POLITECNICO DI TORINO

Master of Science Program Energy and Nuclear Engineering

Master Thesis

# Analysis of the agrivoltaic power plants and practical evaluations

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# ABSTRACT

The intercontinental agreements of the conference of parties, and European policies such as the Green Deal require countries like Italy to respect stringent limits on the production of electricity from traditional sources. Italy's response to this line of action has been the development of the PNIEC and the PNRR, two plans aimed at the development and recovery of the country in every area, with the utmost attention to the energy sector. In this intricate political scenario, agrivoltaic represents an interesting technological alternative for the installation of massive photovoltaic systems in territories where the availability of land is limited. The double use of the land in the Agrivoltaic (AV) sites allows to "doubly harvest from the sun", increasing the land use exploitation with lower environmental impact. This effect strongly depends on the system configuration for both the PV and agricultural sides. In this work it is illustrated a PV plant designed in Southern Italy, in which each hectare can be used for a PV plant with rated power of 0.7 MWp and about 900 Arbequina olive trees. It is analysed the effect of different module layouts on the photovoltaic and crop production, with particular focus on the shadowing effect. This study highlights that there is a trade-off between a high-density PV module arrangement, with high PV production and low agricultural harvesting, and a highly spaced arrangement with lower PV production. Using mathematical model to perform analysis on both the energetic and agronomical sides, this work combines its result into a financial analysis to shape the best investment features. Finally, the "land use saving" analysis is performed to compare the agrivoltaic with the traditional photovoltaic and agricultural plants. The final purpose of this work is to clearly define the value of the agrivoltaic technology in the development of a sustainable energetic horizon.

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*It is important to realize that in physics today, we have no knowledge of what energy is. There is a fact, or if you wish, a law, governing all natural phenomena that are known to date. There is no known exception to this law—it is exact so far as we know. The law is called the conservation of energy. It states that there is a certain quantity, which we call energy, which does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same.*

***Richard Feynman***

# Introduction

The evolution of the human species through the years goes concurrently with new discoveries. From the dawn of the civilization the people tried to dominate the environment to get specific advantages in their life quality. From the discovery of fire to the internal combustion engine, the final conceptual goal has always been the improvement of the human condition above every other entity.
The technology is the catalyst for the realization of the human most inner needs and desires: we used fire to frighten wild animals; we built huts, houses, castles and cities for peaceful living; we casted knives, swords and guns to protect ourselves and maintain our will; we trained horses, projected railways and cars for feel free to move as we always wanted; we challenged the sun power playing with atoms, producing nuclear energy and nuclear bombs.
Thousand years of efforts have conducted us to the nowadays strongly technologized world: today everything is possible, nothing is unattainable, we are the proud and selfish factotum of the universe.
This system, the world we created, is solid but not unconditionally stable, this condition is usually not fully understood.
With the Covid-19 pandemic, we rediscovered that not everything is under human control, we felt again afraid towards nature.
This feeling brought back to the top the discussion about the climate change.
The phenomena of the climate change could bring serious consequences such as increasing of the intense natural phenomena, changes in the food chain and collateral damages linked to the economy of the primary sector.
Once again, the humans would resort to their newest technologies to solve the problem, in fact Renewable Energy Sources are the pivotal point of each strategy to counteract the climate change.
Renewable Energy Sources are defined as resources that draw their final product from reserves that reload in “human” times. The adjective “human” refers to the fact that the amount of time requested to regenerate the used energy is comparable with the average human lifetime, in this way it is ensured that the exploitation of a certain resource by a generation will not interfere with the satisfaction of the basic necessities of the future generations.
Unfortunately, this problem cannot be fixed so easily: using renewables is not the arrival point, but just a step towards the solution.
To counteract the Climate Change, in a measure that anyway would not to be a total restoration of the Earth’s environment before the human impact, we are called to a change of paradigm.

The human race has always acted as a user with respect to the planet, trying to use and dominate its resource, but now the leitmotiv should change from exploitation to sustainability.
Never in the history the human tried a so radical modification to its habits, that's why this challenge is so difficult, but it is surely possible.

# Chapter 1

## 1 RES technologies

The biggest part of the energetic consumption is satisfied using fossil fuels, those sources are not renewable and produce high quantity of green-house gasses (GHG) that damage the balance of the environment balance. The alternative to the fossil fuels is the utilization of Renewable Energy Sources (RES). The renewables are clean energy sources that generate power without greenhouse gas emissions reducing air pollution.

According to IEA (International Energy Agency) in 2019, world total primary energy supply (TES) was 606.5 EJ, the majority of which was produced from fossil fuels. The renewable energy sources, such as hydro, biofuels, solar PV, solar thermal, wind, geothermal and tidal, presently provide a contribution between 15 % and 20 % of world's total energy demand [1]. Even if the results are not so brilliant, on the other hand since 1990 the use of RES has grown at a constant annual rate of +2.1%, a result that becomes even better considering that the growth rate of world TES was lower than this, it accounted a +1.8%.

Among the different kind of renewables, the solar technology is the most growing sector, indeed, the spread of solar plants grows with an average rate of +36.0% each year as it is possible to see in the *figure 1* where all RES growth is analyzed.

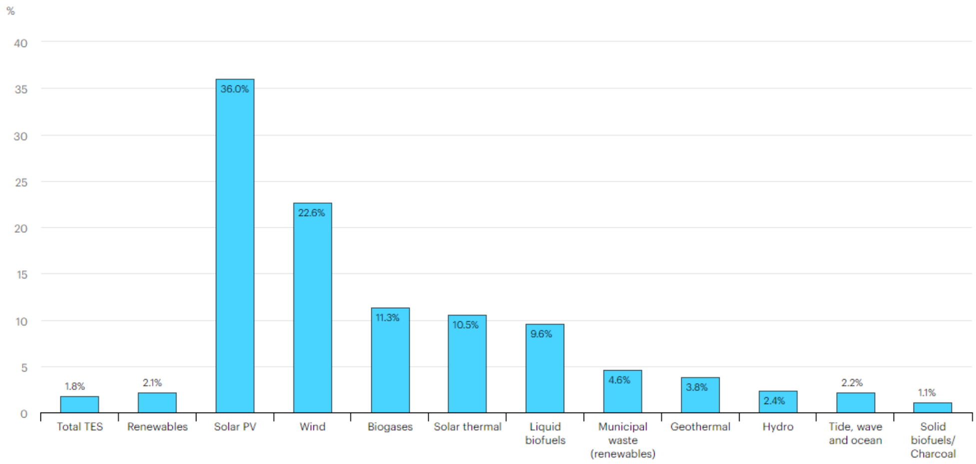



Figure 1: Res grow rate

Europe has the ambitious objective of becoming the world's first carbon neutral continent, and to do so since 1988 adopted a series of measures to promote the use of RES technology for both domestic and utility scale plants.

The photovoltaic module is a smart solution for the direct production of electricity from the sunlight and the European Union consider this technology a pivotal point for the climate action.

These policies linked to the technological advancement decreased the price of the solar plants, triggering a cycle that would increase the spread of the solar panels.

So the soar technology gradually spread from the first satellite application to the nowadays domestic plants, the cost per Watt decreased from \$105.7 in 1975 to \$0.2 in 2020 [2] as shown in the *figure 2* and the modules efficiency almost doubled from 70s' to nowadays reaching more than 26% for the monocrystalline cells [3].

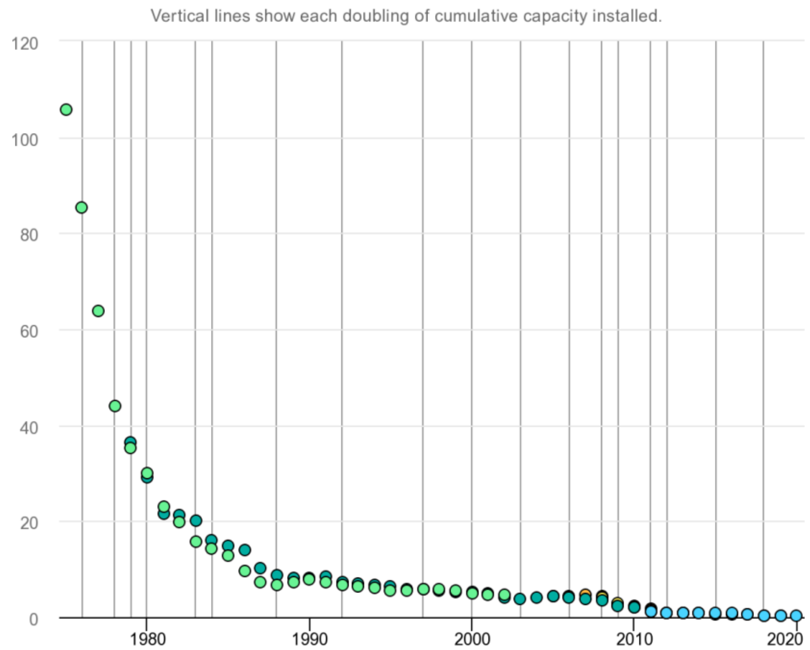



*Figure* 2: PV price from 1975 to 2020

Since the policy of sustainable development takes care of the human growth and development towards the environment, the energetic production is not the only question accounted. The primary sector is the entrance door of the human activity at the expense of the environment, so a radical change of paradigm could not leave aside a new concept of agriculture and farming.

The agrivoltaic (AV) is an interesting project that couples the energetic production from RES with a correct land use in respect with the local biodiversity.

The definition of the AV, as the association Italia Solare states, is the following: «The agrivoltaic [ndr] is a photovoltaic system, which in compliance of the agricultural and livestock use of the soil, even when placed on the ground, not inhibits this use, but integrates and supports it by ensuring the continuity of pre-existing activities or the recovery of agriculture and livestock and biodiversity on the same portion of soil on which the planting area stands, thus contributing to optimize the use of the land itself with positive effects on the territory in employment, social and environmental terms. »

The following paragraphs are about a technical outlook on the photovoltaic technology, while a successive chapter is dedicated to the contextualization of the AG power plants in the European horizon.

## 1.1 General aspect of PV system

The photovoltaic (PV) technology exploits the energy leaded by the solar radiation to directly produce electricity. The operation of the PV systems has no impact on the environment since they do not produce any greenhouse gas into the atmosphere. Moreover, the energy used by the PV modules is re-integrated into nature on human time scale, making the technology sustainable. On the other hand, the electricity production from PV source is not constant, since it depends on the intermittence and stochasticity of the solar source, and the efficiency of the conversion is in the order of 20/22 % for the commercial solutions.

## 1.2 Solar radiation

The Sun is the source of the energy exploited by the PV modules. Inside the Sun the temperature reaches 5800 K because of the energy released by the thermonuclear reactions that take place in its core. For the application discussed here, the Sun can be represented using the black body model, an ideal emitter of heat radiation. The black body has a specific power emission that is function of the wavelength, whose variation gives all the different colour shades recognizable by the human eye and beyond, from the ultraviolet (10 to 400 $nm$) to the infrared (780 $nm$ to 1 $mm$).

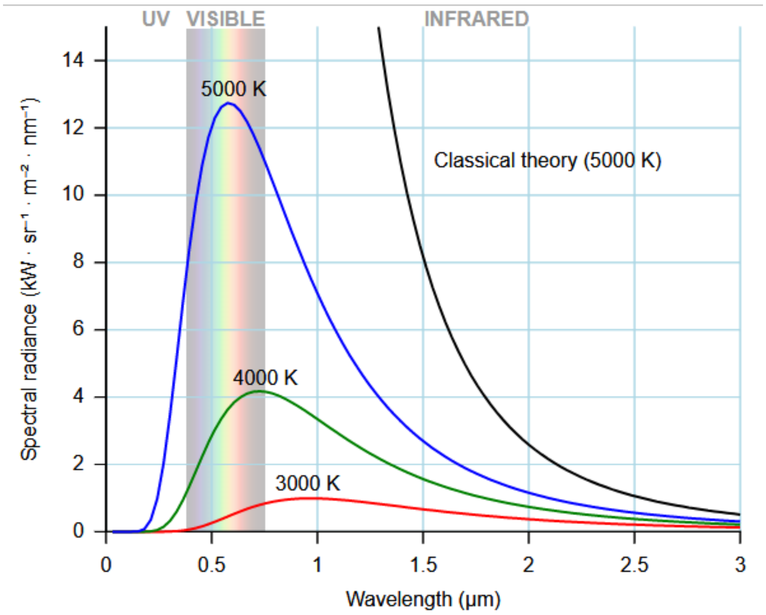



*Figure* 3: Black body spectrum

The solar radiation travels in the space, from the Sun to the Earth, in form of electromagnetic wave. At the edge pf the atmosphere the interaction among the light and the exosphere molecules divides the total amount of light directed to the Earth in three rates: one part is diffused by the molecules; one part is reflected, and a final part goes through the atmosphere reaching the surface. The reflected radiation, as well as the diffused one, in indirect ways would anyhow reach the surface of the planet. Indeed, the global irradiance, that is he total amount of energy that reaches the Earth surface, is given by the sum of the three components: direct, diffuse and reflected. The actual amount of solar energy incident to a certain region is proportional to many factors: the conditions of the atmosphere, the distance between the Earth and the Sun in that period of the year, the inclination of the planet with respect the incoming sunrays. Moreover, there are local drivers linked to the topology and the geographical position of the PV site where it is requested to produce energy.

## 1.3 Photoelectric effect

The energy that a solar PV produced is analysed following the theory of the electronic band structure. This theory is about the levels of energy an electron can assume, it is possible to distinguish valence electrons, electrons in the conduction band: the firsts are on the last available energy level and allow the formation of chemical bonds, the seconds belong to the lowest energy level band. The

Photovoltaic effect takes place thanks to the interaction of an electromagnetic wave with a valence electron, since thanks to the incident energy from the sunrays, the electrons can shift from the valence band to the conduction band. The energy to switch from a band to another is called Energy Gap. The energy gap is different for each material, but it is possible to classify 3 categories: conductors, semiconductors and insulators. In conducting materials, usually metals, the difference between the valence band and the conduction band is minimal, on the other hand, for insulators, the energy required is maximal. Semiconductor materials are the middle ground alternative, for these materials the two bands have an energy difference of about 1 eV as in *figure 4*.

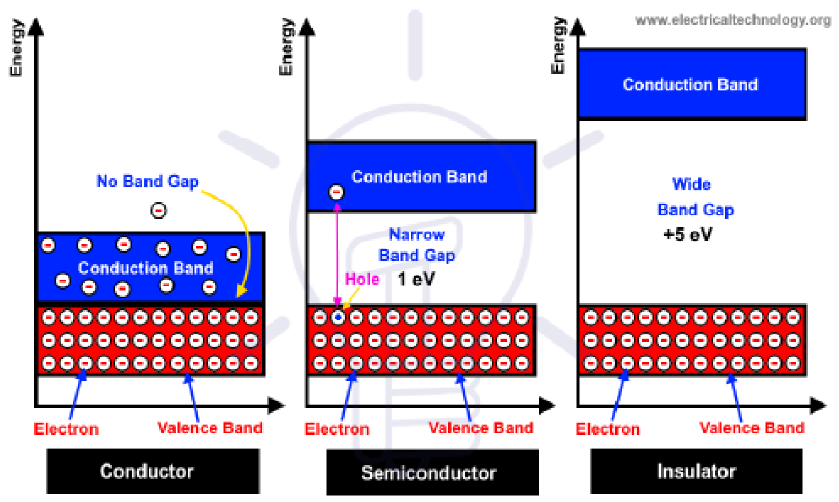



*Figure* 4: Diagram of the electronic band structure for conductors, semiconductors and insulators

To understand how the solar radiation match the energy gap needed by the electrons in the semiconductor material causing the photovoltaic effect, it is needed to consider the quantum form of the light. The quantum theory for the light says that the energy is not evenly distributed on the entire wavefront, but it is concentrated in packages (quantum) of energy that are called photons. When a photon comes to interact with an electron, if the energy carried and given by the photon to the negative particle is enough high, then the molecular chemical bond would break and the so the electron would pass from the valence band to the conduction band. The photon energy must be at least equal to the energy gap to start the photovoltaic effect. The energy carried by a photon is computed using Plank's formula:

$$E_{ph} = \frac{h \cdot c}{\lambda} \quad (1)$$

Where:

- h=Plank's constant
- f=frequency of the wave
- $\lambda$=wavelength
- $c$=light speed

## 1.4 Solar cell

Since the physical principles behind the PV technology have been already discussed, in this paragraph it is analysed the structure and the principle of operation of the solar cell. The solar cells are made using semiconductors, most of the cells are made using crystalline silicon, which can be monocrystalline, polycrystalline or amorphous. The monocrystalline silicon is made by a single crystalline lattice, continuous, without grain borders and high purity level; polycrystalline silicon is different crystal lattices of silicon less pure than the monocrystalline one; amorphous silicon has not a crystalline lattice and its purity is the lowest one. The solar cell can be considered as a diode, since it allows the electricity to flow only in a way. The diode stricture is characterized by two electrodes, one on the front side of the cell (that let anyway the sunrays touch the cell surface) and the other one is on the back. Among the electrodes there is the PN junction formed by the P and the N sides. The P side there are the majority carriers, the holes, and few minority carriers, the electrons. The N side the situation is the opposite, the electrons have the role of majority carriers, and the holes are the minority carriers. Near the junction is a region having no free-charge carriers, the depletion layer, that behaves as an insulator. The doping is used to create a potential barrier thanks to the introduction of trivalent atoms of Boron, for the type P, and pentavalent atoms of Phosphorus, for the type N. The potential barrier contrasts the phenomena of diffusion of electrons, that otherwise would naturally move from areas of higher concentration to areas of lower concentration. A dynamic equilibrium is created thanks to the drift current, that flow across the circuit

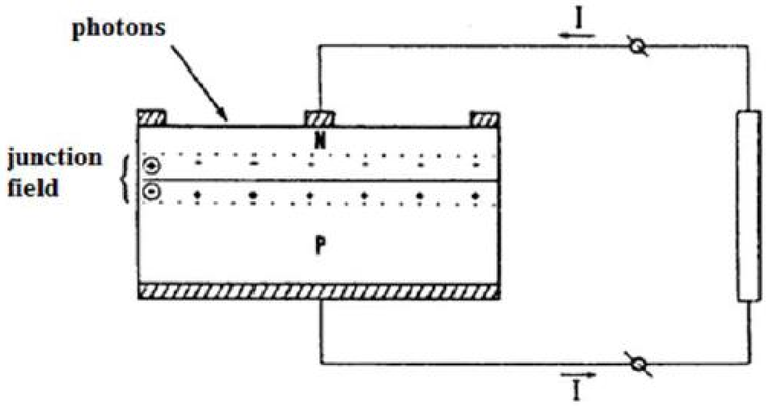



*Figure* 5: Structure of polycrystalline silicon solar cell

In dark condition the solar cell behaves as a diode. The behaviour is characterized by forward bias or reverse bias. In the first case the positive pole of the voltage source is linked to the negative side of the diode, for the reverse bias instead it is the opposite. The forward bias enhances the depletion region among the two sides of the PN junction, while the reverse bias reduces the thickness of the same region. When the electrons have enough energy to overcome the depletion region (usually 0.7 V) there it comes an electricity flow. The current is given by two contributions: the diffusion term and the drift term of the following equation:

$$I = I_0 \cdot e^{\frac{qU}{mkT}} - I_0 \quad (2)$$

Where:

- $I_0$ is the saturation current, defined as the current generated in the diode because of negative voltage

- q is the electron charge
- U is the tension
- m is the quality factor of junction
- k is the Boltzmann constant

If the cell is not in dark conditions, it must be considered the photovoltaic effect, so the production of an electrons flow thanks to the energy subtracted from photons. The electricity created by this effect is opposite to the diffusion current since it is oriented by the junction field, it is defined as follow:

$$I_{ph} = qNA \tag{3}$$

Where:

- N is the number of photons
- A is the area exposed to radiation

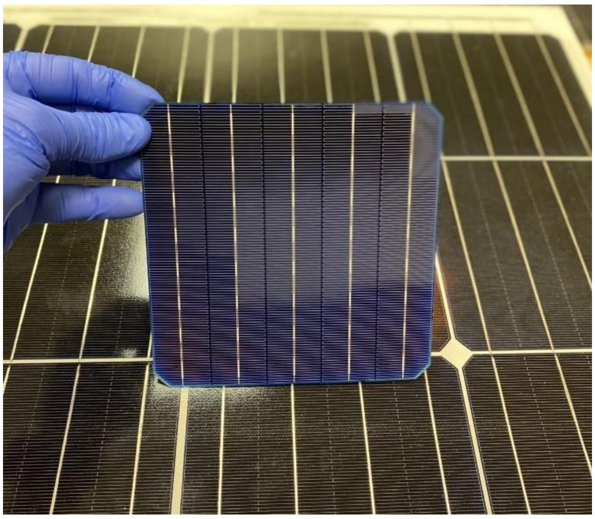


*Figure* 6: Solar cell

To define the characteristics of a cell in light conditions it is needed to set the values of temperature and irradiance, that’s why there are the Standard Test Condition (STC). The characteristic curve of each cell is defined in laboratory by the producer following the STC that are: temperature of 25°C, irradiance of 1000 W/m2, air mass AM=1.5 (1 sun). Air mass (AM) is a dimensionless parameter that is introduced to take into account the effects of the atmosphere, so outside the earth's atmosphere AM = 0. The AM is calculated through the solar elevation angle, it changes with the seasons and hours, it reaches the minimum value when the sun is vertical to the considered surface since the zenith angle $\theta_z$ is at its minimum. The value of AM equals to 1.5 refers to spring/autumn conditions.

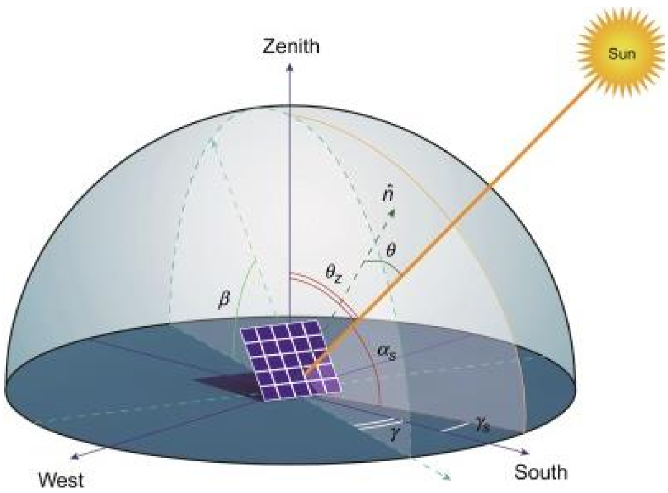



*Figure* 7: Solar angles

$$AM = \frac{1}{\cos{(\theta_z)}} = \frac{p\,[Pa]}{p_0[Pa]\sin{(\theta_z)}} \tag{4}$$

The solar cell, when operating as an electricity generator in STC, behaves as showed in the picture below.

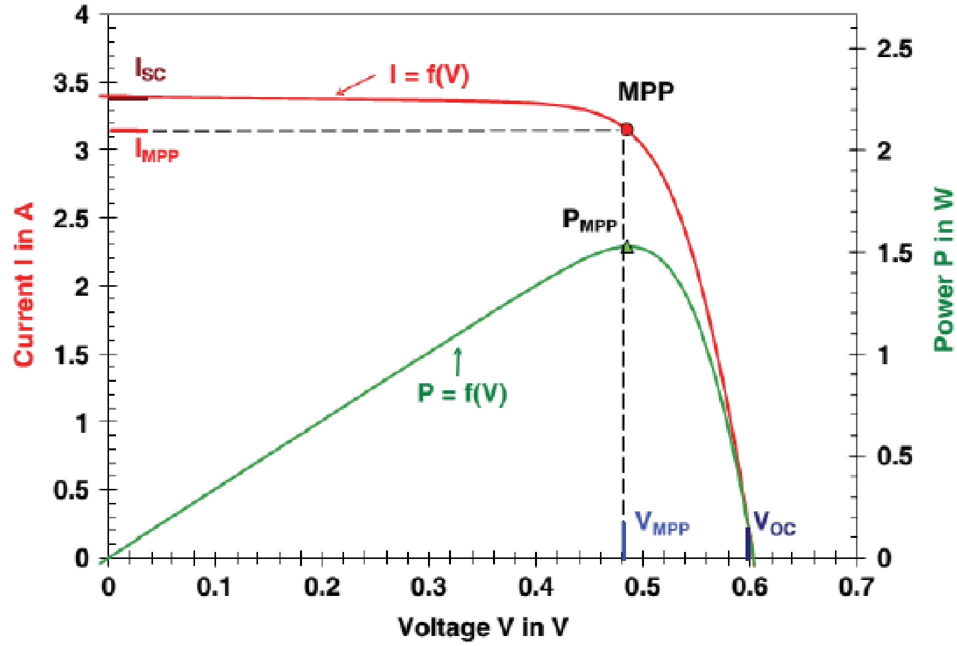



*Figure 8:* I-V and PV characteristic of a solar cell

It is worth to point out some particular values of voltage, current and power from the above *figure 8*:

1. The short circuit current ($I_{sc}$) – is the current flowing in the cirquit when the voltage is equal to zero

2. The open circuit voltage ($U_{oc}$) – is the voltage across the poles when no current flows across the circuit

3. Maximum Power Point (MPP) – this is the operational situation when the cell produces the highest power output. To work always in this situation a device called Maximum Power Point Tracker is needed.

