,0	14497,6	14642,5
"Ritiro Dedicato" mechanism cost		573,15	573,15	573,15	573,15	573,15
Net Income		151280,5	150260,0	149244,2	148233,1	147226,7
Cash flow	-656.726,00 €	151280,5	150260,0	149244,2	148233,1	147226,7
Cumulated cash flow	-656.726,00 €	-505445,5	-355185,5	-205941,3	-57708,2	89518,5
NPV		-506.943,28 €	-359.644,03 €	-214.789,11 €	-72.340,02 €	67.741,15 €

	6	7	8	9	10
ENERGY (kWh)					
Produced Energy	1112112,543	1105439,868	1098807,229	1092214,386	1085661,099
Grid - Injected Energy	47543,7	46165,44	44787,18	43408,92	42030,66
Self - Consumption Energy	1064568,843	1059274,428	1054020,049	1048805,466	1043630,439
Energy from the grid	3028092,574	3074313,604	3120903,863	3167867,686	3215209,444
CONSUMPTION (kWh)					
Total consumption	4092661,418	4133588,032	4174923,912	4216673,151	4258839,883
Self - Consumption (from PV plant)	1064568,843	1059274,428	1054020,049	1048805,466	1043630,439
From the Grid	3028092,574	3074313,604	3120903,863	3167867,686	3215209,444
PROJECT ECONOMICS (€)					
Revenues from the "Ritiro Dedicato" mechanism	1901,748	1846,6176	1791,4872	1736,3568	1681,2264
Saving in energy bills	159685,3	158891,2	158103,0	157320,8	156544,6
Exercise Cost	15362,1	15510,0	15659,4	15810,2	15962,6
Periodic Cost	14789,0	14936,9	15086,2	15237,1	15389,5
"Ritiro Dedicato" mechanism cost	573,15	573,15	573,15	573,15	573,15
Net Income	146225,0	145227,8	144235,1	143246,9	142263,2
Cash flow	146225,0	145227,8	144235,1	143246,9	142263,2
Cumulated cash flow	235743,4	380971,2	525206,3	668453,3	810716,4
NPV	205.491,67 €	340.948,23 €	474.146,94 €	605.123,31 €	733.912,31 €

	11	12	13	14	15
ENERGY (kWh)					
Produced Energy	1079147,133	1072672,25	1066236,216	1059838,799	1053479,766
Grid - Injected Energy	40652,4	39274,14	37895,88	36517,62	35139,36
Self - Consumption Energy	1038494,733	1033398,11	1028340,336	1023321,179	1018340,406
Energy from the grid	3262933,549	3311044,455	3359546,654	3408444,681	3457743,112
CONSUMPTION (kWh)					
Total consumption	4301428,282	4344442,565	4387886,99	4431765,86	4476083,519
Self - Consumption (from PV plant)	1038494,733	1033398,11	1028340,336	1023321,179	1018340,406
From the Grid	3262933,549	3311044,455	3359546,654	3408444,681	3457743,112
PROJECT ECONOMICS (€)					
Revenues from the "Ritiro Dedicato" mechanism	1626,096	1570,9656	1515,8352	1460,7048	1405,5744
Saving in energy bills	155774,2	155009,7	154251,1	153498,2	152751,1
Exercise Cost	16116,5	16271,9	16428,9	16587,5	16747,6
Periodic Cost	15543,4	15698,8	15855,8	16014,3	16174,5
"Ritiro Dedicato" mechanism cost	573,15	573,15	573,15	573,15	573,15
Net Income	141283,8	140308,7	139338,0	138371,4	137409,0
Cash flow	141283,8	140308,7	139338,0	138371,4	137409,0
Cumulated cash flow	952000,2	1092309,0	1231646,9	1370018,3	1507427,3
NPV	860.548,33 €	985.065,21 €	1.107.496,26 €	1.227.874,25 €	1.346.231,42 €