4. Voltage and current at the MPP – since the I and V trend is not linear the highest value of the power (defined as P=P(V)) has not the maximum I and the maximum V, but two definite values called $I_{mpp}$ and $V_{mpp}$

A final remark is that the solar cell can also function as a load, working with negative voltages and currents, taking care not to exceed the limit conditions of the cell which could cause permanent damage.

Since it is important to compute the module temperature in each weather condition, the parameter taken in consideration for the analysis is the NOCT (*normal operating cell temperature*), assuming that the temperature is a direct function of the irradiance. The NOCT is a parameter that is provided by the manufacturer, generally varies between 42 and 50 °C and is defined as the temperature that reaches the module at thermal equilibrium when the irradiance is equal to 800 W/ m$^2$, the outside temperature is 20 °C and the wind speed is 1 m/s.

$$T_{PV} = T_a + \frac{NOCT - 20\ [°C]}{800\ [\frac{W}{m^2}]} \cdot G\ [\frac{W}{m^2}] \tag{5}$$

## 1.5 Influence on the cell of irradiance and temperature

The photovoltaic cell has different performance with different weather conditions, particularly the cell is affected by temperature and irradiance. The characteristic curves about the I(U) curve plotted maintaining constant a variable and changing the other one. There follow the characteristic curves of a PV cell with respect to irradiance and temperature variation.

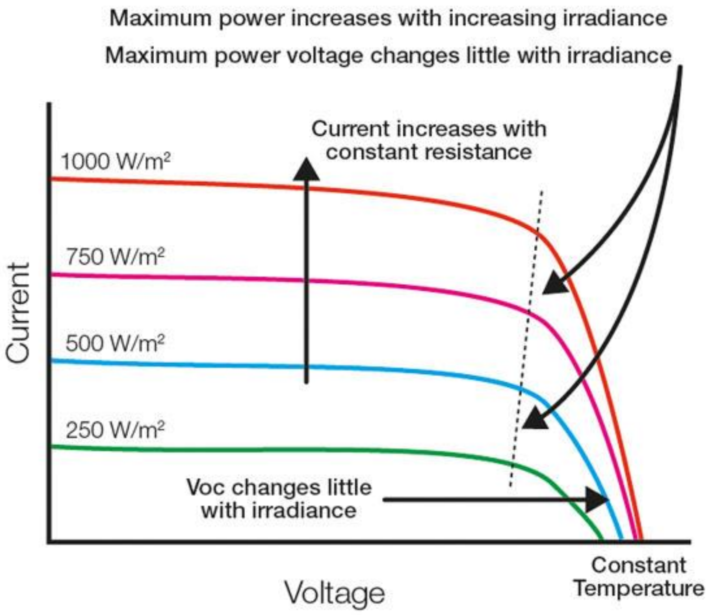



*Figure* 9: Characteristic curves as solar radiation changes

The blue curve in the picture has the same trend of the STC characteristic curve, for the others is clear that the more radiation decreases the less the short circuit current $I_{sc}$ becomes, it is less evident that the same happens for the open circuit voltage $U_{oc}$.

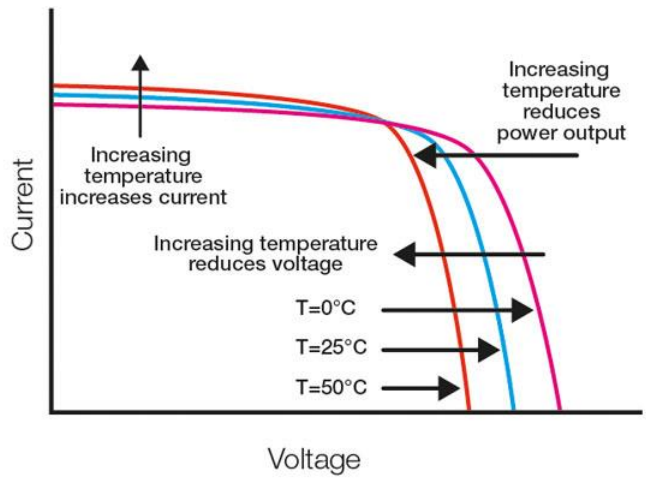



*Figure* 10: Characteristic curves as temperature changes

For the temperature variations it is possible to observe high variations of open-circuit voltage $U_{oc}$ values while the short-circuit current $I_{sc}$ does not vary significantly. It can be pointed out that the more the temperature T increases, the more the bandgap decreases therefor the photovoltaic current slightly increases; the open-circuit voltage $U_{oc}$ decreases as the current $I_j$ increases following the equation $dU_{oc}/dT$=-2,2 mV°C$^{-1}$. The power output reduces with an almost constant thermal gradient, defined by the equation: $dP_M/dT \cdot 1/P_{Mr} \approx$ -0,5 %°C$^{-1}$ for crystalline silicon technologies. Different values can be adopted for other types of solar cells, for instance in the amorphous silicon cells the power thermal gradient has smaller values. In the practical considerations is a reasonable approximation to consider:

- the short-circuit current $I_{sc}$ as dependent only on the irradiance
- the open-circuit voltage as dependent only on the temperature

## 1.6 The efficiency of a solar cell

The efficiency of a photovoltaic cell is defined as the ratio between the maximum power delivered by the cell and the incident solar irradiance, all normalized with respect to the unit area:

$$\eta = \frac{P_{MAX}}{G \cdot A} \tag{6}$$

As all the technologies, the solar cell has some losses. The main elements of losses are the ones that follow:

1. Reflection – the reflection phenomenon takes place because not all the solar irradiance is absorbed by the cell, there will always be a percentage of energy reflected back into the atmosphere. Usual value for this kind of loss is 10%.

2. Energetic threshold – as discussed in previous paragraphs, there is a precise amount of energy that the photons must yield to let the photovoltaic effect to take place. All the photons that give an energy quantity higher than this exact amount literally dissipate energy, on the other hand the photons with less energy content cannot trigger the PV effect, dissipating their low energy. These losses are usually 25% and 20% respectively.

3. Recombination – in the PN junction the electrons and holes could sometimes recombine avoiding the creation of a potential difference. This phenomenon is quite exceptional, it is evaluated in the order of the 2% of the losses.

4. Fill Factor. The diode and the resistances Rsh and Rs dissipate a significant part of the produced electrical energy. Indeed, it is not entirely transferred to the external circuit and, as a consequence, the typical distortion of the characteristic curve of solar cells with respect to the ideal

rectangular shape is generated. This type of loss can represent up to the 20% of the total losses.

## 1.7 Photovoltaic modules

A single Carbon-Silicon cell in optimal conditions of load and irradiance can generate a voltage value U of about 0.5-0.6 V regardless the amount of irradiated surface. On the other hand, as far as the electricity production concerns, it is strongly depending on the surface and typical values of short-circuit current density $J_{SC}$ are $25 — 35\ \frac{mA}{cm^2}$ generating an electricity flow of 4 — 5 Amps for 12.5 cm-side cells and 6 — 8 Amps for 15.6 cm-side cells.

Since in real conditions the voltage and current values that are requested by the loads are much higher, it is needed to connect in series and parallel several cells. In this way the photovoltaic module is formed, it is typically made of 36, 64, 72 or 96 cells connected to each other, in order to generate a current and a voltage enough high for the final use. Once that the cell has been grouped, they are protected using a series of devices since they could break because of atmospheric damage, such as rain, snow, dust and humidity, falling hail.

So, the cells are encapsulated between two EVA sheets (Ethylene Vinyl Acetate) to create a compact structure, then a front glass is opposed to protect the cells letting the sunrays passing through, on the backside of the module is present a closed panel usually in tedlar, all the structure is surrounded by an aluminium frame sealed to the glass.

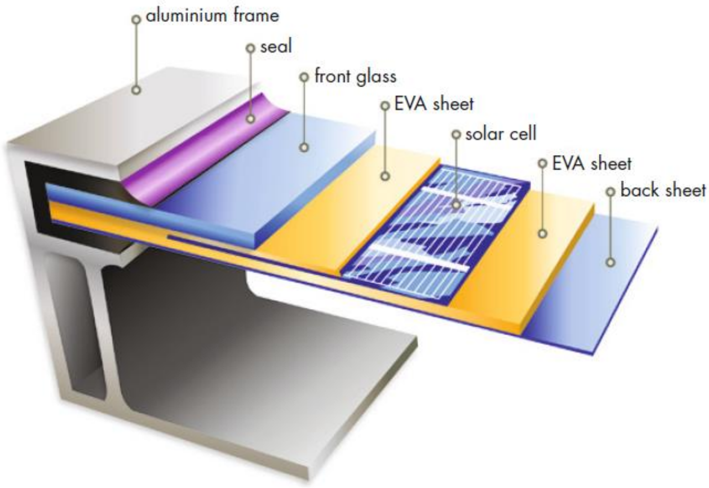



*Figure* 11: Components of a photovoltaic module

When $N_s$ identical cells are series-connected, if a cell has a different I(U) curve because of shading conditions of constructive defects, it occurs mismatch conditions. The overall maximum electricity production of the module would decrease since it would not be $(\mathrm{Ns}-1)\mathrm{U}$ but $(\mathrm{Ns}-1)U^*$, where $U^*$ is the voltage of the shaded/defective cell.

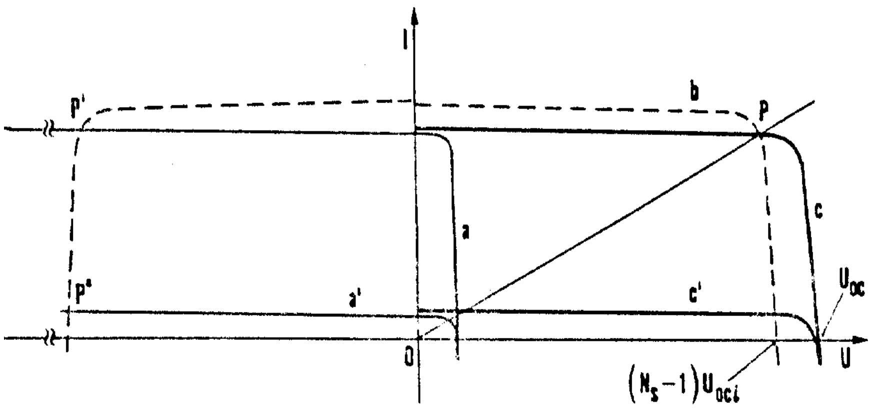



*Figure* 12: I(U) curve of series-connected cells

In *figure 12* it is possible to observe several curves that represent the I(U) characteristic curve of the series-connected cells:

- Curve (a): characteristic curve of a cell with constructive defects;

- Curve (a’): characteristic curve of a shaded cell;
- Curve (c): I(U) curve obtained by summing the characteristics of the normal-operating cells with curve (a);
- Curve (c’): I(U) curve obtained by summing the characteristics of the normal-operating cells with curve (a’);
- Curve (b): characteristic curve of the $N_s$-1 good cells.

In both situations the maximum power of the whole string is significantly lower than the equivalent curve that is possible to obtain with $N_s$ normal-operating cells. The worst effects on the production of the solar system are the mismatch caused by shading.

Mismatch can occur due to shading or construction defects. The procedure for obtaining an I-V curve of different cells is the same as in the case of equal cells.

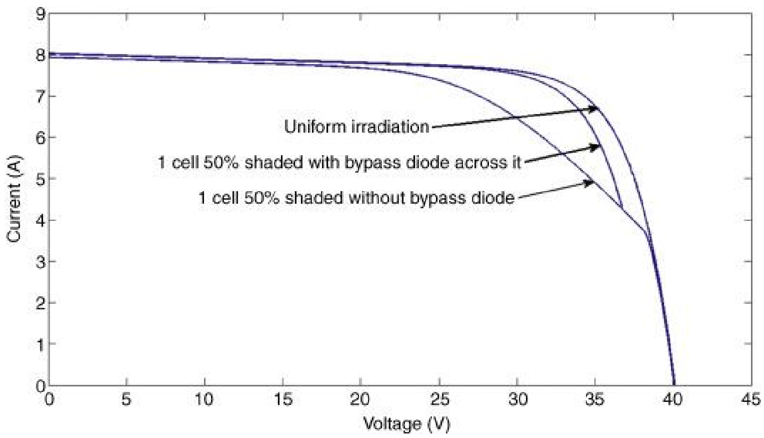



*Figure 13:* Series connection of cells with different I-V characteristics

The series connection of cells with different I-V characteristics causes a module power lower than the sum of the power of each single cell, as can be seen from figure 13. This problem is known as mismatch leaks. The most critical consequence is in the case of significant connection mismatch, when some "defective" cells dissipate the power produced by the other cells. This dissipation occurs in the form of heat with the consequent creation of hot spots, as in *figure* 14.

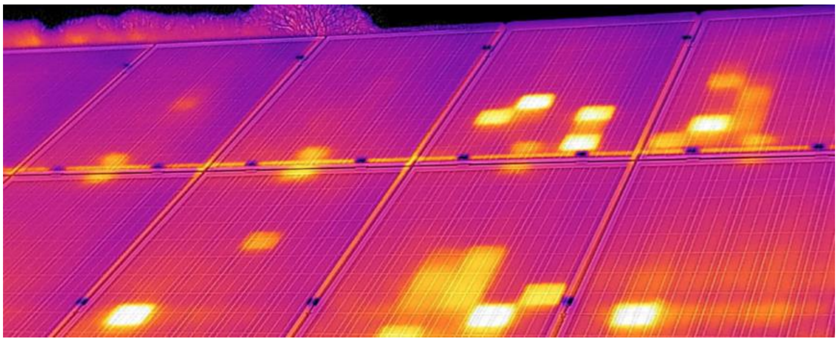


*Figure 14:* Hot spot on the modules

The best way to protect the cell from the formation of hot spots is the connection in parallel of a bypass diode to each cell. *Figure 15* shows the described configuration, approximating the cells to ideal current sources.

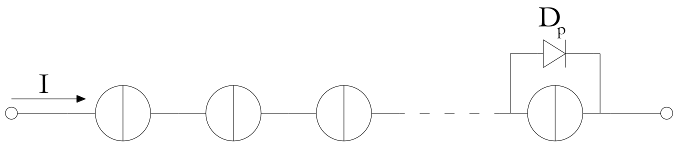



*Figure* 15: Parallel-connected protection diode

The bypass diode acts as a bridge that excludes the defective cell from the circuit, avoiding the mismatch issues and letting the losses limited to a production with a cell less than the nominal amount.

- However, connecting a diode to each cell is not economically convenient in terrestrial applications and a good compromise is to connect a diode to strings of cells (usually groups of 18-24-36 cells) that constitute a photovoltaic module (PV module). In this way the safety is guaranteed but if a cell is interrupted the string does not produce power (no current in the string).

As for the series connected cells, also for the parallel connected ones there are some observations to underline. If $N_p$ identical cells are parallel-connected and one of them has a I(U) characteristic curve that differs from the others, the equivalent characteristic is equal to the sum, for a certain voltage of the currents of the $N_p$-1 cells in good conditions with the current of the different cell.

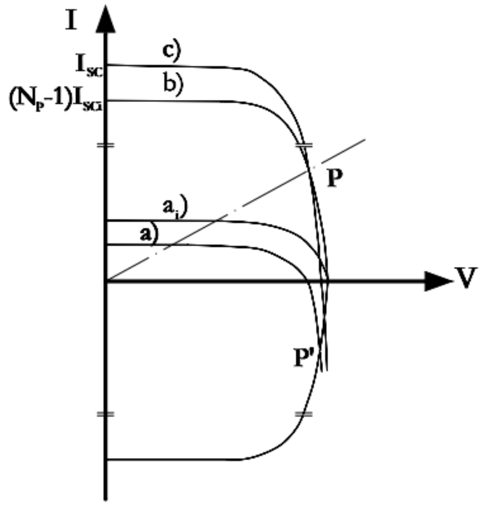



*Figure* 16: I(U) curve of parallel-connected cells

In *figure 16* it is possible to observe several curves that represent the I(U) characteristic curve of the parallel-connected cells:

- Curve (a): characteristic of the defective cell;
- Curve ($a_i$): characteristic curve of a single cell with good performance;
- Curve (c): I(U) curve that is obtained by summing the characteristics of the good-operating cells with curve (a);
- Curve (b): characteristic curve of the $N_p$-1 good cells.

The equivalent I(U) curve of the system has a short–circuit current $I_{sc}$ equal to the sum of the short-circuit current $I_{sc,\,i}$ of the single cells. For the open-circuit voltage $U_{oc}$, the situation is different, it almost corresponds to the minimum value of open-circuit voltage $U_{oc,}$ among the single cells:

$$I_{sc} = \sum_i I_{sc,i} \tag{7}$$

$$U_{oc} \cong (U_{oc,i})_{\min} \tag{8}$$

From the load point of view, differently from the series connection, the open-circuit condition is the worst condition. Indeed, in this situation, the defective cell is forced to absorb the entire current flowing from the $N_p$-1 normal operating cells, so the cell temperature increases creating irreversible damages. On the other hand, in shadowing condition, the parallel-connected cells work as there would be $N_p$-1 parallel-connected cells. As for the series connection, protection diode $D_s$ are the best solution to protect the cells in parallel connection. A diode avoids the current from the $N_p$-1 cell to overload the defective one, but diodes cannot be installed on the single cell connected in parallel. Indeed, the voltage drop at the terminals of a diode is about the same that is generated by the single cell, therefore, it is more conventional to apply the protection diode to strings made of several tens of series-connected cells, as shown in *figure 17*.

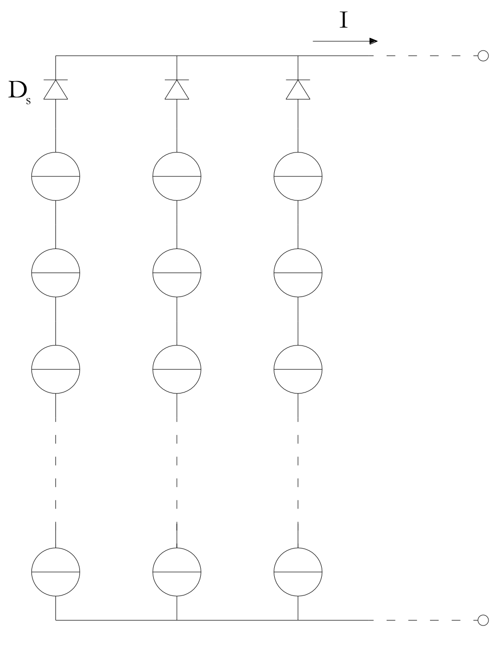



*Figure* 17: Series-connected protection diode

However, in both connections the similarity of the cells if fundamental. Indeed, it is preferable that all the cells have a similar I(U) curve (the *matching* of the cells), in order to avoid the analysed problems. Therefore, the construction of a module is very important and a careful selection of the cells (*sorting*) to be connected each other is required: indeed, it is preferable to use cells that present a I(U) characteristic curve as similar as possible. As a final advice, it is extremely important sort the cells in order to have a I(U) curve as similar as possible among the different devices, but some power losses cannot be avoided: the occurrence of external shading cannot be forecasted and avoided in the sorting of the cells and the maximum power modules are able to produce has anyways a deviation of 2-3% from the pure summation of the single cell maximum output.

## 1.8 Estimation of production

The energy production from a PV plant has many drivers that can influence the final result. The meteorological characterization of the site and a complete description of the installed modules can give out important pieces of information for the productivity estimation of the plant.

The energetic output of the system can be computed using the formula:

$$E_{AC} = H_g \cdot S_{PV} \cdot \eta_{STC} \cdot PR \tag{9}$$

Where:

- Hg - global irradiance on the plane
- $S_{PV}$ - area of the photovoltaic generator
- $\eta_{STC}$ - efficiency calculated in STC
- PR - Performance Ratio, a dimensionless parameter that takes into account different causes of losses.

The PR contains a series of efficiencies related to mismatch, reflection, air mass, electrical connection, temperature, shadowing, DC-AC conversion.

$$PR = \overset{\text{Intrisic mismatich}}{\eta_{mis}} \cdot \underset{\text{dirt and reflection}}{\eta_{d,r}} \cdot \overset{\text{AM ≠1,5}}{\eta_{spect}} \cdot \underset{\text{wiring and blocking diode}}{\eta_{wir}} \cdot \overset{\text{T ≠25 °C}}{\eta_{temp}} \cdot \underset{\text{shading effect}}{\eta_{shad}} \cdot \overset{\text{DC to AC convertion}}{\eta_{PCU}} \qquad (10)$$

The average value of the PR is 0.55 — 0.85, and it is the main parameter to consider for the losses evaluation of the system. The energetic output estimation can be pursued using the following formula too, where $P_N$ is the nominal power of the devices:

$$E_{AC} = P_N \cdot h_{eq} \cdot PR \qquad (11)$$

In this computation there is the term $h_{eq}$, that is defines as the ratio of daily radiation to irradiance and indicates the number of hours in which the system works at nominal power in a given time interval. Both PR and $h_{eq}$ will be considered in the following analysis thanks to the computational power given by the program PVsyst.

Since the energetic production is proportional to the value of PR, it is advisable for the engineers to prevent a series of measures to optimeze the system:

1. The inclination and orientation of the photovoltaic modules must be optimized according to periods of higher or lower consumption. While the optimal orientation is towards the observer (South in the Northern Hemisphere and North in the Southern Hemisphere), the inclination is of the order of the latitude of the place plus a correction to maximize the energy uptake in the period of the year wanted. This correction results in an energy loss that generally does not exceed 5 % of the optimum. Using tracking structures incrreases the cost of the plant but perfectly solves this point.

2. The partial or total shading of the generator during the day, originated by the near presence of houses, buildings, trees...may represent a considerable energetic loss source of energetic losses, despite having passing diodes. A typical value for this observation is 10 %.

3. The dust and the dirt accumulated on the surface of the modules can cause between 4 and 15 % energy losses. This effect depends on the angle of the inclination and the frequency of rainfall.

4. Usually the power of the modules is given in standard conditions of measurement, STC, referring to 1000 W/m2 of irradiance and 25 °C of the cell's temperature. This value is the peak power, that is the nominal power for which you pay when you buy a panel. Power is proportional to increase of irradiance and to decrease of temperature.

5. Rated power. Not all modules have the same rated power assigned by the manufacturer due to the manufacturing processes. Usually the manufacturer ensures that the power of a certain module is in a range of ±10-15 % of the rated power.

6. The mismatch losses are lost from the zoning of slightly different power photovoltaic modules to form a photovoltaic generator. The physical cause that causes them is the connection of modules in series with different short-circuit currents: the "worst" module will limit the current of the series. Similarly, for the voltage of the parallel module connection. In general, the power of a photovoltaic generator is lower (or ideally equal) than the sum of the powers of each module of the modules that make it up. These losses can be reduced with the proper use of passing diodes.

7. The grid-connected photovoltaic inverter is an electronic device with certain losses in its switching components. It is important to select the inverter power according to the power of the photovoltaic generator. There are also losses in the transformer. Master Thesis - Report 70

8. The grid inverter operates directly connected to the photovoltaic generator and has an electronic device for tracking the point of maximum power of the generator. The control algorithms of this device can vary between different models and manufacturers. It is possible to characterize the inverter by a yield curve of the point of maximum power defined as the quotient between the energy that the inverter can

extract from the generator and the energy that would be extracted in an ideal follow-up.

9. It is necessary to carry out an adequate dimensioning, that is the calculation of the section, of the wiring of the installation to imitate the falling ohmic. It is essential to remember that in medium-power and low-voltage systems the currents handled can considerably grow up, requiring cables of large sections. The following diagram shows the path of photovoltaic energy from production to the measuring point.

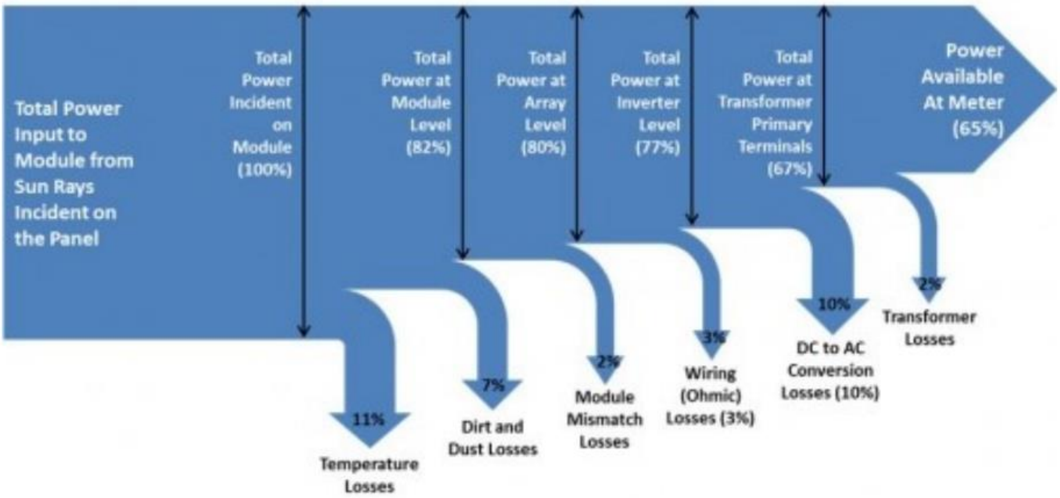



*Figure* 18: Photovoltaic energy diagram, from production to the measuring point[4]

## 1.9 Connection with the load

A photovoltaic system is capable of generating electricity in direct current, but most of the final loads require alternating current. Furthermore, for connection to the distribution network it is necessary that the electric current is alternating and that it complies with certain technical standards. For this it is necessary to use a DC / AC converter, the Inverter. PV inverters are fundamental components in grid-connected or stand-alone photovoltaic systems as they permit to extract the maximum power from PV cells. The switching process takes place through switches and diodes connected in antiparallel. The switches can be of the Mosfet or IGBT type and their movement is activated with a certain frequency, called the switching frequency, which is generated thanks to the PWM (Pulse Width Modulation) technique, by comparing a sine wave with the same frequency as the wave to be generated, with a bipolar triangular wave, thus generating a square wave which regulates the switches.

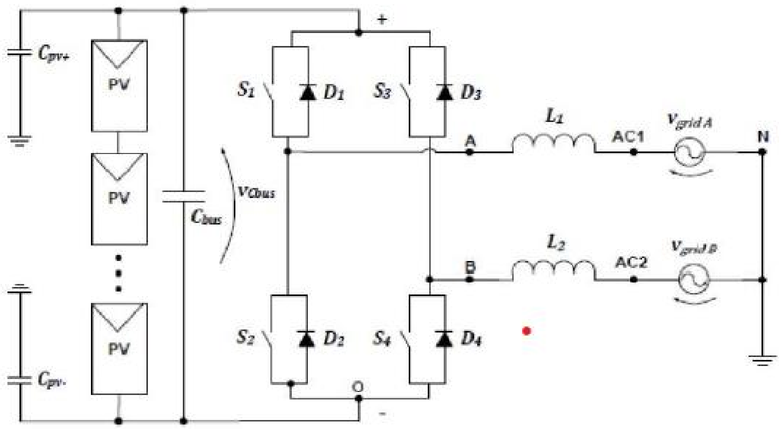



*Figure* 19: Diagram of a full bridge inverter

The pulse-width modulation (PWM) is made possible thanks to the use of transistors arranged in a similar way to how represented in *figure 19.* It is based on the control of the average value of the voltage (and current) that feeds the load, carried out by opening and closing the switch placed between the power supply and the load at a constant high frequency. The power supplied to the load is all the higher, the greater the ON time of the switch, compared to the OFF time. The duty cycle describes the proportion between the time of ON and OFF within the period. The main advantage of PWM is that the lost power loss in the switching device is very low. When the switch is off, there is practically no current, while when it is on there is practically no voltage drop.

To create the desired waveform, the duration of the pulses is controlled. In the *figure 20*, the dark blue track is the desired voltage output for the motor and the red track the PWM waveform.

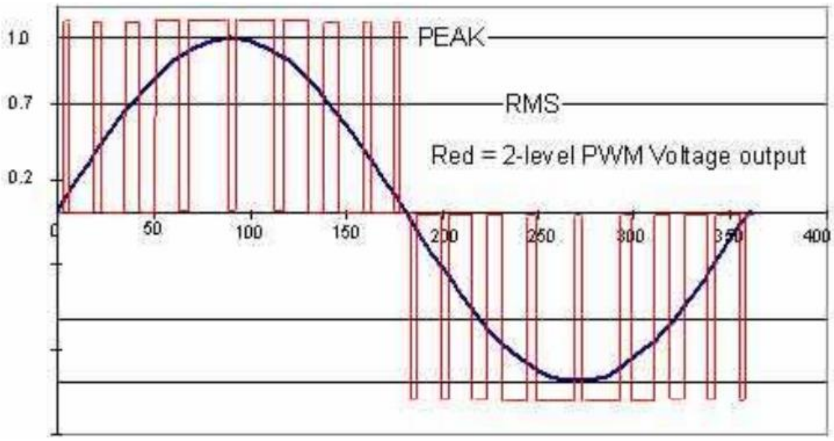



*Figure* 20: Pulse Width Modulation - comparison between a sine wave and a triangle wave

# Chapter 2

## 2 Policy context

During the last 35 years the international community has dealt multiple times with the need to define a common horizon for energy planning because of the issue of the climate change (CC). Renewable sources gained a more and more central point into the discussion since they represent the best way to achieve the ecological, social and economic goals set by each international treaties. Agrivoltaic is one of the multiple projects born from the exploitation of these international strategies. The agrivoltaic power plants represent slavishly the research of a balance between human needs and environmental respect, or in other words the "sustainable development".

### 2.1 International perspective in the energy sector

The climate change (CC) is not a new problem, it was known already in 1908 when the renowned scientist Arrhenius in his book 'Worlds in the making' where wrote: "The enormous combustion of coal by our industrial establishments suffices to increase the percentage of carbon dioxide in the air to a perceptible degree […] any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4°C; and if the carbon dioxide were increased fourfold, the temperature would rise by 8°C". Nowadays professional studies and analytical models unequivocally demonstrate how climate change is no more evadable, rather there will be further changes. The average temperature of the whole planet has increased by about 1.1 ° C on since 1880 ,with harmful strong peaks in areas as the North Pole, where the temperature change in the last century signed a +5°C. The temperature increasing is accelerating the transformations of the ecosystem, such as the melting of the ice, the raising and acidification of the oceans, the loss of biodiversity, desertification and making extreme weather events more and more frequent and acute.

Therefore, the increasing interest in the CC is not due a late discovery of the issue, but to a phenomenon increasing faster and faster than expected.

So, since the relation between CC and human activity is well known, in 1988 the exponents of the international community started to sit down together in conferences to outline a common strategic line to pursue.

## 2.2 The intercontinental point of view

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the United Nations Environment Programme and the World Meteorological Organization, it was endorsed by the United Nations General Assembly. The United Nations General Assembly on December 6 delivered the Resolution 43/53, in which the IPCC is indicated as review maker of three main topics: the state of knowledge of the science of climate change; the social and economic impact of climate change; potential response strategies and elements for inclusion in a possible future international convention on climate.

The IPCC accomplished the task during 5 assessment cycles producing 5 reports:

- The First Assessment Report (FAR) was produced in 1990, it underlined the necessity of a common action since the CC has global consequences. The FAR laid the groundwork for the creation of the United Nations Framework Convention on Climate Change (UNFCCC) the most important international treaty to cooperate against the CC.
  In 1992, thanks to the end of cold war, the cooperation through word's countries was made possible and finally, during the same year in the Rio conference, Conference of Parties was born when 197 states signed the "United Nations Framework Convention on Climate Change".
- The SAR (Second Assessment Report) was produced in 1995 and was the starting point for the formulation of the Kyoto Protocol of two years leater (1997).
- The TAR (Third Assessment Report) was published in 2001 and is an important framework about the effects of the CC on the world's population and, moreover, introduced new strategies to let people cohabit with the incoming intense changes and phenomena.
- The Fourth Assessment Report (AR4) in 2007 laid the ground work for a post-Kyoto agreement, focusing on limiting warming to 2°C.
- The Fifth Assessment Report (AR5) was finalized between 2013 and 2014. It provided the scientific input into the Paris Agreement.

Nowadays the IPCC is still working, it is elaborating four documents for the Sixth Assessment Report (AR6) expected for the 2022. The AR6 will include: a report about the global warming as asked by the Paris Agreement (2015); two specialistic report about Climate Change and Land and Ocean and Cryosphere in a Changing Climate (SRCCL and SROCC); a refinement of the IPCC Guidelines on National Greenhouse Gas Inventories. [4]

The **Conferences of Parties** (COP) are the supreme decision-making body of the UNFCCC. In the COP all the member states are represented, and they can all together review the international strategies against the CC implementing the Convention or using institutional and administrative arrangements. The main duty of the COP is to supervise the international communications and the emissions of the parties, in this way it collects the data for further interventions and sets future goals. The conference of Parties meets up each year, the site should be Bonn, where the secretariate of the UNFCCC is situated, unless a member state does not propose himself as hosting country. The first COP took place in Berlin in 1995, it was about to enforce the efforts against the CC. The Tokyo protocol was signed in 1997 during the third Conference Of Parties. The main objective of Kyoto Protocol was the reduction of Green House Gas (GHG), so all the signers had to reduce of about 5% their GHG production. Italy signed for a reduction of the 6.5% of its emissions, corresponding to 33,9 $MtCO_2eq$.The greenhouse gases object of the reduction targets are:

- $CO_2$ (carbon dioxide), produced by the use of fossil fuels in all energy and industrial activities as well as in transport;
- $CH_4$ (methane), produced by waste landfills, livestock farms and rice crops;
- $N_2O$ (nitrous oxide), produced in the agricultural and chemical industries;
- HFCs (hydrofluorocarbons), used in the chemical and manufacturing industries;
- PFCs (perfluorocarbons), used in the chemical and manufacturing industries;
- $SF_6$ (sulfur hexafluoride), used in the chemical and manufacturing industries.

The GHG are defined basing on the most common one of their category, the carbon dioxide ($CO_2$). In the figure it is possible to compare the global warming potential of each GHG compared to the base level of the $CO_2$ on a time period of 100 years.

| Gas | Atmospheric Lifetime | 100-year GWP[a] | 20-year GWP | 500-year GWP |
|---|---|---|---|---|
| Carbon dioxide ($CO_2$) | 50-200 | 1 | 1 | 1 |
| Methane ($CH_4$)[b] | 12±3 | 21 | 56 | 6.5 |
| Nitrous oxide ($N_2O$) | 120 | 310 | 280 | 170 |
| HFC-23 | 264 | 11,700 | 9,100 | 9,800 |
| HFC-125 | 32.6 | 2,800 | 4,600 | 920 |
| HFC-134a | 14.6 | 1,300 | 3,400 | 420 |
| HFC-143a | 48.3 | 3,800 | 5,000 | 1,400 |
| HFC-152a | 1.5 | 140 | 460 | 42 |
| HFC-227ea | 36.5 | 2,900 | 4,300 | 950 |
| HFC-236fa | 209 | 6,300 | 5,100 | 4,700 |
| HFC-4310mee | 17.1 | 1,300 | 3,000 | 400 |
| $CF_4$ | 50,000 | 6,500 | 4,400 | 10,000 |
| $C_2F_6$ | 10,000 | 9,200 | 6,200 | 14,000 |
| $C_4F_{10}$ | 2,600 | 7,000 | 4,800 | 10,100 |
| $C_6F_{14}$ | 3,200 | 7,400 | 5,000 | 10,700 |
| $SF_6$ | 3,200 | 23,900 | 16,300 | 34,900 |

*Figure* 21: Global Warming Potential for different GHGs [5]

During the Kyoto conference was developed the “emission trading”, it helps the countries to reach their GHG reduction goals. Each state can buy from another signer the right to produce a certain amount of GHG in order to not overcome the limits imposed by the Kyoto Protocol, or, on the other hand, if a state has already reached its goals, it can sell its quote of GHG to be produced.

Despite the aforementioned new measures and strategies, the Kyoto protocol has been a failure. The Kyoto Protocol caused political clashes among the member state that have undermined the stability of the pact from within. The main reason behind the malcontent is the assignation method for the GHG emission reduction for each country. The assignation method is planned to be based on the total GHG emission of each state in the year 1990, this leads to the conclusion that the emerging economies, that in 1990 had low emissions compared to the 2005 ones, were favourite over the developed countries. Moreover, there were some periocular cases that discouraged the international community to pursue the Tokyo objectives such as: China never signed the contract and USA signed but did not ratify the act.

The goals as well as the problems of the Tokyo protocol let the debate continue for the following Conferences Of Parties. The majority of the political disputes were solved 5 years after the Tokyo conference, in Bonn in 2001 for the COP 6-bis (named so because the voting session from the COP 6 were not over by the end of the COP6). Thanks to the COP 6-bis it has been possible to define common strategies basing on the outlines of the Kyoto Protocol. The final chapter of this process is the COP 7 that took place in Marrakech in 2001. During the COP 7 the reaction to the climate change was enforced since the measures introduced by the Tokyo Protocol were considered “too shy”, moreover the commission defined that the data regarding the emissions and the achievement of the goals should be completely clear, defining a compliance regime to respect by all di signers. The discussion about the emerging countries was faced during the Marrakech conference, but in the end finding the solution has been demanded to future summits.

The COP15 was held in Copenhagen in 2009 and extended the same agreement for all the parties, for developing countries too, solving the problem about the emerging economies. The limits imposed were still only 60% of what it would take to keep the temperature below +2°C. The Copenhagen conference showed a good approach but inability to link technical skills and political problems.

The Cancun conference, the COP16 of 2010, considers the points put on the table by Copenhagen with a clearer willingness to cooperate to reduce the GHG level so as not to exceed +2 ° C.COP16 underlined the concept of transparency at the international level to monitor step by step the responsible for GHG emissions. This method would have led to the assignment of limits in a different way respect to Kyoto, which had caused so many problems. The gap that had arisen in COP15 between the measures taken and the technological capacity was bridged by the creation of a system for the diffusion of technological knowledge, known as the "UNFCC technology mechanism", which is based on three lines: established governance, a "technology executive committee" and an “implementation arm” with national designed entities.COP16 also provided for the allocation of finances, the “green climate founds”, to allow emerging states to access sustainable developing.

The next fundamental step for sustainable development is certainly the year 2015. In 2015 in Paris was held the COP 21, an event that will mark global political decisions from then on


*Figure* 22: Paris agreement

The Paris agreement, or the COP21, is the result of 20 years of negotiations. The Paris conference took place in 2015 but the treaty was signed in 2016, by 170 different countries. As the Cancun conference, the COP21 PA requires all parties to undertakes efforts towards reaching global peak of emission as soon as possible in order to find a balance between emission and sinks by the half of the century. A key element of the COP221 is that there is a Nationally determined Contribution, so every country has the ability to sets its own targets following the principle for which “everybody does its best”. Since the loss and damage evaluation is associated with CC production, the Paris Agreement supports developing country with capacity building and technology.

The Paris Agreement showed strong intent and measures as emerge from the 3 main goals of the conference:

1. Temperature control - holding the temperature variation 2°C under the preeindustrial level.
2. Resilience – increasing the ability to adapt and overcome the adverse impact of the climate change on the human activities.
3. Financing – giving to al the signer the economic means to pursue the objectives towards low greenhousegas emission with a slimate-resilient development.

In the Paris Agreement there is finally a connection between the key principles of Mitigation and Adaptation born in Cancun and a real action from the signers of the chart. Mitigation and Adaptation are fundamental concepts that can be illustrated as follow:

- Mitigation is about long term goals. The mitigation strategies are set in order to overcome the problems found in the Kyoto protocol. The long term objectives need to be stated and communicated by each country, no matter if it is a developed or a developing country. Of course developed countries should take the lead of this changing movement, but all signers must join. The chosen goals must be enough brave and ambitious, some of these are: the maximum accepted temperature increase at only 1.5 °C ; fast reaching of the Green House Gasses peak in order to start the decarbonization process as soon as possible; carbon neutrality or balance between produced carbon (anthropic activities) and absorbed carbon (green areas).
- -Adaptation is about learning how to live with the effects of the climate change. It is crucial for developing countries, they need to develope in the direction of better resilience in order to resist to extreme weather events. The

developing countries can use intergovernmental founds, that are substantiated by the Paris Agreement’s procedures, in order to face the “adaptation” challenge, since the developed countries need to face majorly the “mitigation” rather that the “adaptation”.

Both mitigation and adaptation should follow the concept of progression that for the PA is about a continuous sequence of cycles that changes every time the goal changes, according to the idea of “no back sliding”.

## 2.3 The European point of view

Leaving aside the conference of parties, the European Union developed its own program about the sustainable development since the year 2000. The Millennium Development Goals were the first real commitment of the old continent to counteract poverty, hunger, disease, illiteracy and environmental degradation.

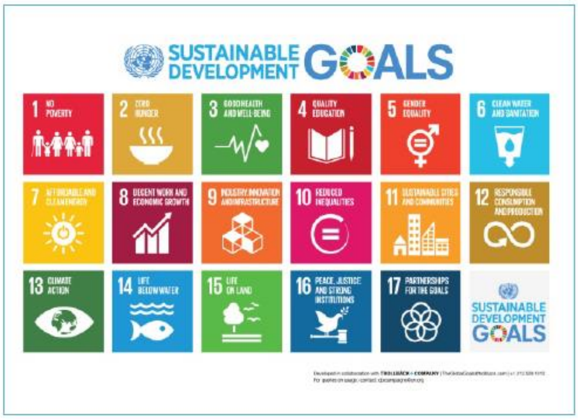



*Figure* 23: Sustainable development goals

The Sustainable Development Goals continue the work of the Millennium Development Goals that preceded them and represent common goals on a set of world issues. The Sustainable Development Goals are 17 objectives contained in a grand plan action on which the governments of the 193 UN member countries have reached an agreement. Countries are committed to achieving the goals by 2030. The 17 Global Goals concern all countries and all individuals and are :

1. overcoming poverty:

2. defeat hunger:
3. Ensure good health
4. Ensure quality education
5. Ensure gender equality
6. Ensure clean water and sanitation
7. Provide affordable, renewable energy
8. Promote good employment and economic growth
9. Building innovation and infrastructure
10. Reduce inequalities within and between countries;
11. Create sustainable cities and communities
12. Ensure responsible use of resources
13. Fight against climate change
14. Sustainable use of the sea
15. Sustainable use of the land
16. Promote peace and justice
17. Strengthen the partnership for the goals

The Global Goals for sustainable development are inseparable goals as they are interconnected. For example, it is not possible to end hunger and give access to food sources if people are not prepared to face the effects of the climate change such as floods and droughts, which can endanger the earth, crops and livestock. Economic growth alone is not enough: it is necessary for society as a whole to see its living conditions improve.

The European Green Deal is a document presented in December 2019 that aims to zero net emissions of greenhouse gases by 2050 for all the European community. The Green Deal pursues the zero-emission objective, encourages the economic growth decoupled from resource use, and approves community policies. The Green Deal represents a set of indications for the European countries, but the committee does not write rules, the single states do it for their own administrations.

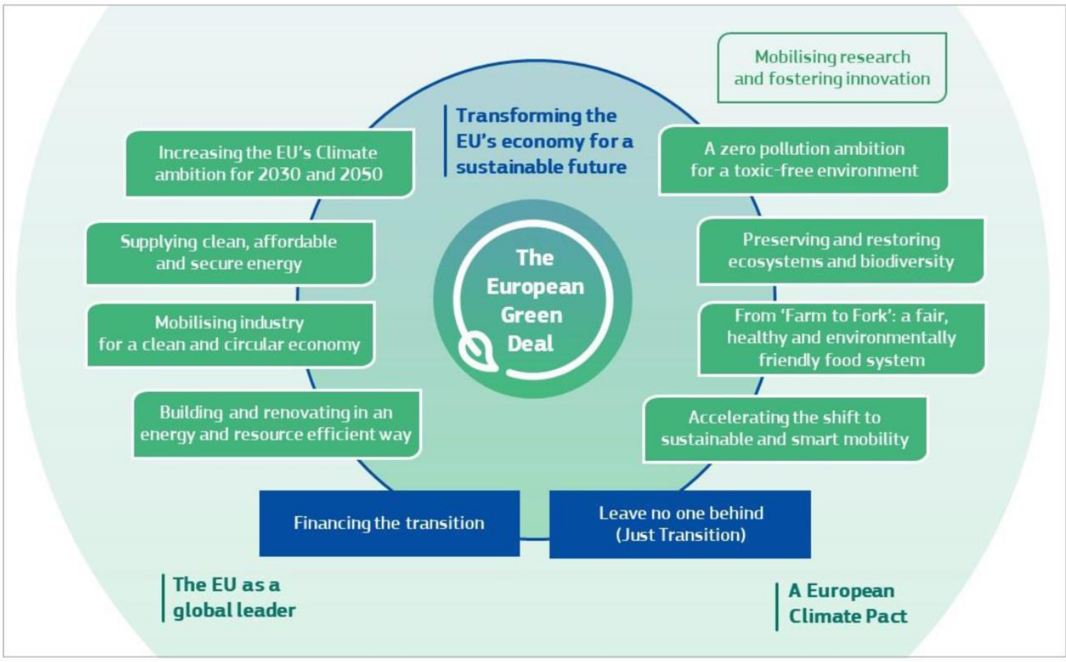



*Figure* 24: The European Green Deal

The Green Deal is a short document (only 24 pages), but it touches all the topics needful for the sustainable development. There are some indispensable concepts at the base of the act: the EU is considered as a global leader whose action is fundamental for the contrast to the CC; the innovation and research have a key role in the accomplishment of the objectives; the "leave no one behind" philosophy should be posed at the base of each field of research. Following the Green Deal, there are 8 actions necessary for the achievement of the carbon neutrality in 2050:

1. **Zero pollution action plan for water air and soil**
   In order to protect the ecosystem and preserve the resources for the future generations, it is recommended to develop policies for the management of air, nature, soils, water, industry, plastics, chemicals. The cyrcular economy, that is a production and consumption model that involves the sharing, the reusing,and the recycling of existing materials for as long as possible, has a key role fo the zero pollution action.

2. **Preserving and restoring ecosystems and biodiversity**
   To protect the envirnoment from the dangerour human activities, there are a series of programs, as Nature2000, about the increment of the forest

areas and the improvement of acquatic resource to reduce the land use request.

3. **'From Farm to Fork'**
   In a parallel way to the point 2, the project "from farm to fork" aims to decrease the impactant of primary sector. For the production of food is designed a fair, healthy and environmentally-friendly food system.The aim is to make the European agriculture and food production sustainable, for example by using precision agriculture or by reducing water and food losses along all the chain.

4. **Emissions reduction by 2050**
   The emission reduction is a prerogative goal for the Green Deal to reach the carbon neutrality. The transport sector is pivotal for the reduction of greenhouse gasses in the atmosphere. To improve the air quality the Green Deal promotes the development of green alternatives such as sustainable fuel, public transports, smart traffic management and more astringent legislations.

5. **Building renovation**
   To boost renovation rate of buildings, reduce energy poverty and increase the job occupation both in private and public sectors, a series of actions is promoted, such as: building more energy efficient buildings, reviewing the Construction Products Regulation, and setting a new financing scheme called “InvestEU”.

6. **Industrial improvement**
   The European industrial sector by 2050 should be cleaner and more secure than nowadays. The overall system should move towards a decarbonization perspective. In order to go on in these direction, the Green Deal encourages the coutries to the implementation of directives related to energy efficiency and renewables, and to improve evaluation and review of the Trans-European Network.

7. **Economy transformation**
   Aiming for the climate neutrality it is needed to integrate market and financials mechanisms with circular economy principles .
   Transparency on the emissions data, easy access to the climate policy guidelines, sharing the ambitions about carbon emission are hey points to accomplish the main task.
   Other important step is a new and more ambitious adaptation strategy to sustain mitigation efforts, making the environment more resilient, restoring water systems aiming to preserve biodiversity, creating laws and plans to avoid further emissions.

8. **GHG emission neutrality within 2050**
   This final point is the most generic and omnicomprensive one. Here there is the final set of advises for the reaching of the most ambitious goal of the chart, the carbon neutrality. The European Green Deal has set new energy and climate targets that will require the reduction of Green House Gases (GHG) to 55% in 2030 and climate neutrality in 2050.

## 2.4 The Italian point of view till the year 2019

Italy has been strongly damaged by the Covid-19 pandemic since Italy was the first EU country to have to impose a generalized lockdown. The Italian economy is still suffering more than the other European countries' ones because of the effect of the Coronavirus. But the Italian country was already fragile from an economic, social and environmental point of view. Between 1999 and 2019, the GDP in Italy grew by a total of 8%, while in the same period in Germany, France and Spain, the increase was approximately 30%, 32% and 43% respectively. Italy holds the record for the highest rate of children between the ages of 15 and 29 not engaged in study, work or training in the EU. The participation rate of women in employment is only 54 percent, almost 15% below the European average. [6]These problems are even more pronounced in the South of the country. Some of the reasons behind the difficulty of the Italian economy to keep pace with other advanced European countries is the productivity trend, much slower in Italy than in the rest of Europe.