	16	17	18	19	20
ENERGY (kWh)					
Produced Energy	1047158,888	1040875,934	1034630,679	1028422,895	1022252,357
Grid - Injected Energy	33761,1	32382,84	31004,58	29626,32	28248,06
Self - Consumption Energy	1013397,788	1008493,094	1003626,099	998796,5746	994004,2973
Energy from the grid	3507446,566	3557559,703	3608087,227	3659033,884	3710404,466
CONSUMPTION (kWh)					
Total consumption	4520844,354	4566052,797	4611713,325	4657830,459	4704408,763
Self - Consumption (from PV plant)	1013397,788	1008493,094	1003626,099	998796,5746	994004,2973
From the Grid	3507446,566	3557559,703	3608087,227	3659033,884	3710404,466
PROJECT ECONOMICS (€)					
Revenues from the "Ritiro Dedicato" mechanism	1350,444	1295,3136	1240,1832	1185,0528	1129,9224
Saving in energy bills	152009,7	151274,0	150543,9	149819,5	149100,6
Exercise Cost	16909,4	17072,7	17237,7	17404,4	17572,7
Periodic Cost	16336,2	16499,6	16664,6	16831,2	16999,5
"Ritiro Dedicato" mechanism cost	573,15	573,15	573,15	573,15	573,15
Net Income	136450,7	135496,5	134546,4	133600,2	132657,9
Cash flow	136450,7	135496,5	134546,4	133600,2	132657,9
Cumulated cash flow	1643878,1	1779374,6	1913921,0	2047521,1	2180179,0
NPV	1.462.599,51 €	1.577.009,74 €	1.689.492,83 €	1.800.079,01 €	1.908.798,04 €

Table 5.7: Project economics

Analysing the data from the table above, it is possible to compute the profitability of the project through the NPV calculation.

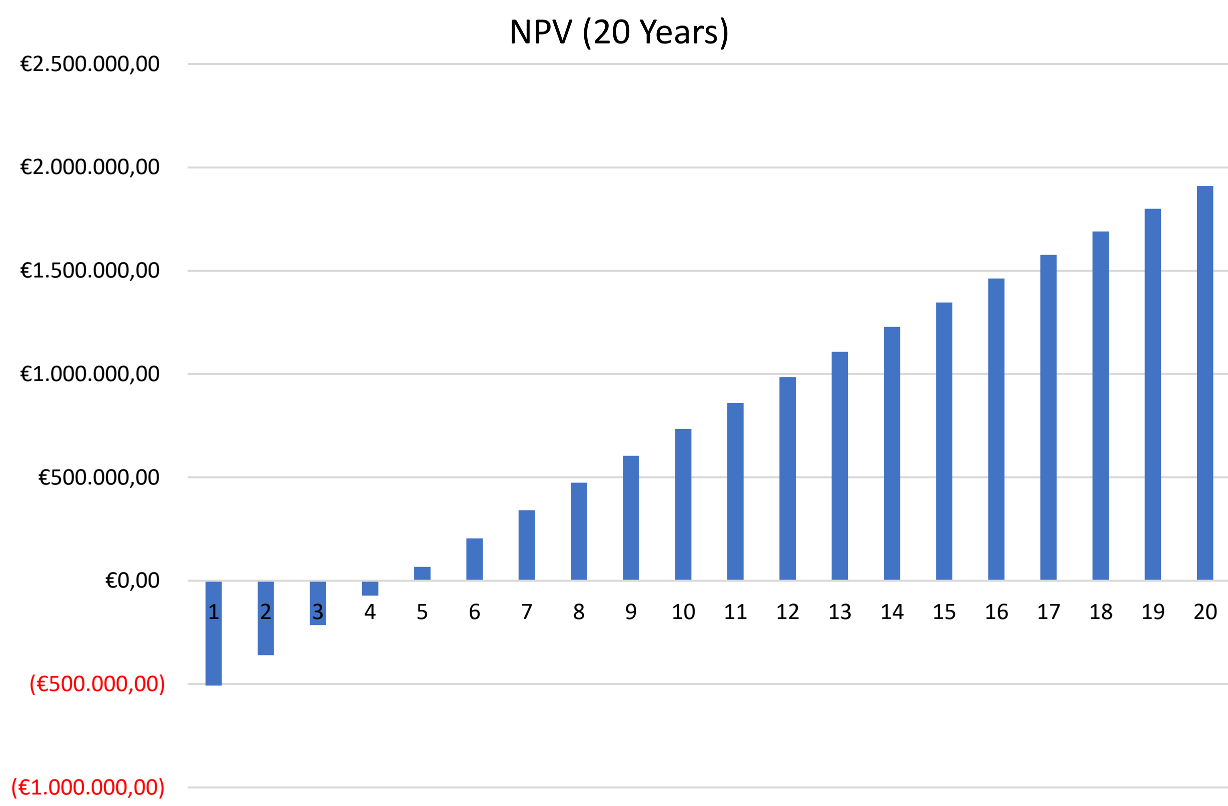

Figure 5.5: NPV analysis

Thus, looking at figure 5.5, it is notable that the payback period (time that it takes for the project to reach the breakeven point), is between the fourth and fifth year.