Among the causes of the disappointing productivity trend is the inability to seize the many opportunities linked to the digital revolution. The Italian working class is grouped mainly in small and medium-sized enterprises, which have often been slow in adopting new technologies and moving towards higher value-added products. These shortcomings have led to a drop in public and private investments which slowed down the necessary modernization processes of the public administration, infrastructures and production chains. In the last 20 years, total investments in Italy have grown about half of the euro area average [6]. In detail, while the share of private investment has increased, that of public investment has decreased although market entry barriers remain high in several sectors

From an environmental point of view, Italy is particularly vulnerable to climate change: the increase in heat waves and droughts are the most probable extreme events. The richest areas are coastal towns, deltas and floodplains which are likely to suffer also the effects of intense rainfall and sea level rise. These areas are also very populated, in fact, according to estimates by the Higher Institute for Environmental Protection and Research (Ispra), in 2017 the 13% of the population lived in areas classified as high risk of landslides or floods. About the per capita emissions of climate-altering gases in Italy, after a sharp decline between 2008 and 2014, the value remained substantially unchanged until 2019, decreased during the generalized lockdowns and subsequently started to rise again.

Following the directives of the European Green Deal about the reduction of Green House Gases (GHG) to 55% in 2030 and climate neutrality in 2050, Italy has adopted two strategic plans: the PNIEC and the PNRR.

### 2.4.1 The PNIEC

The PNIEC, in Italian: “piano nazionale integrato per l’energia e il clima” was adopted in December 2019 and is based on three main elements: the Prosumer, the Green Deal, the Energy union.

The Prosumer is the pivotal point of the energetic development of the country, it is defined as customer whose role in the energy sector is not only passive, but active too. The same word “prosumer” is the combination of producer and consumer.

The Green Deal represents the direction in which the PNIEC unfolds as stated in the law n. 160 of 27/12/2019. Therefore, the goals pursued by the PNRR, and the GD are stackable even if the ones from the Italian act are more relatable to the problems of the country.

The Energy Union is an organization at European level, whose strategy was presented on 25 February 2015 by the Juncker commission. The Energy Union wants to offer to European consumers safe, sustainable, competitive, and accessible energy. There are several measures put into play by the European Commission to achieve the objectives set. Periodic reports are the tool for monitoring the progress of the plan's key priorities. The entire strategy of the Energy Union is based on 5 fundamental pillars:

1) Secutiry
2) Market
3) Efficiency
4) Decarbonization
5) Research

The objectives of the PNIEC are clear, measurable and are about all the 5 pillars abovementioned. In order to achieve the EU target of at least 32% renewable energy in gross final energy consumption in 2030 (article 3 of EU Directive 2018/2001), the energy production from renewable sources follows an indicative trajectory which by 2022 must reach a value equal to at least 18%. The Italian trend for each renewable source hypnotized in the PNIEC is illustrated in the *graph 1*.

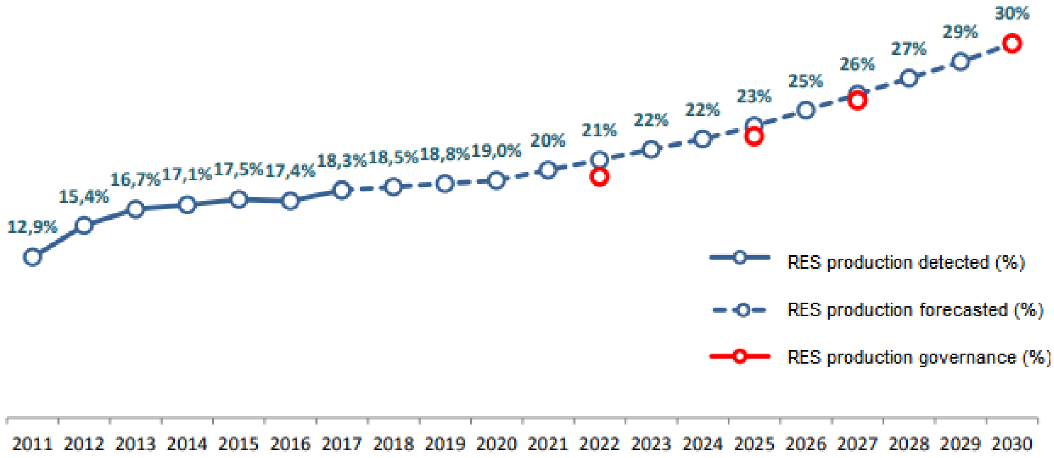



*Figure* 25: RES production from 2010 to 2030 [7]

Italy intends to follow a path of growth of renewable resources to reach the target of 30% of the gross final consumption of energy from RES, in 2030. Specifically, in 2030 a gross final consumption of energy from renewable sources is expected equal to approximately 33 Mtoe, compared to the total 111 Mtoe of energy consumed. In the *Table 1* there are some pieces of information about the decarbonization horizon for the European Union and Italy.

*Table 1* PNIEC OBJECTIVES [7]

| | EU | Italy (PNIEC) |
|---|---|---|
| RES incidence on energetic consumptions | 32% | 30% |
| RES incidence on transportations | 14% | 22% |
| Energy reduction w.r.t. 2007 | 32.5 | -43% |
| GHG reduction for not ETS sectors | 30 | 33% |
| Electric interconnettctivity | 15% | 10% |

The electricity sector will lead the growth of renewables reaching by 2030, 16 Mtoe of generation from RES, equal to 187 TWh. The sector will cover 55.0% of gross final electricity consumption with renewable energy, thanks to the strong penetration of renewable electricity production technologies, mainly photovoltaic and wind.

The diffusion of large ground-mounted photovoltaic systems is important for the achievement of the 2030 objectives. In order to achieve the 2030 targets, it will be necessary not only to stimulate new productions, but also to preserve the existing ones.

### 2.4.2 The PNRR

The pandemic crisis presented a major challenge for the European Union, which responded with the Next Generation EU (NGEU). The NGEU is a program of unprecedented scope and ambition, which includes investments and reforms in order to accelerate the ecological and digital transition and improve workers' formation following greater gender, territorial and generational equity. For Italy, the NGEU is an unmissable development opportunity. Italy must improve its production system and intensify its efforts to fight poverty, social exclusion and inequality. The NGEU can be an opportunity to resume a sustainable and lasting economic growth path by removing the obstacles that have avoided Italian growth during the years. The plan must be appropriately shaped for the needs of Italy.

Italy is more exposed to climatic risks than other European countries, due to its geographical configuration, its territorial specifications, and the too many ecological abuses that have occurred over time. Italy can benefit more from the IRR and more quickly than other countries, thanks to the relative scarcity of traditional resources (e.g., oil and natural gas) and the abundance of some renewable resources, especially in the South which has up to 30% – 40% more irradiation than the European average. Italy has a natural, agricultural and biodiversity ecosystem of inestimable value, which represent the distinctive element of its cultural identity and its history, which cannot be ignored for future economic development. Italy is the nation that benefits the most from the two main instruments of the NGEU: the Device for Recovery and Resilience (RRF) and the Recovery Assistance Package for Cohesion and the Territories of Europe (REACT-EU). The RRF alone provides resources for 191.5 billion euros, to be used between 2021 and 2026, of which 68.9 billion are non-repayable grants.

The RRF mechanism requires member states to present a package of investments and reforms, so Italy has formulated the National Recovery and Resilience Plan (PNRR). If Italy wanted to make full use of its financing capacity through RRF loans, it would have access to around € 122.6 billion.

The PNRR is fully consistent with the NGEU and largely satisfies the parameters set by the European regulations on the “green” and digital projects. The Plan develops through a series of reforms that improve the features of all the sectors named in the PNRR such as: reform of the public administration, reform of the juridic processes, reform of the rationalization and simplification of the companies activity, the improvement of the health supply chain, but mostly the innovation for national strategies about sustainable development, mobility; environment impact and climate change.

It is estimated that the investments from in the Plan will have a significant impact on the country's economy. In 2026, the year in which the Plan would conclude, gross domestic product will have increased by approximately 3.6 percentage points compared to the previous trend. For the last three years of implementation of the plan (2024-2026), employment is expected to be 3.2 percentage points higher than in the current period.

The RRF founds distribution, for the reaching of the aforementioned results, are spread on three major areas:

1) digitization and innovation
2) ecological transition
3) social inclusion

For each one of these point it is accounted a percentage of the whole budjet assigned by the EU al illustrated in the *graph 2.*

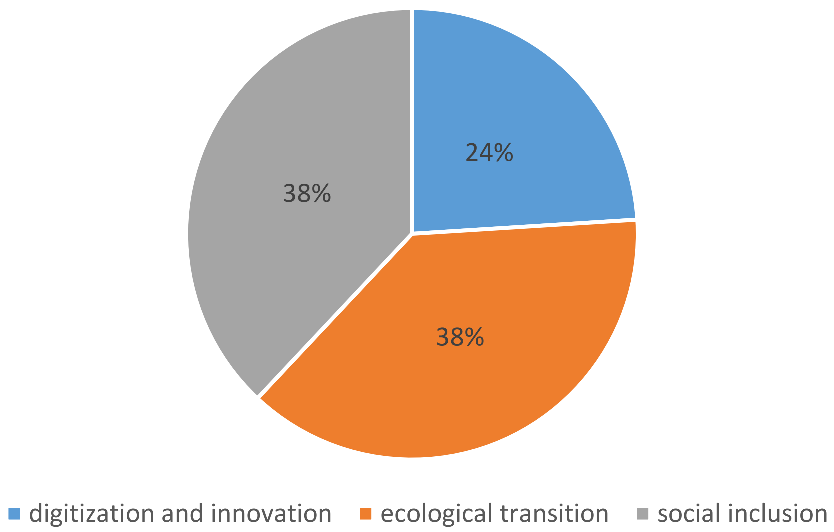



*Figure* 26: RRF founds allocation

The Plan is divided into sixteen Components, grouped into six Missions. The latter are in line with the RRF Regulation as practiced in the lines above. The six missions of the PNRR are:

1. Digitization, innovation, competitiveness, culture and tourism
2. Green revolution and ecological transition
3. Infrastructure for sustainable mobility
4. Education and research
5. Inclusion and cohesion
6. Health

The Mission2:" The green revolution" is the most interesting point of the list for this thesis. The Mission 2 ‹‹deals with the major issues of sustainable agriculture, the circular economy, the energy transition, sustainable mobility, the energy efficiency of buildings, water resources and pollution, aim to improve the sustainability of the economic system and ensure a fair and inclusive transition towards a society with zero environmental impact. […] To achieve progressive decarbonisation, interventions are planned to significantly increase the use of renewable energy sources, through direct investments and the simplification of authorization procedures for renewables, the promotion of agrivoltaic and biomethane. ›› [6].

For the mission 2 there are only from the PNRR more than 59 billion euros. The mission 2 is composed by 4 main subtopics:

1. Circular economy and sustainable agriculture
2. Renewable energy, hydrogen, grid and sustainable mobility
3. Energy efficiency and building renovation
4. Protection of the territory and of the water resource

The huge amount of money is distributed on these 4 voices as shown in the *graph 3*.

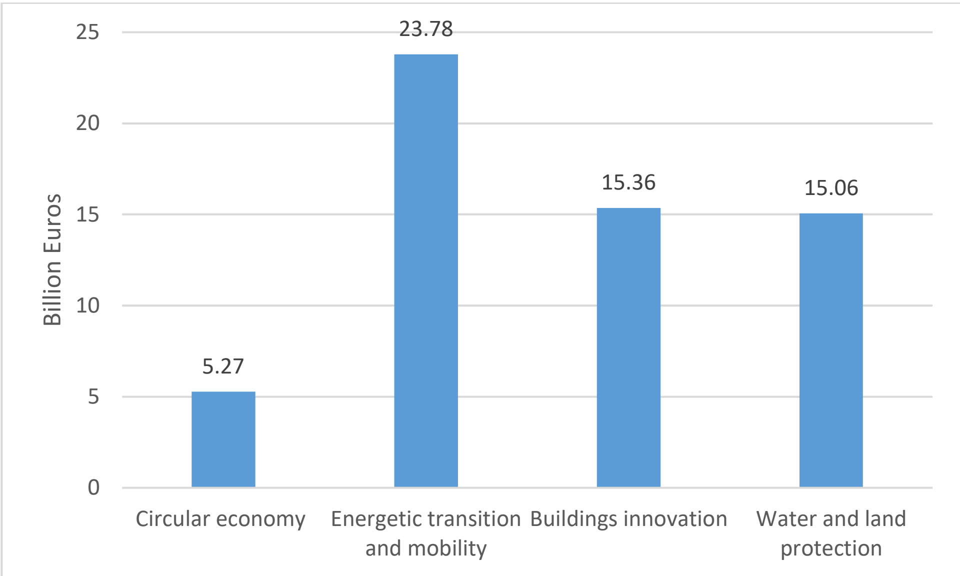



*Figure* 27: Mission 2 founds allocation

The global and European goals for 2030 and 2050 (egg Sustainable Development Goals, Paris Agreement goals, European Green Deal), are very ambitious. They aim at a progressive and complete decarbonization of the system that will lead Europe to be the first continent with net zero emissions. This objective can be achieved by strengthening the adoption of circular economy solutions, protecting nature and biodiversity and ensuring a fair, healthy and ecological food system. The Italian behavior on theme of emissions per capita and green energy production is quite good if compared with the European average trend. Looking at the *Graph 3.4* possible to see that from 2008 to 2019 Italy has always produced less greenhouse gasses (GHG) than the European average. In 2019 the Italian production of GHG has been the 22% lower than the European one.

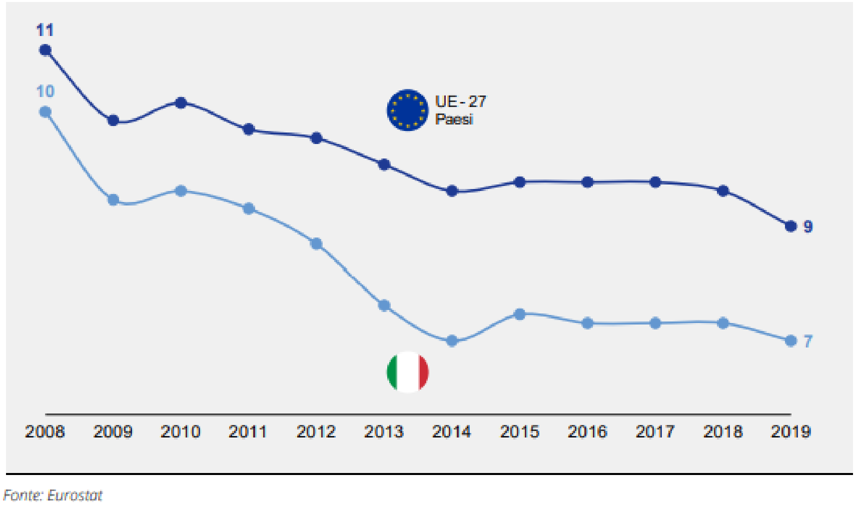



*Figure* 28: Greenhouse gas production per capita in Italy and in Europe in tons per year

The production of electricity from renewables in Italy follow the trend shows in the *graph 6.* In 2005 the energy produced from traditional source was the 84% as in the rest of Europe. Till the 2011 the Italian renewable production was lower than the European average, but then it overcomes the continental trend ramping up with a very steep annual increment that slowed down only in 2015. From the year 2012 to the 2019 Italian RES production has always been relatively higher than the European one even if in the 2019 the difference is of only 1 percentage point (34 for EU and 35 for Italy).

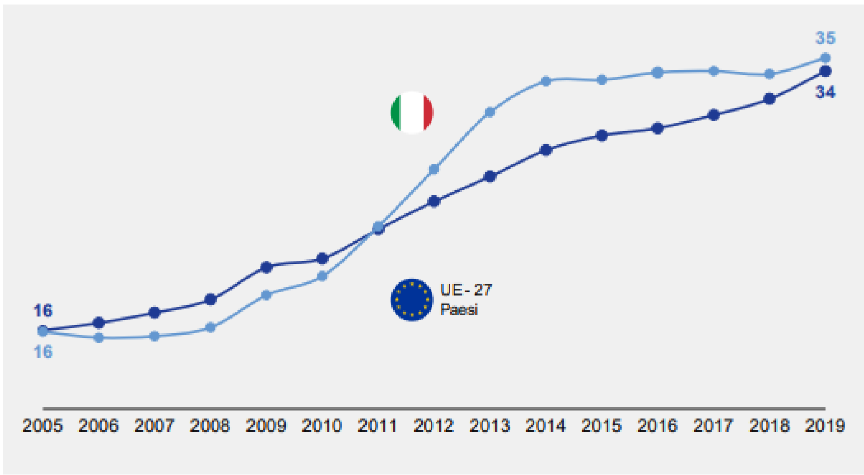



*Figure* 29: Percentual weight of RES on global energy production

Although the data are encouraging, to meet the target climate neutrality set for 2050, it is necessary to focus the objective for the 2030 to double the percentage of electricity from renewable energies. The RES in 2030 must produce 241 TWh, with an incidence on consumption of approximately 72% on the global electricity demand [8]. About the emission production the industry is expected to cut 43% of emissions compared to 2019, reaching approximately 87 million tons of $CO_2$ in 2030 [9].

### 2.4.3 The "Simplification Decree"

To achieve the progressive decarbonization of all sectors, the Mission provides investments, reforms, and incentives to increase the penetration of renewables in Italy. To rapidly evolve the strategies illustrated in the PNRR, it is essential to avoid bottlenecks in the Italian system that could delay investments and project implementation. According to ENEL, one of the main operators in the electricity sector, considering the current rate of issuance of authorizations for the construction and operation of renewable plants, it would take 24 years to reach the country targets, with reference to the production of energy from wind sources, and 100 years for the achievement for the solar plants. Streamlining the authorization procedures and the bureaucratic process is essential. In compliance with the PNRR time schedule, a decree-law was approved with the simplifications necessary to facilitate the energy transition.

The decree-law (DL) is the "simplification decree" (in Italian "decreto semplificazione") whose conversion law no. 108/2021 was approved by Parliament on 28 July, ad is in force from 31 July 2021.The decree is aimed at defining the national regulatory framework to simplify the achievement of the goals and objectives established by the PNRR and by the PNIEC.

Focusing on renewable sources and the "Ecological Transition", the decree dedicates the entire Title I to the simplification and acceleration of the "Environmental and Landscape Procedure", unfolding through the following points:

a) **Identificazione dei progetti strategici PNRR-PNIEC e loro qualificazione**

   Creation of two parallel processes for projects defined as strategic and for those that are not. The processes to be followed will have distinct timelines.

The variety of PNRR projects is well circumscribed, while the definition of PNIEC projects, can include all projects relating to energy production plants from renewable wind and photovoltaic sources.

**b) New single environmental provision regulations (PUA)**

The single environmental procedure streamlines the obtaining of the necessary authorizations for the creation of a plant. To avoid procedural burdens, is given right to the proponent to not include any authorizations that require too detailed design level of the project.

This solution should make the timing and articulations of the PUA procedure more predictable, fast and easy.

**c) New PAUR discipline**

The intervention should streamline the management of the PAUR procedure, that is the single VIA authorization measure. The PAUR constitutes a very significant part of the authorization procedures for energy production plants from renewable sources. It is also envisaged the convening of a preliminary conference of services as an acceleration tool that will facilitate the preparation of the necessary documentation for the preliminary investigation and environmental impact study. The new PAUR discipline aims to ensure that service conferences and procedural procedures are truly unitary.

**d) Changes to the VIA procedure and verification of eligibility for VIA**

The VIA procedure (verification of environmental subjection) is speeded up and streamlined by the reform described here.

It has been approved the exstension of the application for the VIA under state competence to strategic projects for the PNIEC, with the inclusion of all photovoltaic plants with a power exceeding 10 MW. This measure is aimed to obtain greater consistency in the assessment and avoid disparities between regions or obstacles to authorization deriving from local sensitivities.To increase the speed of bureaucratic operations, if the deadlines for the conclusion of the VIA procedure relating to the PNRR-PNIEC projects are not met, it is envisaged the introduction of the automatic refound to the proponent of 50% of the investigation rights. A special central body is also created, made up of dedicated professional, to evaluate all PNRR-PNIEC projects.

e) **Acceleration of procedures for renewable sources, storage and circular economy**

Here there is a group of reforms:

- • raising the power threshold to 20 MW for photovoltaic projects authorized with PAS in production areas and exclusion from environmental assessment procedures
- Using the PAS procedure for the repowering operations
- The reintroduction of the incentives for the agrivoltaic plants even if they are not clearly mentioned in the first decree.

# Chapter 3

## 3 Agrivoltaic systems

The development of a new photovoltaic technology in the agricultural sector plays a crucial role in the decarbonization process and the fundamental objectives for the years 2030 and 2050 for. In all Europe to achieve the goals of the Green Deal, reaching 1320 GW of installed, it would need to install more or less every day a photovoltaic park as extensive as the largest existing today (about 500 MW) for 10 years long [10]. Since one of the problems that slow down the most the growing of the photovoltaic plants is the availability of lands, agrivoltaic offers a valid alternative for the land use optimization. According to Alessandra Scognamiglio, researcher of ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development) in Innovative Devices Laboratory at the Portici Research Centre: ‹‹Agrivoltaic is a sector with unique characteristics, able to combine energy, new technologies, agriculture and landscape conservation, also to protect local communities and their activities, with benefits in terms of environmental, economic and social sustainability››. As for Italy, the data collected by Terna (the entity that manages the electricity transmission grid), in 2021 the current electricity needs at national level are met at 22% by photovoltaics. To meet the goals of the Greed Deal, it is estimated that Italy must cover 60% of demand through the sun's energy. To reach this level of production it will be necessary an area of panels in the order of 50 thousand hectares, or 500 square kilometers also considering the needs of energy storage, equal to about three times the surface of the city of Milan.

There are different opinions about the agrivoltaic, not all of them agree with respect to its use on a large scale. According to Enzo Cripezzi, the Lipu (the Italian league for the protection of birds) coordinator for Puglia and Basilicata, to be damaged by the agrivoltaic would be the landscape peculiarities and the fauna species of high conservation importance, which use the agroecosystems as resources for nutrition, reproduction and rest.

There would be several species whose habits would be bothered by the agrivoltaic plants: the eyelet, the lark, different species of birds of prey such as the kestrel falcon or the red kite, in some cases also the sea jay and the sea partridge. In addition to birds, the effect of these plants would also impact on reptiles, amphibians, badgers, porcupines, and wolves. The main antithesis to the development of agrivoltaic, however, is a conceptual question, says Cripezzi: "According to Istat data, between 1995 and 2005 more than 750 thousand hectares of land were urbanized. This quantity would be sufficient to accommodate the plants necessary to ensure the energy transition without consuming new soil.Using the already urbanized surfaces of the territory, for example roads, homes, warehouses, parking lots, industries could be a great chance.

In Italy, more than 7% of the entire national territory is cemented [11] equal to about 2 million hectares of land already urbanized, waterproofed, compromised.

The problem in using these surfaces lies in the fact that they are subject to many legislative constraints: artistic, landscape, physical, proprietary, financial, civil, administrative, condominium, etc. which make it very difficult to install photovoltaic systems.

In conclusion, it is certainly necessary to push a lot on incentives so that the development of solar systems on roofs can increase. On the other hand, the time factor, all the more in a highly bureaucratic state like Italy, requires us to consider other solutions to achieve the objectives set by the Green Deal (the reduction of GHG to 55% in 2030 and climate neutrality in 2050), and so the agrivoltaic technology could be a very strong alternative to push the RES production towards the desired levels.

## 3.1 Agrivoltaic System Definition

Agrivoltaic systems are a new way of conceiving the installation of photovoltaic systems, so a clear dividing line that separates this kind of systems from the traditional ones is still far from being clear. In this paragraph we try to focus on this technology by defining the characteristic points of agrivoltaic systems.

The agrivoltaic solutions are made with fixed systems or solar tracking, with mono or double-sided modules positioned at variable height and density in relation to the planned agro-energy project, be it grazing breeding, cultivation between the rows or arboriculture.

*Figure* 30: Agrivoltaic plant built in the wine sector (© SUN'AGRI) [12]

*Figure* 31: Agrivoltaic plant built on strawberry cultivation (© BAYWA R.E.) [12]

*Figure* 32: Agrivoltaic plant made in combination with pasture [13]

Each agrivoltaic solution must necessarily guarantee the maintenance or start-up of a new agricultural production. The energy production activity will be absolutely conditioned on the actual agricultural management of the areas siting the agro-energy project. The presence and conduction of agronomic activities in conjunction with the production of energy must be verified through the use of devices as the ones of the agriculture 4.0 classification and annually documented with appropriate reports.

There is not an official task to define at the Italian level the agrivoltaic technology, but in order to find the pillars for the AV , three associations representatives for both energetic and agricultural sides: ANIE Rinnovabili [14], Elettricità Futura [15], Italia Solare [16], signed the document "I sistemi agro-fotovoltaici" in which is defined the shape of these new systems. An agrivoltaic plant (AV) is defined as a system in which agricultural activity and energy activity coexist and insist on the same portion of territory. In order to identify a clear perimeter for this type of system, it is needed to define minimum requirements that all AV systems must comply to be defined as such. By agricultural activity we mean the whole spectrum of activities ranging from cultivation of crops to pastoral activity, including beekeeping. Agrivoltaic systems can be implemented both on unused agricultural areas and on those where agricultural activity is already present.

The agricultural activity will in any case be compatible with the territorial context of reference and can continue even after the disposal of the solar plant. As far as the cultivation of soil by energy activity is concerned, this should be declined as an area not usable for agricultural purposes. To this end, it is necessary to define: the total area of the project, the area that can be used for agricultural purposes, the area that cannot be used for agricultural purposes.

The total area of the project is defined as the agricultural area before the implementation of the AV system. The Area usable for agricultural purposes is defined as the portion of the area of the plot that can continue to be used for agricultural purposes without intervention even after the implementation of the AV system. The Area not usable for agricultural purposes is instead the portion of the plot that after the realization of the AV system is no longer temporarily available for use for agricultural purposes until the end of the useful life of the photovoltaic system. With regard to the entire AV system, there are two categories: AV systems with elevation from the ground ("HIGH AV"); ground-level AV systems ("INTER-ROW AV"). The HIGH AV systems have raised photovoltaic systems below which agricultural activity can be carried out, while the INTER-ROW AV systems are arranged on interlayers of PV modules alternating with area interfiles in which carry out the agricultural activity. Below are the representative schemes of the two categories.

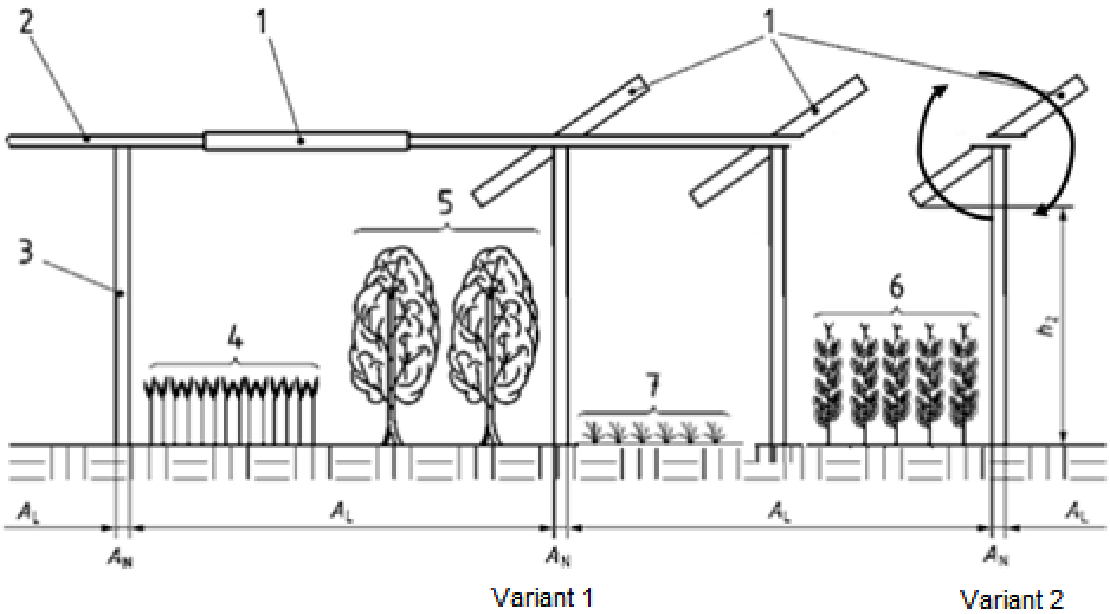



*Figure* 33: HIGH AV representation (frontal view)

*Table 2* HIGH AV representation legend

| | |
|---|---|
| $A_L$ | Agricoular field |
| $A_N$ | Non agricoular field |
| $h_2$ | Height for agricoular purposes |
| 1 | Solar modules |
| 2 | Counter-glazing |
| 3 | Elevation element |
| From 4 to 7 | Agricoular activity |

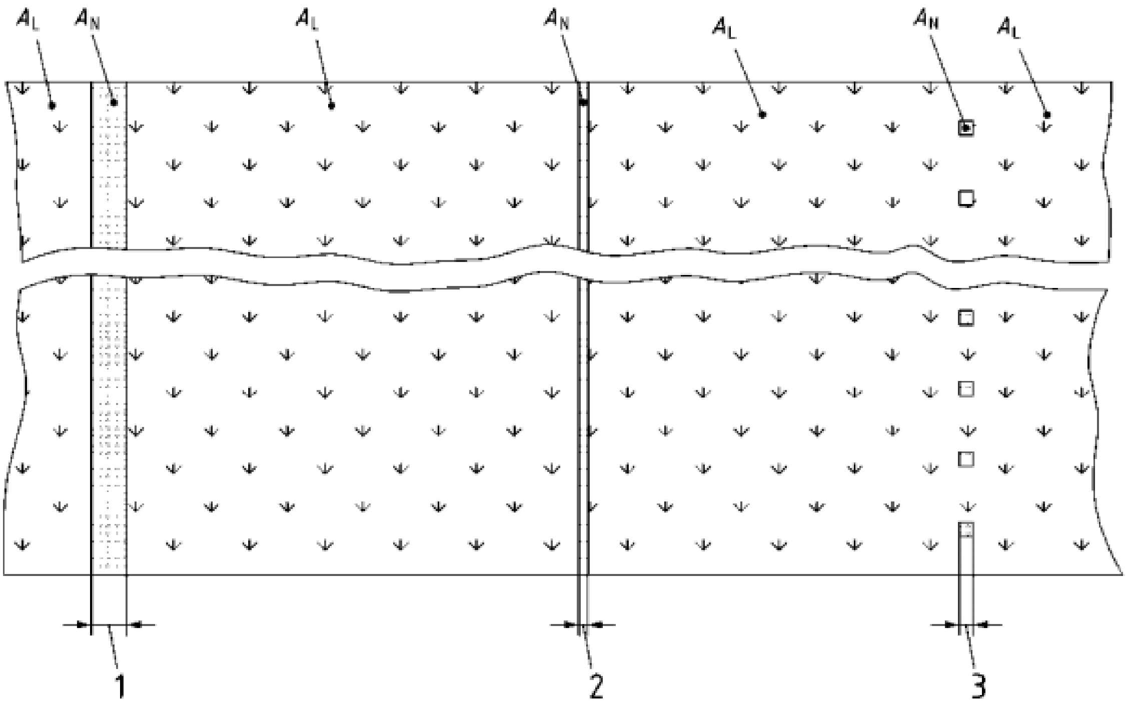



*Figure* 34: INTER-ROW AV representation (view from above)

*Table 3:* INTER-ROW AV representation legend

| | |
|---|---|
| AL | Agricoular field |
| $A_N$ | Non agricoular field |
| 1 | Variante 1: impianti fissi e con tracker |
| 2 | Variante 2: impianti fissi verticali |
| 3 | Variante 3: impianti fissi e cont tracker |

In conclusion, a project, in order to be qualified as an AV system, must possess all of the following characteristics:

1. demonstrate the feasibility of the AGRO activity both during the authorization request phase and annually for the entire duration of the authorization ;
2. adopt at least one system for monitoring and controlling significant factors of production;
3. limit the area not usable for agricultural purposes so that it does not exceed 30% of the "total project area".

About the choice of the photovoltaic module, fundamentally, all types of solar modules can be used in agrivoltaic systems [17]. Nowadays 95% of the global PV market is covered by modules with wafer-based silicon solar cells. In case of a transparent back covering (glass, foil), the spaces between the cells allows the light to largely pass through and reach the plants below. Conventional modules, have spaces between the cells that account up to 5% of the surface area; those spaces can be enlarged, and the module frames replaced by clamp mountings to increase light transmission. If the module is bifacial, it can also use the ambient light incident on the reverse side for the power generation. In the bifacial modules the efficiency can grow up to 25% (typically between 5 and 15 percent), depending on the amount of solar radiation on the rear side of the module. In agrivoltaic configurations the amount of light available on the reverse side of the modules is particularly high, since the row-to-row distance is large, and the supports are tall. The type of mounting structure must be adapted to the specific agricultural application and its respective needs. Here it is important the variation in height in case of play and the working width of the agricultural machines to be used. Using structures that are very high above ground level guarantees better synergistic effects between photovoltaics and agricultural production but, on the other hand, the investment costs for the mounting structure increase together with the height, due to the greater amount of steel used. The spacing of the rows, and the height of the agrivoltaic system are of pivotal importance since they determine the availability of light and, therefore, must be adjusted to meet the needs of the crops grown under the system. The tracking technology for PV modules can be of two main types: single axis and double axis. With single-axis photovoltaic tracking, the modules follow the sun horizontally based on the elevation of the sun or vertically based on the azimuth. Two-axis trackers do both at the same time, maximizing energy efficiency. However, two-axis systems risk creating much more shadow over the underlying crops. For agrivoltaic systems, permanent concrete foundations are not recommended in order to preserve valuable agricultural land, stacked foundations or special anchors are used instead. Like this. since no concrete is used, the system can be disassembled without leaving any trace on agricultural land.

Other important features of the agrivoltaic plants are not strictly connected with their own definition, but with the improvements that they bring to the energy production sector and the primary sector.

Compared to a soil without panels an agrivoltaic plant receives about 40% less direct sunlight. On the other hand, agricultural land has the capacity to generate energy that is significantly higher than that required for agricultural production. The smart combination of solar and agricultural infrastructure can enable rural communities to become more competitive and sustainable. The co-location of agriculture and photovoltaics allows the achievement of greater efficiency in land use. Several studies indicate that agrivoltaic systems can increase land use efficiency by up to 60-70%, compared to equivalent traditional monosystems. For example, in Germany an agrivoltaic plant recorded a yield of 103% compared to a control, while photovoltaic systems generated 83% of the electricity that would have been generated on the similar plot of land, in this way the efficiency of land use increased by 86%. Dual land use also serves to diversify farmers' incomes, protecting the socio-economic development of rural communities even in the event of extreme drought. [18]

The presence of photovoltaic structures on the cultivated field is not only disadvantages from the point of view of the crop production. The shading of the field results in a slightly altered microclimate under the modules. Possible effects on the microclimate have been studied in the United States [19] and France [20]. The solar radiation available for the plants may vary depending on the layout considered in the technical project. The lower the height of the supports, the more pronounced the microclimatic changes. Thanks to the presence of the modules, the ground temperature and to a lesser extent also the air temperature is reduced on particularly hot days. Wind speed may also decrease depending on the orientation and design of the system. Soil moisture losses are reduced, while at the same time the level of air humidity can increase. With regard to atmospheric precipitation, measures should be taken to minimize the risks of soil erosion since partial cover of arable land leads to uneven distribution of rainfall and related problems such as the runoff of nutrient-rich soil, silting up, washing of seedlings or eutrophication of surface water. For systems that only partially block rain or do not do it at all, it is necessary to consider possible changes in air circulation, air humidity and risks of infection for fungal diseases when selecting the type of crop. It is added that a lower plant temperature can also prolong the time needed to reach the maturity of the crops, so the selection of the type of crop is fundamental. Agrivoltaic probably offers the greatest potential for synergistic effects with special crops in the sectors of viticulture, orchards and vegetable cultivation, mainly due to the creation of more value per unit area. Positive experiences with agrivoltaic systems have already been made in the cultivation of leafy vegetables with lettuce. Like the celery crop in Heggelbach in Germany, lettuce responded positively to a slight reduction of about 30% showing an increase in leaf area growth [17]. In viticulture, agrivoltaic structures can protect plants from increased solar radiation and temperature changes due to climate change that can lead to sunburn and drying of fruits on the vine. Plants need light for photosynthesis, and the amount of the needed incident light differs in each specie. The light saturation point is defined as the minimum amount of incident light on the plant that allows to start the photosynthesis process at a constant rate. If the light on a plant is lower than the saturation point, the crop could even be damaged. The lower this light saturation point is for a plant, the better suite it is for growing under an agrivoltaic system.

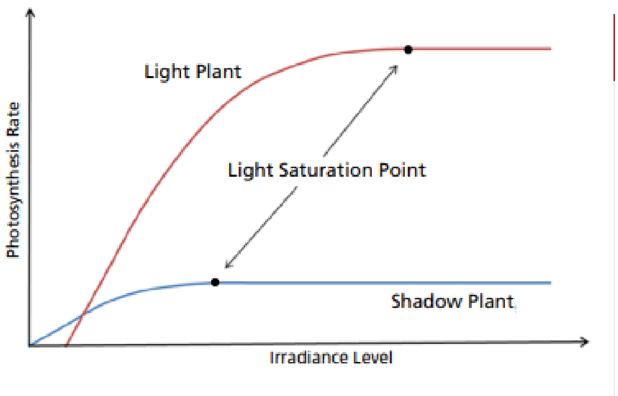



*Figure* 35: Light saturation point as function of crop kind and incident irradiation

## 3.2 Agrivoltaic in Italy

In order to achieve the goals of the European Green Deal, in Italy, it is estimated that about 70 GW of new RES capacity will be needed by 2030 to guarantee the 70% of electricity consumption from renewable sources by 2030 [15]. Of the additional 70 GW, solar will be able to ensure 50 GW by both upgrading of existing plants and new installations. However, considering that since 2014 the photovoltaic sector has grown by an average of 400 MW/year, it is clear the need to accelerate the current development trend in order to guarantee the energy transition that our country has set itself to realize. In the *figure 36* there is the installed capacity in Italy from 2015 to the year 2030 according to inertial trend and the Green Deal best suitable trend. The picture shows how incentives and new policies are absolutely necessary.

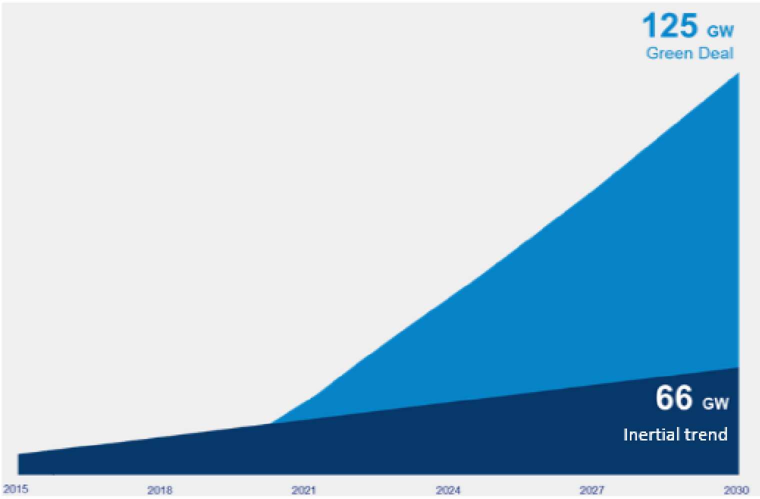



*Figure* 36: Development trend of the RES plants according to green deal and nowadays pace of growth

In general, the market for the development of new renewable capacity in Italy is characterized by plants very small size if compared, for example, with the situations of other countries that have equally ambitious energy transition objectives. In addition, the processes of issuing authorizations for the construction of new plants are too long and not compatible with the decarbonization objectives timeline. With the current pace of installation of new RES plants, the 2030 targets would be achieved in 2085 [15]. Italy could never reach its ambitious goals for 2030 using only roofs and industrial or degraded areas for new photovoltaic plants, even if the exploitation of those areas is fundamental.

In this regard, a study by the Politecnico di Milano [21] analyzed the abandoned areas available in our country, noting that only a small part of them could host utility-scale photovoltaic systems. Moreover, even the hypothesis of exclusive use of building roofs seems unrealistic despite the high theoretically available surface area of over 200,000 ha [7] due to the high fragmentation of the realizations, the current pace of small/medium-sized installations, the variety of construction types and roofs whose state is not always suitable with respect to the technical parameters to be guaranteed (inclination, exposure, static capacity). In this context, the expected growth of photovoltaics by 2030 will have to provide for a wider involvement of farmers and will have to evaluate the inclusion on the ground, on agricultural areas, of PV plants especially through plant solutions able to integrate energy production in agriculture and to contribute, if the conditions are met, to relaunch its activity in abandoned land that cannot be used in rural areas. It is believed that the agricultural and energy supply chains are not in opposition but that they can be partners in more or less complex agro-energy projects, and in different forms. On the basis of what has been anticipated, compared to the estimated total of new 50 GW of photovoltaic systems, about 35 GW may consist of ground installations, mainly made up of agricultural and industrial areas, while about 15 GW can be traced back to plants built on roofs [15]. With particular reference to the development of the new 35 GW of photovoltaic systems on the ground, even assuming to provide for their installation only on agricultural areas, the total amount of land needed for the AV plants would be about 0.1 million hectares. The incidence of the land occupation is illustrated in *figure* 37. The total amount of land is 16.5 million hectares, of which 12.8 million are for proper agricultural use and 3.7 million are not actively used by the farmers. The weight of the PV plants is only the 0.5% if compared with the total available are, and the 1.9% is only the unused land are considered.

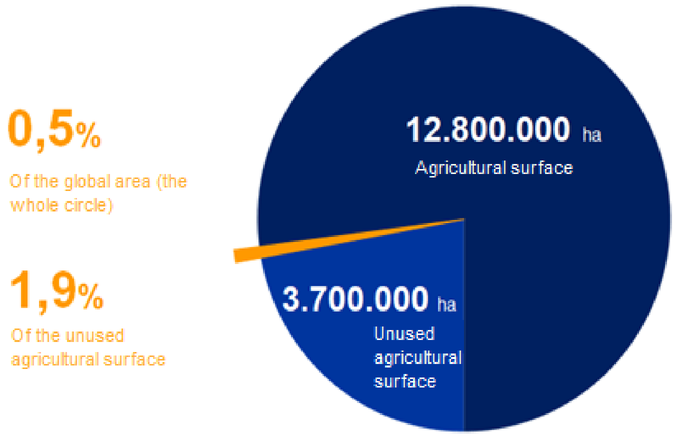



*Figure* 37: PV plant incidence on land occupation in 2030

Regarding the development of the AV system in Italy, the National Recovery and Resilience Plan allocates 1.1 billion euros, between now and 2026, to support the development of agrivoltaic. The agrivoltaic plants have been discussed for long time in the parliament since they are the first important example of sector coupling in Italy. The legislation is ambiguous since in both the PNIEC and in the PNRR there are not specific indications about these plants, for instance in the PNRR there is the "*investment 2.2*" named "*agrivoltaic park*" but the text is very generic and never focusses on the real agrivoltaic plants. Even it is said in the article 65 of the law 108/2021 that ‹‹*no solar plant can be installed on agricultural areas*" ››. This clear misunderstanding of the legislator has been fixed only with the "DL Energia 17/2022" that makes a derogation to the article 65 for the proper agrivoltaic installations. The agrivoltaic plants, to access the incentives, require the proponent to submit a self-declaration that the plant is not located within areas specifically listed and identified by decree of the Minister of Economic Development of 10 September 2010 "Guidelines for authorization of plants powered by renewable sources" which cites, for example, territories included in the world heritage list of UNESCO and areas included in the Natura 2000 network. To be included in the incentive program, agrivoltaic plants must also guarantee the monitoring of agricultural activity also through the application *agriculture 4.0* for verifying "the impact on crops, water saving, agricultural productivity for the different types of crops and the continuity of the activities of the farms concerned ". The law in force provides that in the event of termination of the conditions listed above for the granting of incentives, the benefits themselves also cease. *Agriculture 4.0* follows a new concept of primary sector, in which satellite technology and the use of sensors are made available to professional farmers to optimize European agricultural production while respecting the environment. *Agriculture 4.0* was the subject of a parliamentary interrogation to the European Parliament on April 7, 2021. The commission was asked to answer two main questions:

1- How does the commission intend to overcome the obstacles to the adoption of new technologies in the sector?
2- What funds are dedicated to the collection of data that can be used in the service of the supply chain?

The commission's response can be summarized as follows:

1. In the declaration «A smart and sustainable digital future for Europe's agriculture and rural areas» [22], signed by 26 Member States since 2019, various policy instruments for the implementation of a Community Agricultural Policy (PAC) were discussed. The proposal on the future common agricultural policy (PAC) requires Member States to develop digitization strategies. About the research field, Horizon 2020 [23] promotes the development of cost-effective digital solutions for farmers, business models and demonstration projects with over 200 million euros of budget.

2. The spread of the PAC can be supported by the European Regional Development Fund, the Connecting Europe Facility and the Recovery and Resilience Facility. Free data are available in support of agriculture, such as satellite data generated under the EU space program. The main datasets for the effective use of digital technologies are generated on farms using sensors, for which PAC support can be granted. The PAC is also set to advise farmers on nutrient and fertilization use, on the base of data analysis.

*Figure* 38: Agriculture 4.0 example of interface for a farmer (AGRICOLUS)

The measure of the incentives for the renewable electricity production plants are determined by the Energy System Operator. The procedure for the evaluation of the incentives for the designed plants is described in *figure 39* [24]

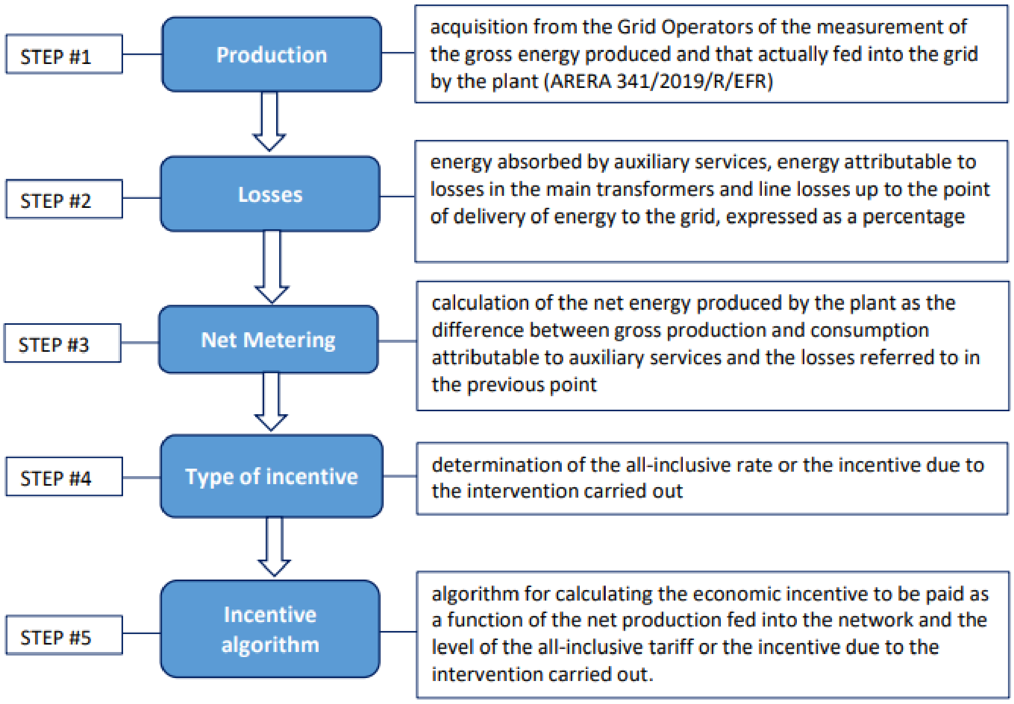



*Figure* 39: Incentives calculation process

The Italian law 04/07/2019 [24] divides the renewable energy plants that can access the feed-in tariffs into categories based on the technology, the renewable source and the type of investment (e.g., for a new installation or for a repowering). The incentives are paid for the electricity produced and injected into the grid regarding the newly built PV plants. In case of storage systems, it is calculated as the lowest value between the net production (equal to the gross production reduced by the consumption of auxiliary services, line and transformation losses), and the electricity actually injected into the network, measured with the exchange meter. There are two different feed-in tariff mechanisms, depending on the nominal power of the system. Plants with rated power ≤250 kW can access an all-inclusive tariff (in Italian, "tariffa omnicomprensiva").

The PV plant receives an average of 66.5 €/MWh, paid by the Italian Energy Services Manager [25]. Plants with rated power >250 kW can access a feed-in tariff, calculated as a function of the local electricity price and the results of reverse auctions in which the various producers participate [26]. As a result, the maximum feed-in tariff is about 20 €/MWh in Northern and Central Italy, while in Southern Italy and the islands, it is about 13 €/MWh. In both cases, the value of the feed-in tariffs is constant, and their duration is 20 years. For instance, following the Italian incentives, for a new construction plant, whose power is lower than 250 kW can access to the all-inclusive tariff can access to an incentive equal to the value $T_{spett}$ whose value is defined by the formula:

$$T_{spet} = T_{rif} \cdot (1 - \%RID_{OFF}) \cdot \left(1 - \sum \%RID_n \right) \qquad (12)$$

Where:

- $T_{rif}$ is determined according to the source and type of the plant and the power, for all photovoltaic systems and for plants registered in a useful position in the auction rankings, the rates set out in Annex 1 to the DM2019 apply, regardless of the date of entry into operation.
- $\boldsymbol{RID_{OFF}}$ is the percentage reduction offered during registration in the Registers (if submitted) or auctions, between 0.01% and 30% in the case of registration in the Registers or between 2% and 70% in the case of registration in auctions, and by virtue of which the plant has been awarded the useful position in the ranking.
- $\boldsymbol{RID_n}$ are all the reductions applicable to the present case such as:reduction of 1% per year for plants that entered into operation after 15 months from the publication of the ranking; reduction for delay in entry into service;reductions in tariffs in the event of recognition of a capital contribution; reductionfor the use of regenerated components; Reduction of the deadlines for entry into service for plants in a useful position in a previous ranking; riduzione for transfer to third parties; riduzione exceeding the deadlines for entry into service for plants already in a useful position in a ranking of the Registers DM2016 and DM2012.