Additionally, it is possible to compute the Internal Rate of Return (IRR) which is 22% for this project.

5.3 Levelized Cost of Energy

The Levelized Cost of Energy (LCOE) will be computed for the project above. In this case, the parameters taken for the calculations are different with respect to a ground-mounted PV plant.

PARAMETERS	AMOUNT	
CAPEX	656.726,00 €	700 €/kWp
OPEX (without discounting)	131.345,20 €	7,00 €/kWp
InvRepl (warranty)	0,00 €	-
ResValue	0,00 €	-
Yield	1.146.084,97	1221,6 kWh/kWp
Degradation	0,60%	0,60%
WACC nominal	2,50%	-
WACC real	0,49%	-
Inflation (European Average in the last years)	2,00%	-
Specific Yield in a year (From PVGIS)	1.221,6 kWh/kWp	

Table 5.8: Parameters used for the LCOE calculation

Therefore, LCOE can be computed.

LCOE	**0,05814**	**€/ kWh**

The difference in the LCOE value of a ground-mounted PV plant with respect to a rooftop is noticeable. This number is crucial because of its proximity to the Italian PUN[21], meaning that the PV plant's average generation cost is almost the same as generating energy from non-renewable sources.

Therefore, it is possible to state that PV plants are palpably a secure investment for self-consumption both for economic and environmental purpose.

---

[21] PUN: Prezzo unico nazionale (unique national price);

Conclusion

This thesis intended to demonstrate the sustainability of photovoltaic solar projects without the national Italian incentives. It is worth repeating that this work was done with data that are valid in northern Italy. Factors such as irradiation, electric energy price, costs of transportation and so on are valid at this latitude and within the Italian territory.

The deductive reasoning behind it, however, is applicable to any reality. There are two main takeaways. The first pertains to self-consumption and the fact that it is economically sustainable without any need for incentives, regardless of the kind of plant. The latter regards selling solar energy and comparing its capability to generate electricity at the same cost as the non-renewable resources used for traditional power plants. It currently still costs more for photovoltaic plants than traditional non-renewable sources to generate the same amount of energy, whether to sell either to GSE or independent traders. This is true for northern Italian latitudes, where 1 kW of installed power generates almost 1.200 kWh/year. The irradiation level plays a vital role in determining project economics. In geographical areas with a higher irradiation level, the parity is reached and PV plants selling energy are already competing with traditional non-renewable source power plants.

The data and market analysis show that the grid-parity of PV plants with the sole purpose of selling energy is not so far in the future for northern Italy. Economies of scale and learning rate decrease costs so that this future is becoming increasingly close. It is important to note that each time the global volume of produced modules has doubled, the average price of modules has reduced by 23 to 24%.

Below the table that shows the results.

PLANT	LCOE	AVERAGE PRICE PAID FOR ENERGY BY FIRMS	SELLING PRICE (MINIMUM GUARANTEED BY GSE-2020)
ROOFTOP	0,05814 €/kWh	0,15 €/kWh	0,04 €/kWh
GROUND MOUNTED	0,079 €/kWh		

Table 6.1: Results

The results show that self-consumption is economically attractive for any type of plant. This is true because the LCOE expresses the average generation cost the plant owner pays to obtain energy from the sun, and purchasing the same energy from the national grid costs more. In contrast, selling the energy either to *Gestore dei Servizi Energetici* (*GSE*) or to independent traders is not sustainable yet. For this analysis the minimum price guaranteed by GSE was taken, even though the actual price fluctuates throughout the whole year. This means that independent from the variations, GSE will pay at least 0,04 € per-kWh produced. Thus, it is significant that if the PV plant owner pays between 0,05814 €/kWh and 0,079 €/kWh, then investment is not worthwhile.

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