On the other hand, if the plant has a nominal power higher than 250 kW, the incentive is computed outside the ranges of the all-inclusive tariff, it is equal to the value of the $T_{spett}$ minus the $P_z$., the $P_z$ is the hourly zonal price of the area where the electricity produced by the plant is fed into the network. The formula for the incentive calculation changes with the intent of the investment, following the table 11 of the source [24] there is the list of the formulas to use for the computation of the incentive value for each category of intervention.

### 3.2.1 State of the art out of Italy

In France the applications of agrivoltaic systems in vineyards are becoming increasingly financed and implemented, systems in combination with pomace fruits, such as apples, are also promising. Compared to other types of agriculture, viticulture as well as olive culture, requires only a height of two or three meters for agrivoltaic systems significantly reducing the costs of the assembly structure [27]. In France, ADEME, the French Agency for the Management of the Environment and Energy, has published studies that define the standards for a plant on agricultural land to be defined as "agrivoltaic. Agrivoltaic in France is defined as a photovoltaic system whose modules are located on the same area as agricultural production, to which they provide a series of services, without causing a significant qualitative and quantitative deterioration in agricultural yield or a reduction in the income generated by agricultural activity. On the commercial level, in 2021 some solar companies operating in France, such as Sun'Agri, REM Tec, Kilowattsol and Altergie Développement et Râcines announced the creation of "France Agrivoltaisme", the first commercial body in the world for the agrivoltaic sector that aims to federate and establish a dialogue between the actors of the supply chain at the service of agriculture. The association "France Agrivoltaisme" today has over 50 members and more than 10 thousand affiliates. Among the several recent AV plants in France there is the one based on tracking system inaugurated in March 2021 by the sun'Agri company that has developed on three hectares of orchard with stone fruits (i.e., cherry trees, apricots and peaches). In this system the panels are installed at a height of 6 meters and can rotate 90 degrees. The configuration adopted in this plant allows to reduce the heat on the plants up to 3 degrees centigrade, ensuring excellent resistance to the heat of the underlying plants [28].

*Figure* 40: Agrivoltaic with solar tracking system in France © Sun-Agri

Remaining in Europe, another important example for the AV development is Germany. Germany intends to accelerate the development of the photovoltaics by preparing to multiply by three the green power installed on fields and moors through new ad hoc financing to be included in the energy package presented at Easter 2022. The intervention in favor of the German AV aims to generate 80% of electricity from renewable sources in less than nine years, improving the current trend by about 40%. The government expects as many as 200 GW of solar plants to be built on agricultural areas. The intervention has a very wide scope, by way of comparison the current quota is around 60 GW. The measure will make it possible to finance agrivoltaic systems on all arable land. And it will give municipalities the power to establish specific nature conservation requirements when entering into contracts with developers. In Germany, expensive protection systems are often needed to alleviate the risks induced to the yields and quality of apples due to climate change. Agrivoltaic can reduce these costs. At the same time, only 60-70% of the available light is enough for optimal yields of apples [17]. Fraunhofer ISE is planning a pilot plant in an organic orchard in Rhineland-Palatinate in order to study the effects of photovoltaic modules on pest infestation and crop yields compared to the use of conventional protective equipment. Synergistic effects are also expected in the cultivation of hops: the assembly structure can be used for both hops and photovoltaic modules, thus substantially reducing the costs for cultivation.

*Figure* 41: Wheat harvest with suspended PV modules

Germany recognizes the absolute need to protect agricultural production and the environment. Environment Minister Steffi Lemke said: "A crucial task in this legislature is to promote the expansion of renewable energy and combine it with the protection of nature and species. We need both [...]we want to design the necessary expansion of open spaces and agricultural photovoltaics in a way compatible with nature: linking it to conservation criteria, the simultaneous rehydration of the moors and an expansion of installations in disadvantaged areas".

Going on the other side of the Atlantic Ocean, in the United States, the AV plants implementation is as deep as in Europe. For instance, the State of New Jersey has set the aggressive goal for 100% renewable energy by 2050 according to the national Energy Master Plan from 2019. This path will require 32,000 megawatts of installed photovoltaic electricity that will require utilizing both developed and currently undeveloped land, including farmland, for photovoltaic infrastructure. Pursuing the 2050 objective, in June 2021, the New Jersey Legislature passed the Dual-use Solar Act, which enable a limited number of farmers to have agrivoltaic systems on their property while the technology is being tested, observed and refined. The New agrivoltaic development program received $2M in the 2022 specifically for building Research and Demonstration Agrivoltaic Systems on their Research Farms. These systems will allow for detailed experimentation and engineering that would not be possible in a commercial setting [29].

In USA the agrivoltaic become not only a way of making the most of the territory to produce energy, but also an opportunity to sensitize local communities to a new model of development. An example is the Jack Solar Garden in Colorado, this agrivoltaic installation has 3,276 photovoltaic modules and powers about 300 homes with an electricity production that is around 1.2 MW. In this plant educational tours and volunteer activities are periodically organized involving students, teachers and local communities to disseminate the energy and agricultural model adopted at the structure. At the Jack Solar Garden site researchers from the InSPIRE project, from the United States Department of Energy (DOE), have carried out some studies in which is shown how agrivoltaic can increase the yield of some crops while reducing the need for water and creating cooler microclimates thanks to the shading of photovoltaic panels [30].

Finally in China, in the Binhe New District, on the eastern bank of the Yellow River, the largest agrivoltaic plant in the world is about to be built. The Baofeng Group has been working since 2014 to revive 107 square kilometers of desert in Ningxia province. The land will be cultivated with Goji berries, respecting the local environment. The project is the result of the agreement between the Baofeng group and Huawei's Solar division. There have been already installed 640 MW of photovoltaics power with structure 2.9 meters above the ground. The final aim is bringing the final capacity to 1 GW with 13,000 smart string inverters. All modules have single-axis automatic tracking technology that allows them to move relative to the position of the sun reaching more than 20% higher energy production than traditional photovoltaic power plants. This AV system makes innovation its distinctive feature, it is equipped with a program to carry out remote diagnosis, quickly and accurately identify any faults and even anticipate them, a wireless broadband system, drones for aerial inspection. According to Huawei, the photovoltaic power plant is able to effectively reduce the evaporation of soil moisture, to an extent of between 30 and 40 per year; initial estimates claim that vegetation cover has allegedly increased by 85 percent, significantly improving the regional climate [31].

# Chapter 4

# 4 Modelling of the agrivoltaic plant

The system taken into account in this thesis is a combination of PV structures and crop. To correctly model an AV system, it is first necessary to understand that it is not possible to proceed exclusively as if there were only the photovoltaic system. Agrivoltaic plants have the peculiarity of "harvesting twice from the sun", that is why it is necessary to take into account not only photovoltaic production, but also agricultural yield. During the definition phase of the plant, it is needed to consider that the two plants, the photovoltaic and the agricultural, will influence each other, so multiple considerations are necessary. There is a clear compromise to be respected in order to obtain good agricultural production at the same time as high energy production: as the number of modules present in an area increases, the less soil will be available for agricultural activity, but above all the hours of solar radiation available to plantations will decrease. Considering what has been said so far, in this thesis the purpose is to propose an evaluation method for agrivoltaic production highlighting the differences between the various configurations proposed both in the agricultural and energy fields. The evaluation process follows a schedule that unfolds simultaneously through the development of the agricultural and photovoltaic system as illustrated in *figure* 42.

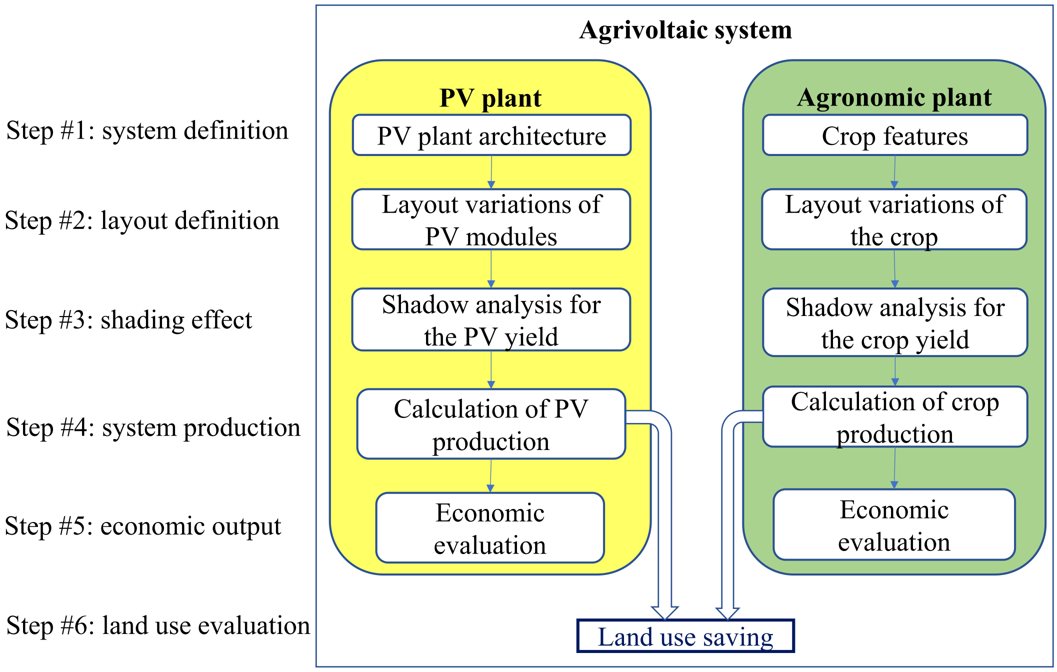



*Figure* 42: Agrivoltaic System Modelling

As *figure 42* shows, there have been followed 6 steps for the modelling of the AV system. The arrival point is the evaluation of the *Land Use Saving*, since the pivotal point of this technology is the dual use of the land for multiple purpose in order to increase the productivity of each fraction of soil.

Here there is an introduction for the 6 steps followed in the analysis, but in the following paragraphs they will be analysed one by one both for the PV and the Agricultural sides.

**Step #1: System definition**

In this first point the technical characteristics concerning the components of the photovoltaic system are analyzed, such as the modules and the support structures, and also for the agricultural plant, for which the type of crop, its features and the harvesting method are defined.

**Step #2: Layout definition**

In the second step of the analysis, once the elements present in the scenario have been defined, the different configurations taken into consideration during the study are illustrated. In this analysis we focused on the study of the variation in plant manufacturability in relation to the distance between the strings of the PV plant.

**Step #3: shading effect**

The shading effect is the most elaborated part of the analysis for both the sides of the agrivoltaic plant. The solar energy production is affected by shadowing, generating losses in the electricity output. Also, the crop yield is affected by the shadows of the PV modules. For the analytical evaluation of agronomic losses, a model already present in literature has been used, adapting it to the features required by this application.

**Step#4: System production**

Since all the parameters necessary for the evaluation of manufacturability are already pointed out, the characteristic values for both agricultural and energy production are defined. For electrical manufacturability, PVsyst software was used.

**Step#5: Economic output**

To perform a solid evaluation of this kind of activity and to determine which layout may be the best, the instrument of economic analysis has been adopted. This study has been performed using the cash flow analysis method.

**Step#6: land use evaluation**

Finally, to demonstrate the validity of agrivoltaic technology above the traditional solutions, a method present in the literature will be applied for the evaluation of a coefficient indicative of the optimization of land use.

## 4.1 Models adopted in the analysis

For the evaluation of the PV production, the crop yield and the land use there have been considered models already present in literature. The PV production, evaluated using the commercial software PVsyst®, exploits the "one diode model" to define the electricity production and its peculiarities. The crop yield is difficult to assess using deterministic models, but in order to shape the possible output of the agricultural side of the AV plant, the model proposed in [32] using the observations of H. Marrou [33] and C. Dupraz [34] has been considered enough solid. The land use has been evaluated using the Land Equivalent Ratio, that is a parameter developed in the Dupraz's analysis to compare the productivity of a field with multiple productions with a traditional one.

## 4.2 Modelling of PV Production

### 4.2.1 Single Diode Model

The behaviour of a photovoltaic cell is analysed by the PVsyst® program using an equivalent circuit, that in literature is known as the "single diode model".

The main components of the equivalent circuit are:

- Ideal current generator to represent photovoltaic current.

- Antiparallel diode through which the current of the diode flows. It represents the straightening effect of the electric field generated within the P-N junction. To take into account the real behavior of the junction, the diode is associated with an ideality factor. This parameter contains information about the charge transport and the recombination process that takes place within a real diode.

- Shunt resistance, placed in parallel to the current generator and the diode. It is due to the non-ideality of the solar cell and explains the leakage current (ISH) on the side surfaces caused by imperfect insulation. Ideally the value of this resistance should be infinite to avoid losses, but in reality it is not physically possible. However, its value can be increased by increasing the thickness of the side surfaces.

- Series resistance, placed in series to the other components of the circuit. It takes into account the losses that occur through the electrical contacts through the front electrodes. The main impact of the series resistance is the reduction of the Fill Factor.

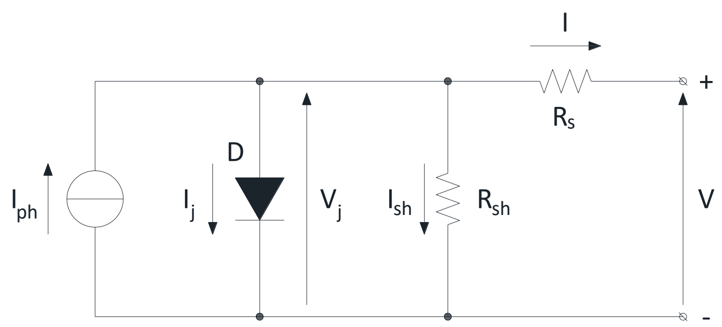



*Figure* 43: single diode model

The fill factor, FF, is a measure of the quality of the p-n junction and the cell resistances:

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{oc} \cdot I_{sc}} \tag{13}$$

Where:

The numerator defines the point of maximum power (W)

$V_{MPP}$ is the MPP voltage (V)

$I_{MPP}$ is the MPP current (A)

$V_{oc}$ is the open circuit voltage (V)

$I_{sc}$ is the short circuit current (A)

The FF improves for high values of $R_{sh}$ and for low values of $R_s$. On the one hand, the parallel resistance is related to the slope of the I-V curve around $I_{sc}$. The series resistance, on the other hand, is related to the pendant in $V_{oc}$. The higher the value that the fill factor assumes, the better the cell quality. In this case, $R_s$ and $R_{sh}$ have a not very significant influence. The influence of the resistances on the I-V curve can be seen graphically in *figures* 44 and 45.

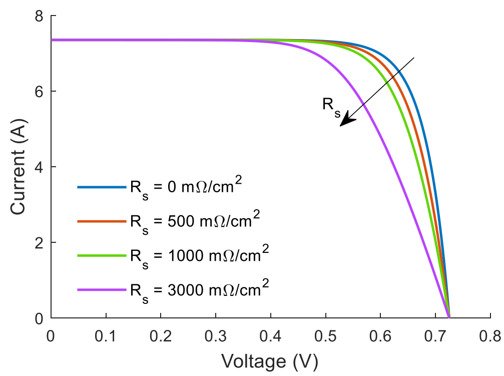



*Figure* 44: Dependence of the I-V curve on the parallel resistances

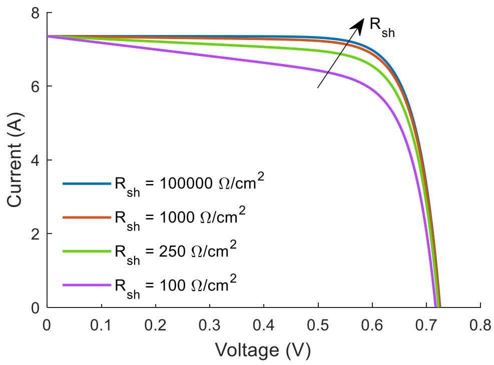



*Figure* 45: Dependence of the I-V curve on the series resistances

The circuit shown in the ***Errore. L'origine riferimento non è stata trovata.***43 can be solved with respect to current and with respect to voltage.

In the first case the following calculation is obtained.

$$I = I_{ph} - I_j - I_{sh} \tag{14}$$

Where:

- $I$ is the cell output current (A)
- $I_{ph}$ is the photogenerated current (A)
- $I_j$ is the current in the diode (A)
- $I_{sh} = \frac{V_j}{R_{sh}}$ is the current in the parallel resistance (A)

$$I_{ph} = q_e \cdot N_{ph} \cdot S \tag{15}$$

Where:

- $q_e = 1{,}602 \cdot 10^{-19}$ C is the charge of the electron
- $N_{ph}$ is the number of incident photons in ($\mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$)
- $S$ is the surface of the cell ($\mathrm{m}^2$)

$$I_j = I_o \cdot \left(e^{\frac{q_e \cdot V_j}{n \cdot k_B \cdot T_c}} - 1\right) \tag{16}$$

Where:

- $I_o$ is the reverse saturation current of the diode (A)
- $V_j$ is the voltage on the diode (V)
- $n$ is the ideality factor of the diode
- $k_B = 1{,}38 \cdot 10^{-23}$ J $\cdot$ K$^{-1}$ is the Boltzmann constant
- $T_c$ is the p-n junction temperature (K)

Combining the previous formulas, it is obtained the following expression:

$$I = I_{ph} - I_o \cdot \left( e^{\frac{q_e \cdot V_j}{n \cdot k_B \cdot T}} - 1 \right) - \frac{V_j}{R_{sh}} \tag{17}$$

Tension can be expressed with the following formulas.

$$V = V_j - R_s \cdot I \tag{18}$$

Where:

$V$ is the cell output voltage (V)

Obtaining $V_j$ from $I_j$ expression and replacing into the previous formula:

$$V = \frac{n \cdot k_B \cdot T}{q_e} \cdot ln \left( \frac{I_{ph} + I_o - I - I_{sh}}{I_o} \right) - R_s \cdot I \tag{19}$$

The open circuit voltage is obtained when $I = 0$

$$V_{oc} = \frac{n \cdot k_B \cdot T}{q_e} \cdot ln \left( \frac{I_{ph} - I_{sh} + I_o}{I_o} \right) \tag{20}$$

Voltage and current equations is finally obtained combining the respective solutions:

$$I = I_{ph} - I_o \cdot \left( e^{\frac{q_e \cdot (V + R_s \cdot I)}{n \cdot k_B \cdot T_c}} - 1 \right) - \frac{V + R_s \cdot I}{R_{sh}} \tag{21}$$

The short circuit current is obtained when $V = 0$

$$I_{sc} = I_{ph} - I_o \cdot \left( e^{\frac{q_e \cdot R_S \cdot I}{n \cdot k_B \cdot T_c}} - 1 \right) - \frac{R_s \cdot I}{R_{sh}} \tag{22}$$

About the energy production, the formula and the considerations are the same reported in the paragraph 1.9.

### 4.2.2 Thermal model

The effect of temperature on the modules in PVsyst are analysed considering the technical data of each module to express the variation of power, voltage and current in function of the temperature.

$$\gamma = \frac{dP_M/P_M}{dT} \tag{23}$$

$$\beta = \frac{dU_{OC}}{dT} \tag{24}$$

$$\alpha = \frac{dJ_{SC}}{dT} \tag{25}$$

Where:

$T$ is the temperature

$\gamma$ is the coefficient of variation of power respect to temperature

$P_M$ is the maximum power

$\beta$ is the coefficient of variation of voltage respect to temperature

$U_{OC}$ is the open circuit voltage

$\alpha$ is the coefficient of variation of current respect to temperature

$J_{SC}$ is the short circuit current

Once the coefficients are defined, the variation of the module characteristics is computes using the formula below:

$$P_M(G,T_C) = P_M(STC) \cdot \frac{G}{1000} \cdot (1 + \gamma_{pm} \cdot \Delta T_C) \tag{26}$$

$$U_{OC}(G,T_C) = U_{OC}(STC) \cdot (1 + \beta_{Uoc} \cdot \Delta T_C) \tag{27}$$

$$I_{SC}(G,T_C) = I_{SC}(STC) \cdot \frac{G}{1000} \cdot (1 + \alpha_{SC} \cdot \Delta T_C) \tag{28}$$

$$\eta(T_C) = \frac{P_M}{G \cdot A} = \frac{P_M(STC) \cdot (1 + \alpha_{SC} \cdot \Delta T_C)}{1000 \cdot A} \tag{29}$$

Where:

$\Delta T_C$ is the temperature difference between $T_C$ and $T_{STC}$

$P_M(G,T_C)$ is the module power at temperature $T_C$ and irradiance $G$

$U_{OC}(G,T_C)$ is the module voltage at temperature $T_C$ and irradiance $G$

$I_{SC}(G,T_C)$ is the module current at temperature $T_C$ and irradiance $G$

$\eta(T_C)$ is the module efficiency at temperature $T_C$ and irradiance $G$

To obtain the surface temperature of the modules $T_C$a thermal model is used.

$$U \cdot (T_c \cdot T_{amb}) = \alpha \cdot G_{inc} \cdot (1 - eff) \tag{30}$$

With:

- $T_{amb}$ is the ambient temperature, according to the weather database dataset
- $T_c$ is the module temperature
- $G_{inc}$ is the incident irradiance on PV array
- $\alpha$ is the absorption coefficient of solar irradiation, computed as the difference of 1 and the normalized reflection

- $eff$ is the PV efficiency calculated according to the operating conditions of the module.
- $U$ is the heat transfer factor

Where the cell temperature ($T_{cell}$) is computed as follow:

$$T_{cell} = T_{amb} + \frac{1}{U} \cdot [\alpha * G_{inc}(1 - eff)] \quad (31)$$

For the $U$ parameters the formulation is the following:

$$U = U_c + U_v \cdot v \quad (32)$$

Where :

- $U_c$ is the constant contribute
- $U_v$ is the variable contribute
- $v$ is the wind speed

There are some default values proposed basing on the system configuration, for modules set with air circulation all around as in this thesis: $U_c$=29 $W/m^2 \cdot K$ and $U_v = 0 \frac{W}{m^2 \cdot K\ m/s}$.

This model takes into account about the NOCT considering the following thermal balance:

$$U(T_{cell} - T_{amb}) = \alpha \cdot G_{inc} \cdot (1 - eff) \quad (33)$$

In which substituting the expression of U, the NOCT condition is revealed:

$$(U_c - U_v) \cdot (NOCT - 20\ °C) = \alpha \cdot 800 \frac{W}{m^2} \quad (34)$$

Once the cell temperature is obtained the losses are easily computed using the percentual losses described in the product datasheet.

$$Loss = \epsilon \cdot (T_{cell} - 25°C) \tag{35}$$

Where:

- Loss is the percentual loss in voltage/current/power.
- $\epsilon$ is the value of the specific loss indicated into the datacheet

### 4.2.3 Software procedure

To perform the simulation of the photovoltaic part of the AV plant, the software PVsyst® has been used. The version taken into account is the PVsyst® 7.2 for students. This software deals with many photovoltaic systems: grid-connected, stand-alone, and includes weather and PV systems components databases. The preliminary design of the plant, as well as Project Design and simulation, can be analyzed using this software. For the preliminary evaluation, PVsyst® gives the results about the system yield evaluations performing calculations on monthly values, using only a very few general system characteristics and parameters. Within the framework of a project, it is possible to perform different system simulation runs and compare them.

Features like the plane orientation (with the possibility of tracking planes or shed mounting), and the specific system components can be set by the user. The creation of the PV array (number of PV modules in series and parallel) is assisted by the program, and also the inverter model, battery pack or pump are easy to select thanks to the PVsyst® hints. Further in the analysis, the user can specify more detailed parameters and analyze fine effects like thermal behavior, wiring losses, module quality, mismatch and incidence angle losses, horizon (far shading), or partial shadings of near objects on the array, and so on.

To perform the shadow simulation, it is needed to create a 3D representation of the photovoltaic field that can be obtained with external software, too. The results from the PVsyst® calculations include several simulation variables, which may be displayed in monthly, daily or hourly values.

Finally, PVsyst® can perform also an economic analysis, using real component prices, any additional costs and investment conditions, giving as output many useful economic indicators.

Here it follows the illustration of the procedure followed for the simulation of the plant descripted in the present work.

The first step for the simulation of a new plant, is choosing the kind of system it is meant to model. For the purpose of this work, the grid connected plant has been adopted. So, the first step is to open PVsyst® and click on the "greed connected" project design.

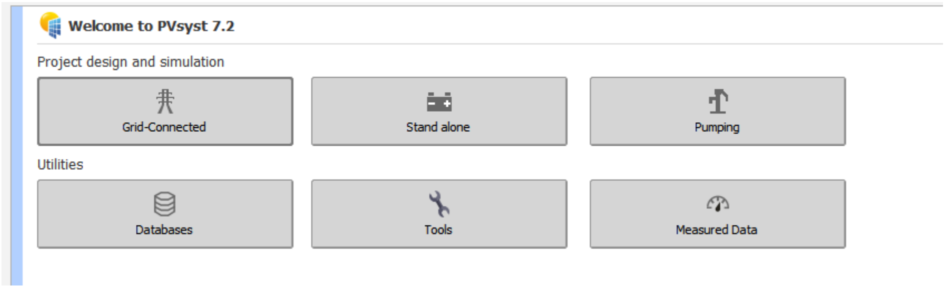



*Figure* 46: PVsyst® initial window

Now a new project needs to be implemented. The program shows the window represented in *figure 47*:

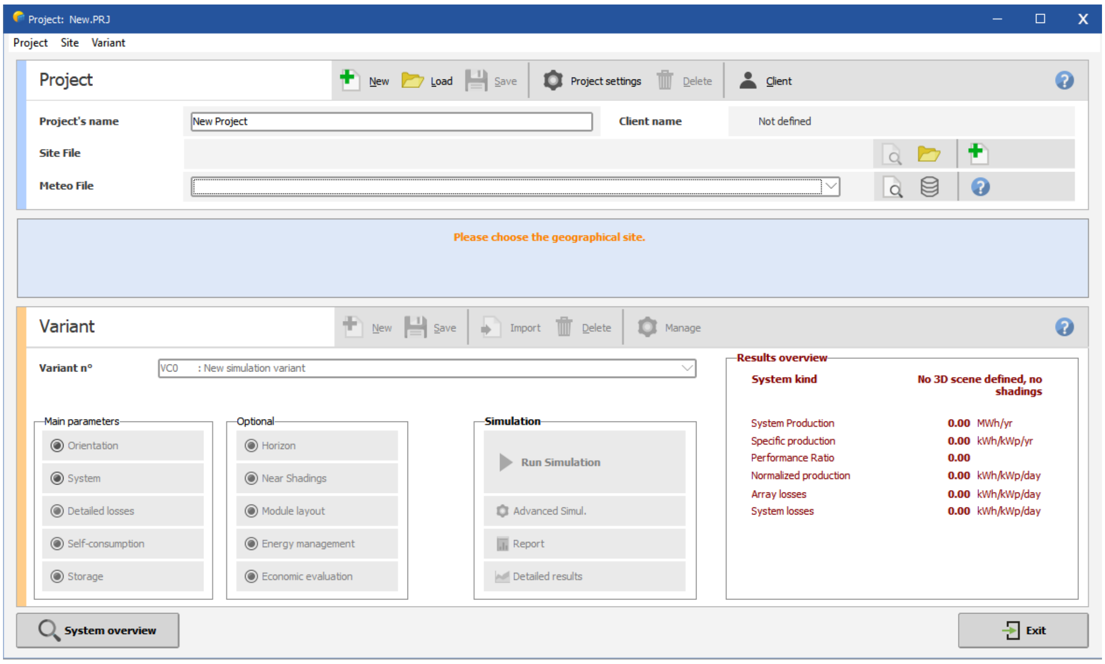



*Figure* 47: PVsyst® main project window

During each step of the process the program PVsyst® shows us some messages, giving instructions about what to do. The messages are classified basing on their colour: red means that the suggested tips are an unavoidable action to accomplish to continue the simulation; yellow means that something is not optimally implemented, but anyway it is acceptable; green means that everything is fine with the designed parameters.

As the *figure 47* shows in its yellow message, it is needed select a geographical site. To create a new site, it is needed to insert the project name, then select a new site file clicking on the "+" icon on the right side of the window. In this way it is possible to write the location coordinates in the proper space in a window like the one showed here below.

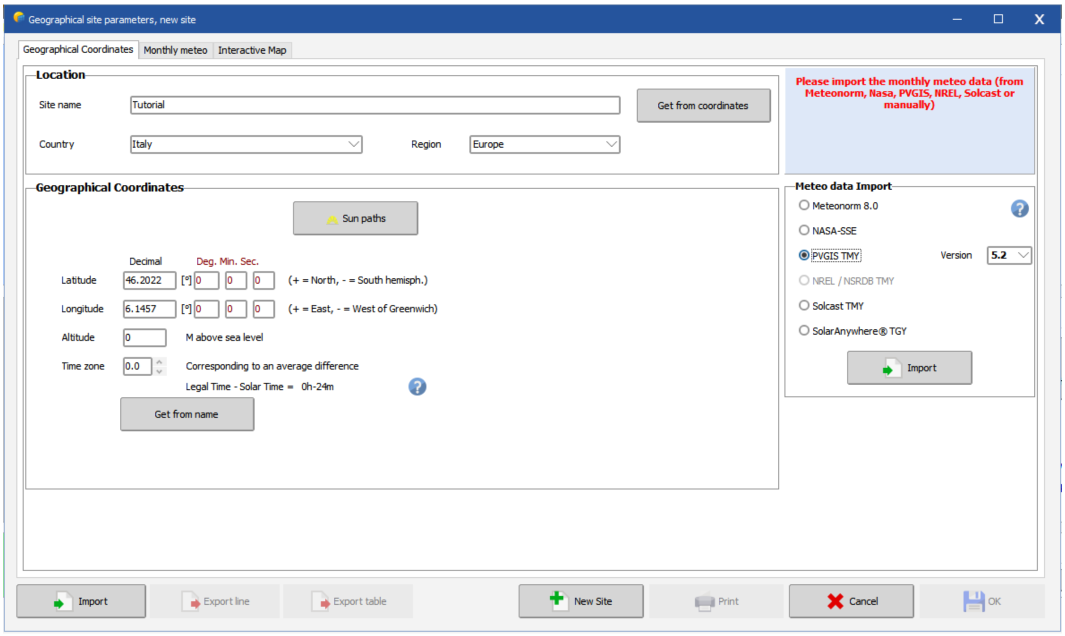



*Figure* 48: new geographical site

As the *figure 48* shows there are many weathers database from which it is possible to import data: Meteonorm 8.0; NASA-SSE; PVGIS TMY; Solcast TMY; Solar Anywhere. Once the database has been selected, click on "import" and continue saving the progress.

Now the program automatically goes back to the main project window, but now it is possible to insert the orientation and system parameter (as suggested by the red message from the PVsyst®).

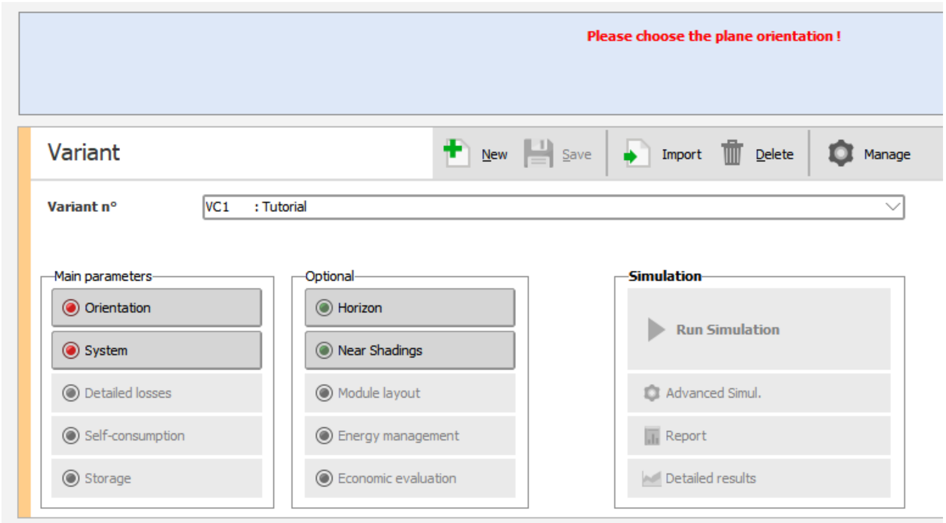



*Figure* 49: PVsyst® main window: parameters definition

By clicking on "orientation" it is possible to access the window illustrated in *figure 50*. From this tab it is possible to select from a drop-down menu the type of module between fixed, monoaxial tracker and biaxial tracker. Each category has several possible alternatives, for example for fixed modules it is possible to choose between: fixed tilted plane, several orientations, seasonal tilt adjustment, unlimited shields, unlimited sun shields. It is possible to enter additional specifications in the area on the left side of the window, to better define the characteristics of the module. For example, in *figure 50* the chosen module is based on a tracking system, and it has been specified that the maximum inclination is 55° both to the east and to the west (see phi min / max in the image), and the backtracking system is activated.

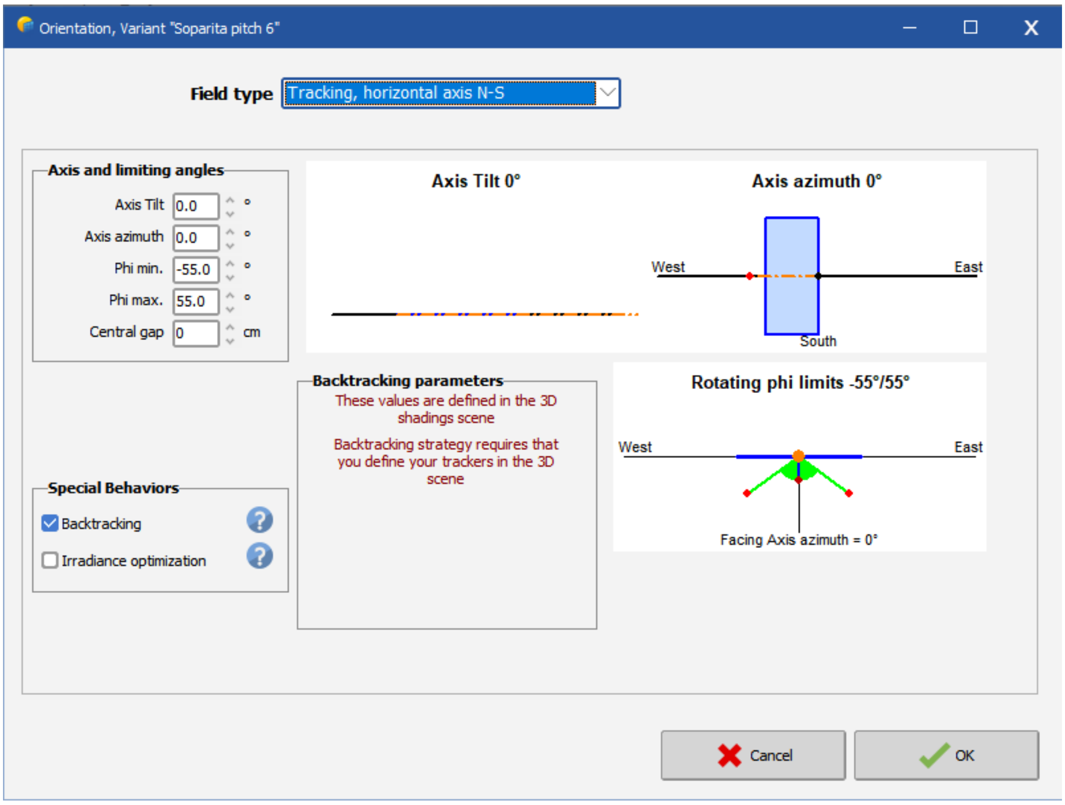


*Figure* 50: PVsyst® orientation settings

Once the orientation is defined, click on "ok", save the project and return to the main project window. Now it's time for the "system" definition, so click on the proper button. Now the program opens a window like the one represented in picture 5.8. At this step it is needed to insert in the upper part of the window the nominal power (or the available area) of the plant. After that in the box below it is possible to select the desired PV modules among a series of models from many producers. If the PV model is not present in the list offered by the program, it is possible to add a new one clicking on "database" in the Pvsyst® initial window or modify an already present module clicking on "Open" on the right of the PV module space. Remember to activate the bifacial modality if it is available in the actual plant. Once the PV modules are defined, the program automatically import the information of the model and computes the thermal losses, showing up the results in the bottom of the window. Following these results, the correct inverter setup must be implemented. As for the modules, there is for the inverters too, a list of models of various power from different manufacturers. It is worth to remember that in the left bottom part of the window, there is the possibility to change the number of modules in series and parallel, but this customization may affect the system performance. First, changing the number of modules in series can make the selected inverter inappropriate for the plant, because the voltage of the array/string changes as the number of element in series increases/decreases. Secondly, if this modification is apart from the 3D model that will be presented in the following step, PVsyst® will detect a contrast among the 3D scene and the project settings.

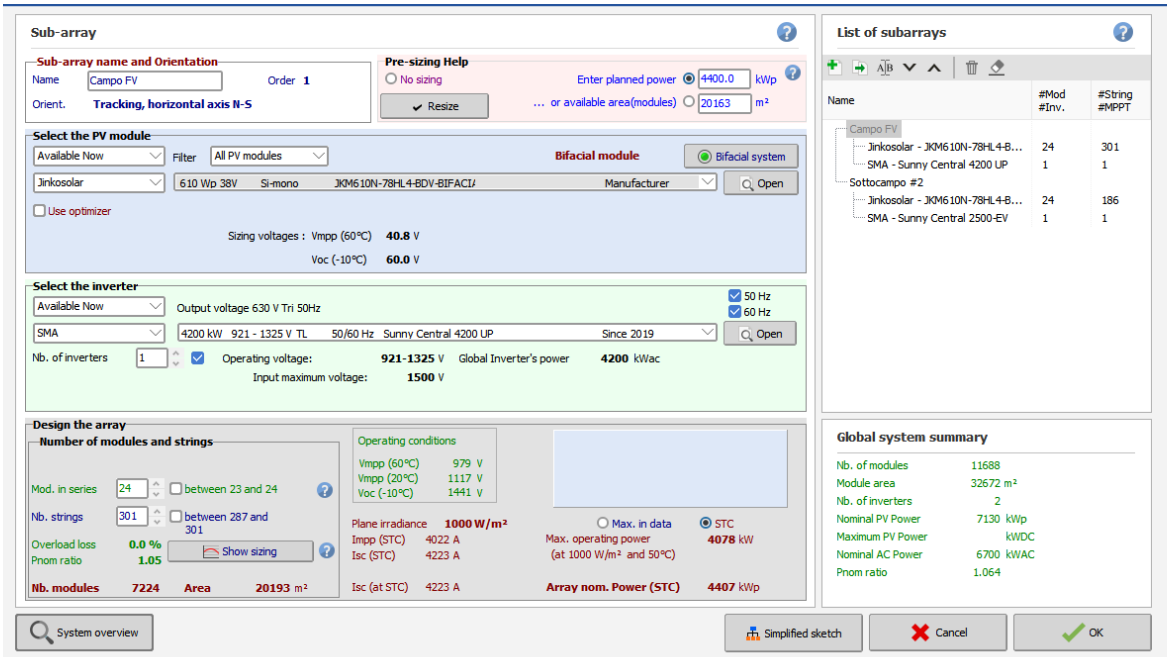


*Figure* 51: system definition

Since some plants could be very wide, and the topology could lead to articulated solutions about the modules-inverter linking, it is possible to define different subarrays in the column on the right side of the window. For instance, in *figure 51* there are 2 sub-arrays, the first one is named “Campo FV” and it is characterized by a nominal power of 4400 kWp, it uses 7224 modules made by Jinkosolar in series of 24, and it is provided of 1 centralized inverter produced by SMA whose power is 4200 kWp; the second one is named “Sottocampo 2” and has 4464 Jinkosolar modules in series of 24, all linked to a centralized SMA inverter whose power is 2500 kWp.

As usual, after the definition of the parameters, it is needed to save and go back to the “main project window”.

Now clicking on “near shading” is possible to define the shadow losses.
The window that opens at this point is represented in the *figure* 52.

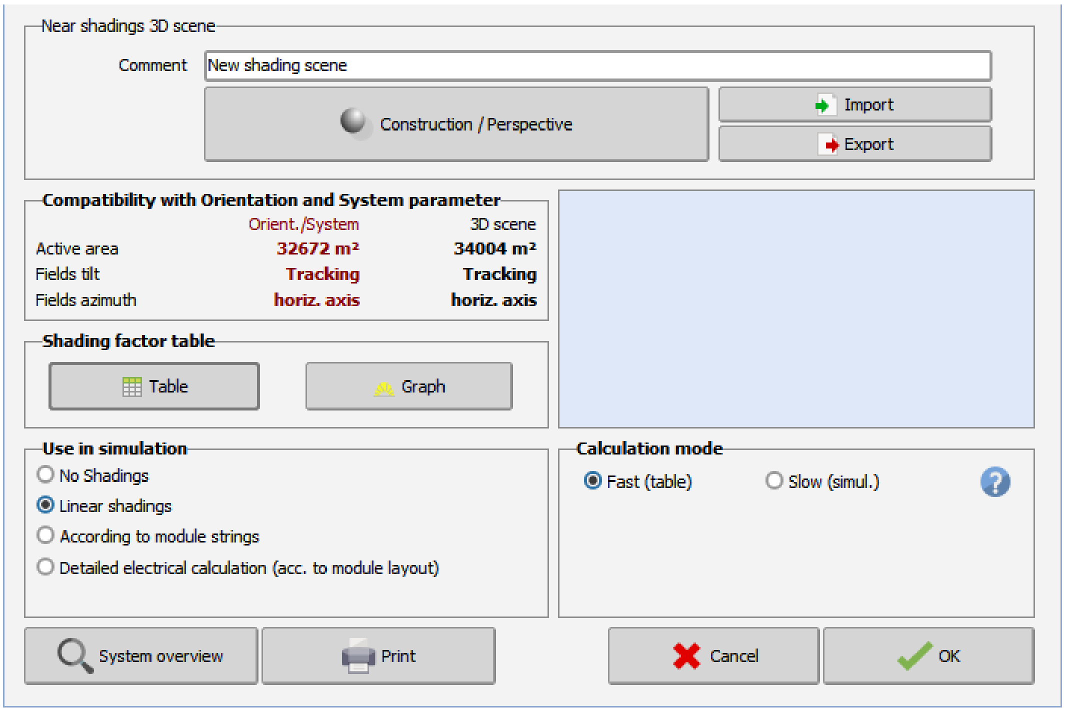



*Figure* 52: PVsyst® shading conditions

Clicking on Construction/Perspective it is possible to access a build designing tool in which the user can create or import a 3D scene to adopt during the shadowing simulation.

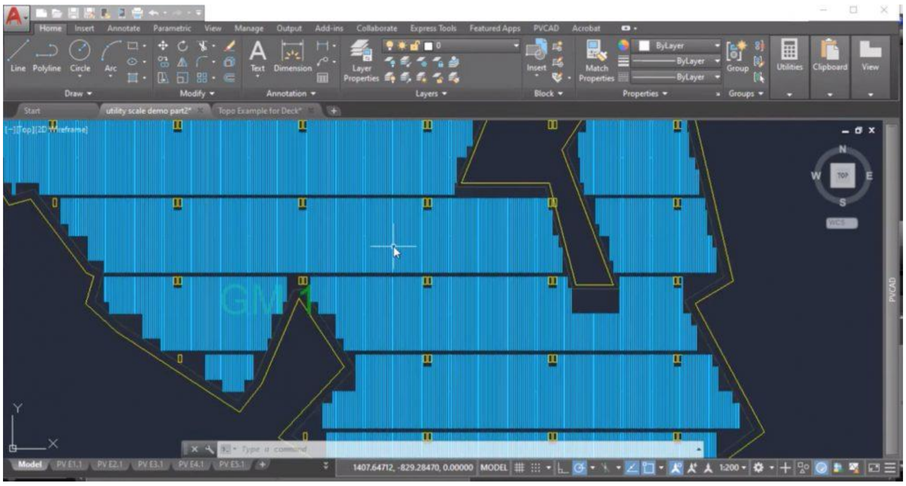


*Figure* 53: Modules to be imported in PVsyst® represented in external program

In PVsyst® now is available the 3D scene of the plant, as visible in the *figure 54*.

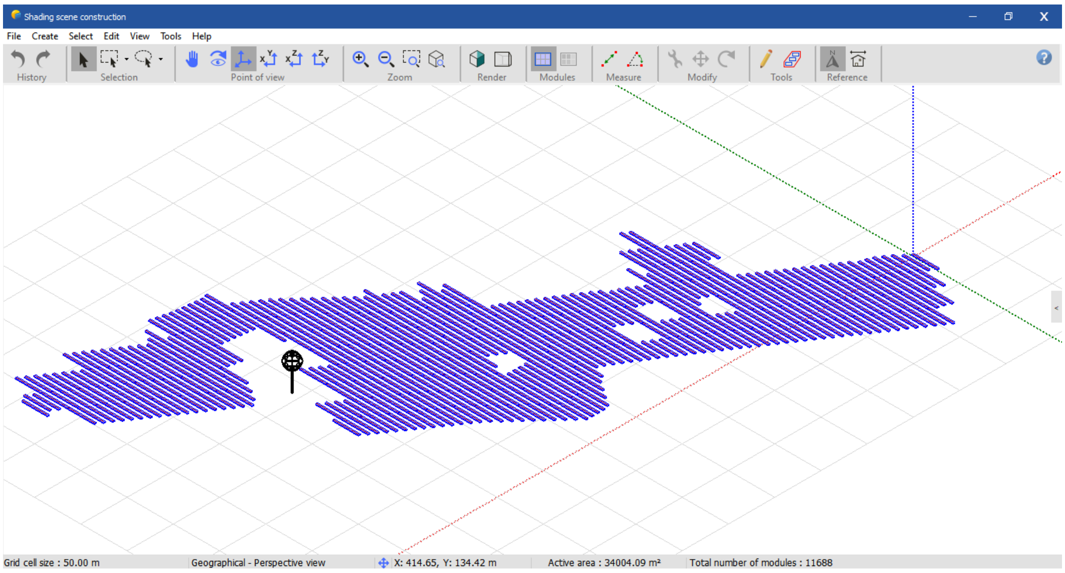



*Figure* 54: 3D scene in PVsyst®

Now is possible to close this window and compute the shading factor table by clicking on the button "table". With this procedure the program computes the short shadow losses, mainly caused by the shadow of the modules on other modules.

Shading factor table (linear), for the beam component, Orient. #1

Close Print Export Help

Recompute

Plane orientation
Tracking, horizontal axis N-S
With Backtracking

**Shading factor table (linear), for the beam component, Orient. #1**

| Azimuth / Height | -180° | -160° | -140° | -120° | -100° | -80° | -60° | -40° | -20° | 0° | 20° | 40° | 60° | 80° | 100° | 120° | 140° | 160° | 180° |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 90° | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 80° | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 70° | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 60° | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 50° | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.002 | 0.002 | 0.001 | 0.000 | 0.000 | 0.000 |
| 40° | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.002 | 0.002 | 0.001 | 0.000 | 0.000 | 0.000 | 0.001 | 0.002 | 0.003 | 0.003 | 0.002 | 0.001 | 0.002 |
| 30° | 0.004 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.004 | 0.004 | 0.003 | 0.001 | 0.000 | 0.000 | 0.001 | 0.003 | 0.005 | 0.004 | 0.004 | 0.004 | 0.004 |
| 20° | 0.006 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.007 | 0.007 | 0.007 | 0.005 | 0.002 | 0.005 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.006 |
| 10° | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.009 | 0.014 | 0.004 | 0.006 | 0.003 | 0.002 | 0.003 | 0.009 | 0.014 | 0.011 | 0.014 | 0.002 | 0.001 |
| 2° | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.002 | 0.002 | 0.001 | 0.002 | 0.001 | 0.001 | 0.001 | 0.001 | 0.002 | 0.006 | 0.003 | 0.001 | 0.001 |

**Shading factor for diffuse: 0.001 and for albedo: 0.000 (tilt: 0.0°, azim.: 0.0°)**

*Figure* 55: Shading factor table for short shadows

The table showed in *figure 55* has very low values, that's because the backtracking is activated during the simulation.

Long shadows losses, or horizon losses are computed thanks to the skyline that is defined thanks to the site coordinates. The results for the horizon losses can be consulted going back to the main project window and clicking on "horizon".

Finally, the complete system simulation can be done by clicking in the main project window the button “start”. After the computational time it is possible to access the results from the window that automatically appears, that is represented in the *figure 56*:

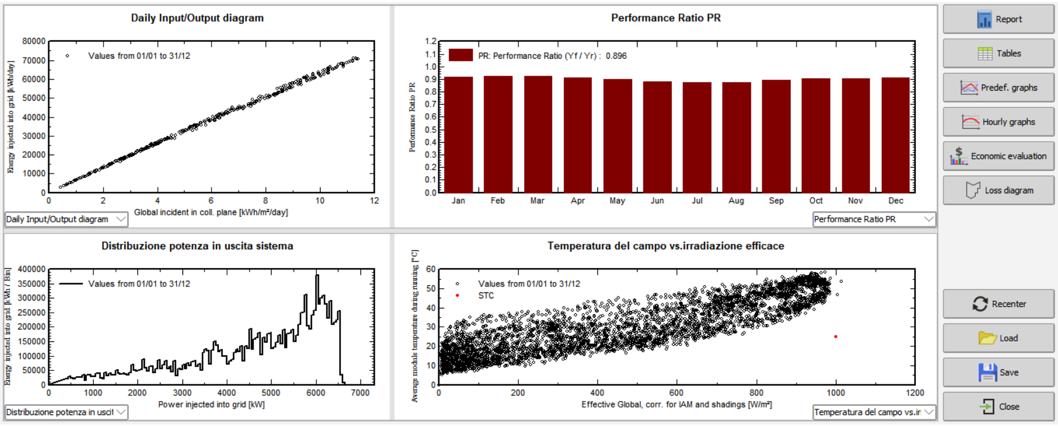



*Figure* 56: simulation results window

Clicking on “Tables” or “Predef. graphs” it is possible to access a multitude of interesting results as showed in the following picture.

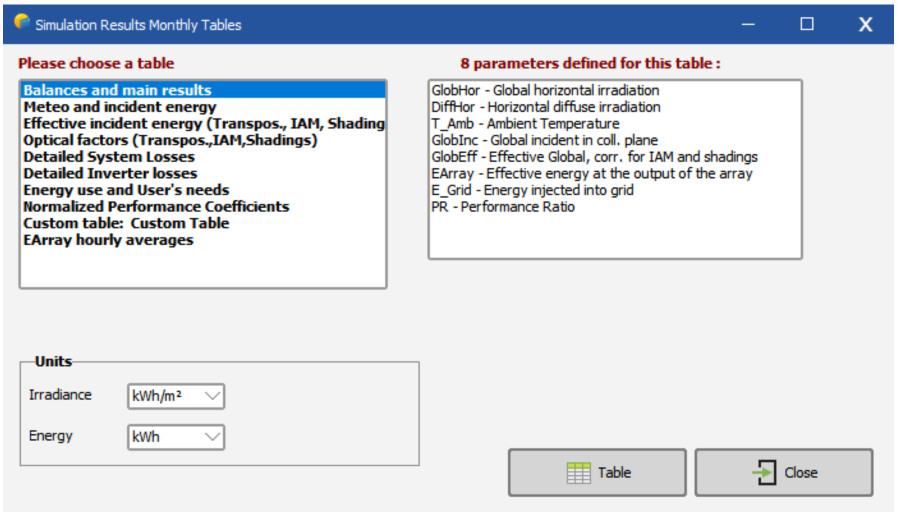



*Figure* 57: results of the simulation in tables and graphs (a)

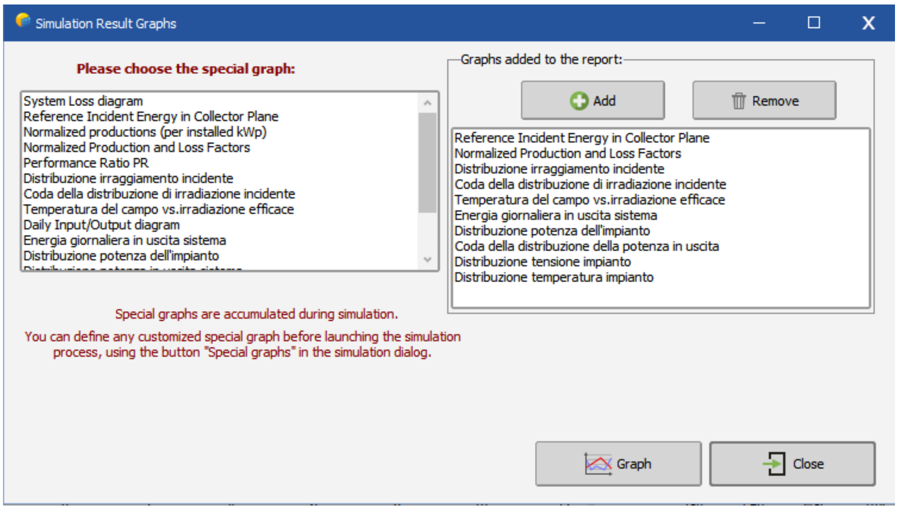



*Figure* 58: results of the simulation in tables and graphs (b)

A customized graph can be created clicking on “hourly graphs”, where it is possible to select the variables to plot on the axis.

At this point the economical evaluation can be set in the program.
The economical evaluation follows simple steps:

1. Click on economical evaluation on the right side of the results window.
2. Insert all the parameters for investment and charges

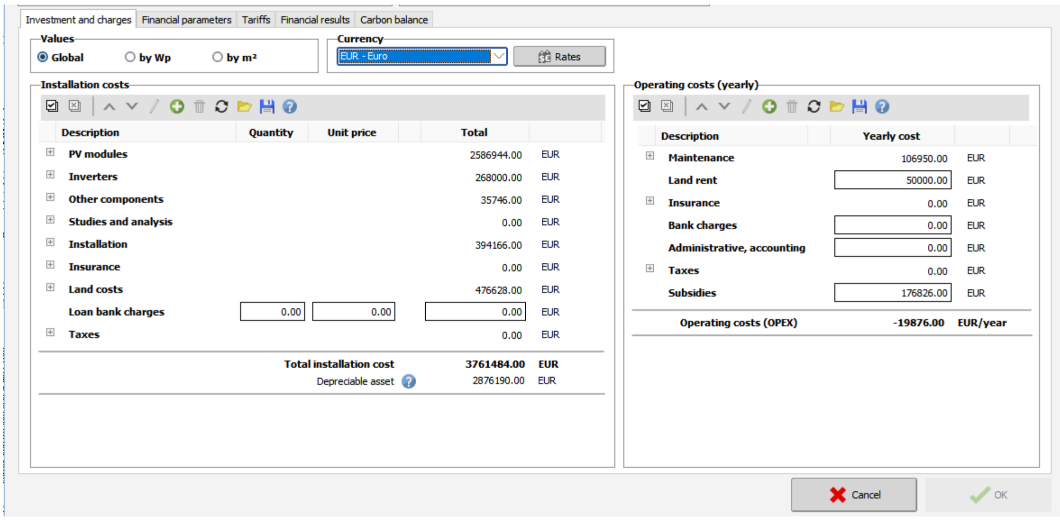


*Figure* 59: PVsyst economic analysis: investment and charges

3. Insert all the financial parameters

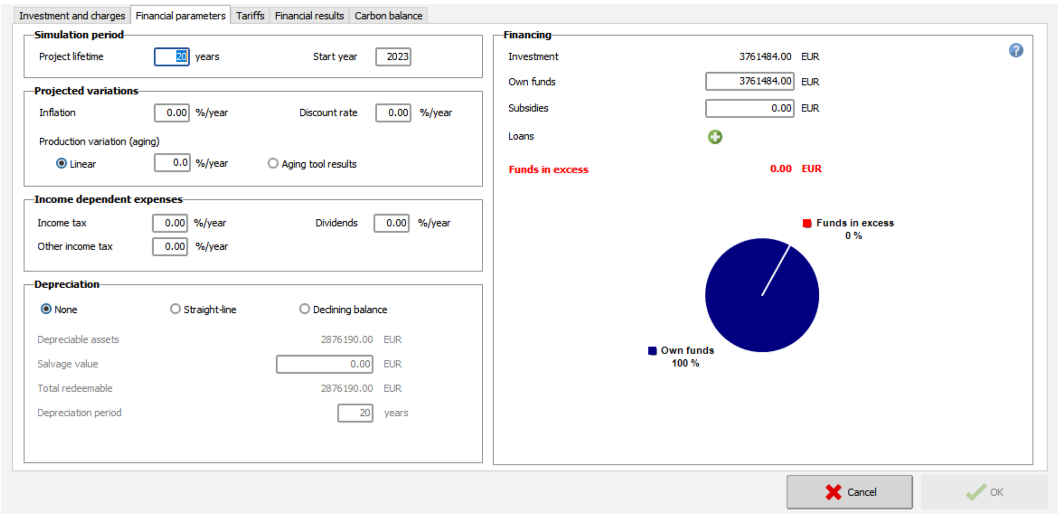


*Figure* 60: PVsyst economic analysis: financial parameters

4. Define the tariffs

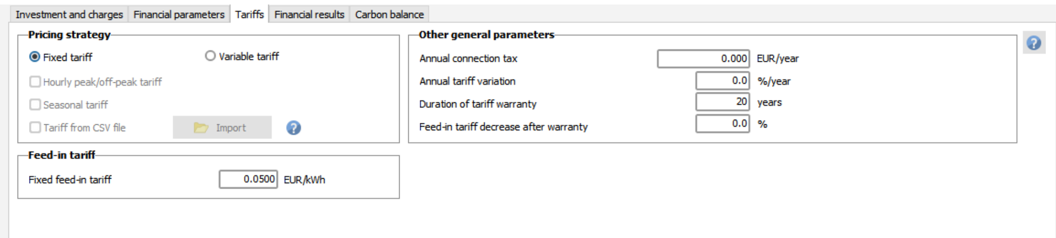
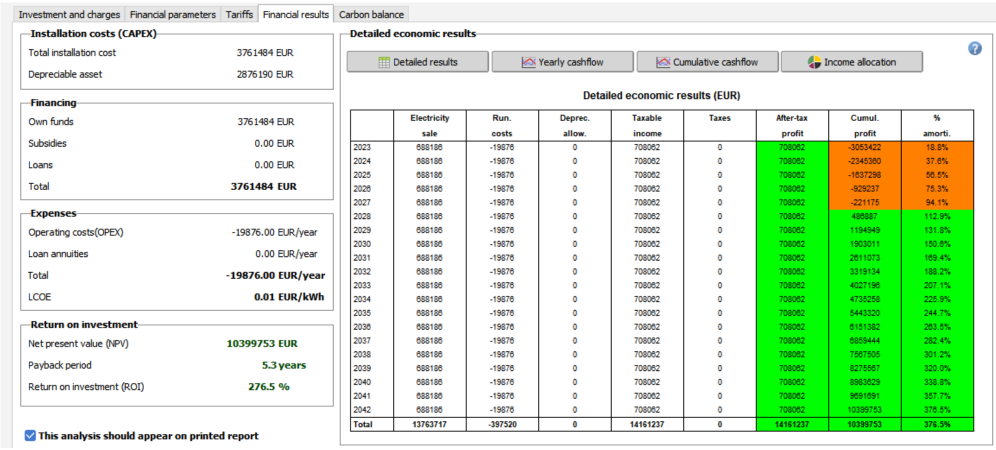



*Figure* 61: PVsyst economic analysis: Tariffs

5. Finally consult the results of the analysis for the financial calculations and carbon savings




Detailed economic results (EUR)

| | Electricity sale | Run. costs | Deprec. allow. | Taxable income | Taxes | After-tax profit | Cumul. profit | % amorti. |
|---|---|---|---|---|---|---|---|---|
| 2023 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | -3053422 | 18.8% |
| 2024 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | -2345360 | 37.6% |
| 2025 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | -1637298 | 56.5% |
| 2026 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | -929237 | 75.3% |
| 2027 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | -221175 | 94.1% |
| 2028 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 486887 | 112.9% |
| 2029 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 1194949 | 131.8% |
| 2030 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 1903011 | 150.6% |
| 2031 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 2611073 | 169.4% |
| 2032 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 3319134 | 188.2% |
| 2033 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 4027196 | 207.1% |
| 2034 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 4735258 | 225.9% |
| 2035 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 5443320 | 244.7% |
| 2036 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 6151382 | 263.5% |
| 2037 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 6859444 | 282.4% |
| 2038 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 7567505 | 301.2% |
| 2039 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 8275567 | 320.0% |
| 2040 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 8983629 | 338.8% |
| 2041 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 9691691 | 357.7% |
| 2042 | 688186 | -19876 | 0 | 708062 | 0 | 708062 | 10399753 | 376.5% |
| Total | 13763717 | -397520 | 0 | 14161237 | 0 | 14161237 | 10399753 | 376.5% |

*Figure* 62: PVsyst economic analysis: Financial results and Carbon Savings (a)

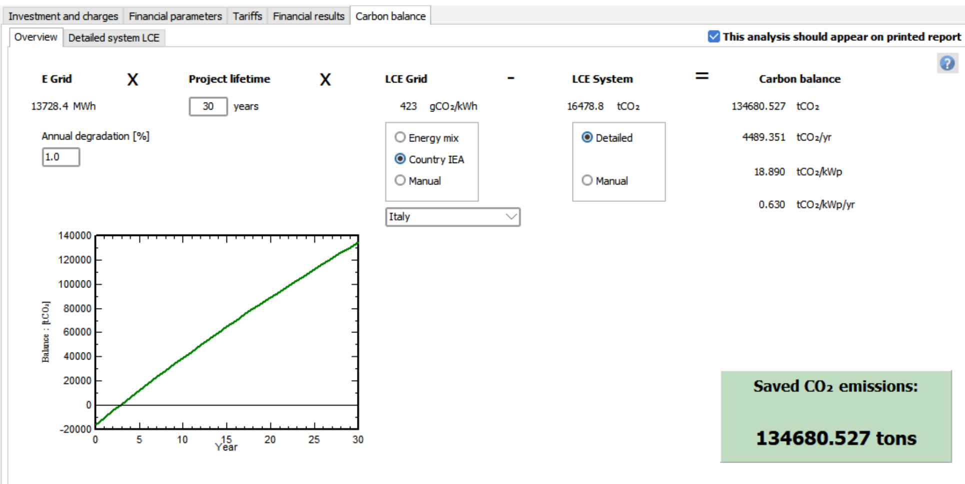



*Figure* 63: PVsyst economic analysis: Financial results and Carbon Savings (B)

Going back to the "simulation result window" now it is possible to click on "report" to print a PDF file on which are reported all the information about the plant just simulated.

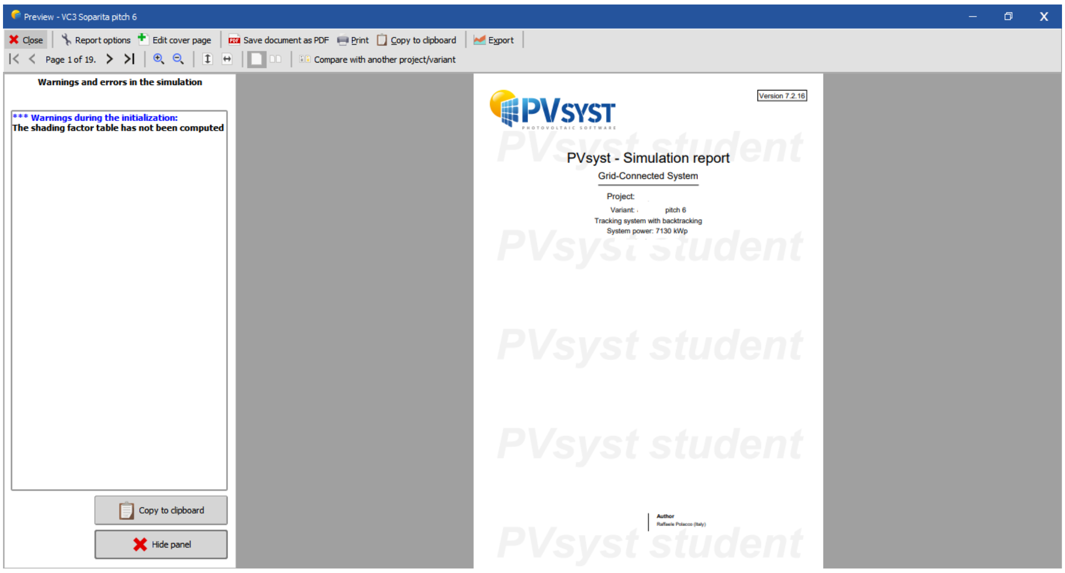



*Figure* 64: first page of the simulation report from PVsyst

## 4.3 Calculation of crop yield in case of shadowing

The calculation of the crop yield is a result that interest a long series of variables: sensitivity of the crop to the temporal/spatial intensity of shade, weather conditions, microclimate factors, irrigation/rain amounts, temperature, humidity, minerals in the terrain, are only some of them. Moreover, the variables change for each crop specie, so there is a proper set of constrains for each crop.

Since this thesis is focused on the agrivoltaic technology, the purpose of the crop yield modelling is not the faithful representation of the crop life cycle, rather it is the research of experimental approach to find the way the crops and the PV modules interact with each other, influencing their productivity.

The modelling approach starts from the consideration according to which the crops under the PV plant, experiment a micro clime different from the one of the whole sites. The main factor that influences the clime alteration under the panels is the shadowing. So, among all the possible parameters, the shadowing is the dominant one. The shadowing effect is evaluated as the fraction of the usual irradiation that the crop would receive. Following this approach, it has been adopted a model already present in literature. The model proposed in the scientific article "*Agrivoltaic Farm Design: Vertical Bifacial vs. Tilted Monofacial Photovoltaic Panels*" by Rehan Younasa et al. is based on the same observations listed above. According to the Rehan Younasa's model (from now on referred as *Crop Model*) the crop yield can vary under the local climate of an AV farm as compared to an open farm.

In the *Crop Model* among various factors, the effect of the intensity of radiation is the most dominant for crops grown in an AV farm as assessed by Marrou in [33]. In the *Crop Model* it is assumed a linear relation between crop yield and the shade intensity. This may not apply in general to every crop but could be a good approximation for a set of crops as demonstrated in [34], where for durum wheat yield in an AV farm there is a good linear correlation to a broad range of photosynthetically active radiation (the spectral range of solar radiation from 400 to 700 nm.) at various panel densities.

The *Crop Model* computes the agricultural production as a fraction of the crop yield in the traditional plants.

$$Y_c(AV) = Y_c(TR) \cdot P \tag{36}$$

$$Y_c(AV) = Y_c(TR) \cdot [m \times R_{GR} + (1 - m)] \tag{37}$$

- P is the ratio of $Y_c(AV)$ and $Y(TR)$
- $Y_c(AV)$ is the crop yield in the AV plant
- $Y_c(TR)$ is the crop yield for a traditional crop plant
- $m$ is the crop sensitivity to shadowing.

The sensitivity to shadowing is in the range $[0 - 1]$, the lower it is, the less are the effect of shadowing on the crop production (when *m* is close to 0, the shadow effects on the crops are negligible).

The *Crop Model* is based on two variables, so there are a lot of possible output. Here, to represent the trend of this model, the set of values in the table 4 is proposed:

*Table* 4 crop model example

| Shadow sensibility | Solar radiation | Yield |
|---|---|---|
| $m$ | $R_{GR}$ | Y |
| 1 | 0 | 0 |
| 0.9 | 0.1 | 0.19 |
| 0.8 | 0.2 | 0.36 |
| 0.7 | 0.3 | 0.51 |
| 0.6 | 0.4 | 0.64 |
| 0.5 | 0.5 | 0.75 |
| 0.4 | 0.6 | 0.84 |
| 0.3 | 0.7 | 0.91 |
| 0.2 | 0.8 | 0.96 |
| 0.1 | 0.9 | 0.99 |

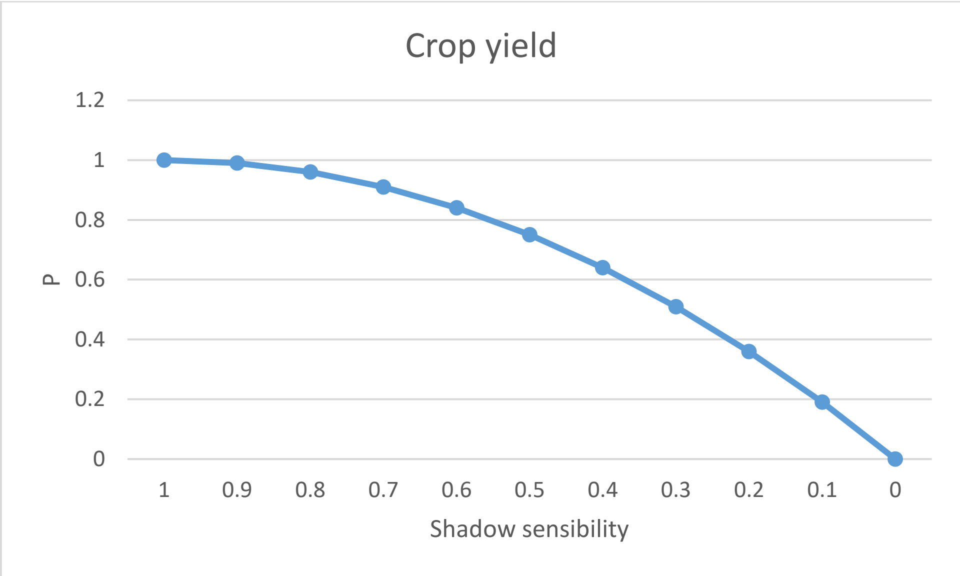



*Figure* 65: AV crop production as a fraction of the traditional

## 4.4 Land saving calculation

The agrivoltaic technology allows to better exploit the available land, providing the possibility to doubly harvest from the sun. The land saving has been evaluated as indicated in [34], with the Land Equivalent Ratio (LER). LER is a dimensionless parameter used in literature to evaluate the performance of AV farms:

$$LER = \frac{E_{AC}(AV)}{E_{AC}(PV)} + \frac{Y_c(AV)}{Y_c(TR)} \tag{38}$$

Where:

- $E_{AC}(AV)$ is the estimated annual electricity production per hectare (GWh/year/ha) from the simulated agrivoltaic system
- $E_{AC}(PV)$ is the estimated annual electricity production from a traditional PV plant (GWh/year/ha).
- Yc(AV) is the estimated crop yield in the AV system,
- Yc(TR) is the estimated crop yield in a traditional field.

In this thesis the energy produced by the photovoltaic plant, both in the agrivoltaic and in the traditional layout, is computed by the PVsyst software using the approach described in paragraph 2.9.

The LER is useful to compare the ground use considering two different methods of production. The LER expresses in easy way the amount of soil that is saved using the following relation:

$$L_{saved} = (LER - 1) \cdot L_{AV} \tag{39}$$

Where:

- $L_{saved}$ is the amount of land saved using the AV system
- $L_{AV}$ is the land used in the AV application

As an example, consider specific production per unit of land for the traditional plants. Define and the agrivoltaic yield as a percentage of the photovoltaic and agricultural yield. For sake of simplicity fix the agricultural yield for the AV equal to the 70% of the traditional production, but in the analysis produced in the “case study” it is evaluated thanks to the *Crop Model*. In *table 5* are reported the LER and the percentage of saved land as the PV production from the AV increases.

*Table* 5 LER and land saved using the AV technology

| Traditional production | | Agrivoltaic production | | LER | Land saved |
|---|---|---|---|---|---|
| PV | Crop | PV | Crop | - | - |
| 100% | 100% | 10% | 70% | 0.8 | -20% |
| 100% | 100% | 20% | 70% | 0.9 | -10% |
| 100% | 100% | 30% | 70% | 1 | 0% |
| 100% | 100% | 40% | 70% | 1.1 | 10% |
| 100% | 100% | 50% | 70% | 1.2 | 20% |
| 100% | 100% | 60% | 70% | 1.3 | 30% |
| 100% | 100% | 70% | 70% | 1.4 | 40% |
| 100% | 100% | 80% | 70% | 1.5 | 50% |
| 100% | 100% | 90% | 70% | 1.6 | 60% |
| 100% | 100% | 100% | 70% | 1.7 | 70% |

# Chapter 5

# 5 Techno-economic analysis of the Agrivoltaic System

The financial analysis of the agrivoltaic plants is the coupling of the agricultural and energetic activities. The different outputs are considered separately in the financial analysis reported in this work, even if the solar and agronomic sub-plants influence each other's production. The two sub-plants have in common only the voice about the rent of the land on which the plant will be situated. In the following paragraphs all the technical elements needed for a proper AV system are reported, analyzed and discussed in order to take a picture of the financial resources requested for this kind of plants.

### 5.1.1 Technical elements of the PV plant

In this paragraph are described the components and the related works that globally make up the agrivoltaic plant:

1. Electrical
2. Mechanical systems
3. Special systems
4. Monitoring and control system
5. Civil works
6. Hydraulic works
7. Environmental mitigation and insertion system

The electrical system of an AV system consists of an MT line (voltage in the order of 20 kV) that flows into a user cabin, which in turn is connected to a delivery booth; the latter, finally, will be connected to the Primary e-distribution Cabin. For the purpose of connection to the medium voltage network, the user must provide two rooms, one for delivery where only access to e-distribution personnel is allowed and one for energy measurement, in addition another room may be included at the user's sole disposal, where the transformation of electricity can take place.

The electrical substation is a part of the electrical system that houses the terminations of the transmission or distribution lines, electrical equipment and panels, transformers and in general all the devices necessary for control and protection. Electric turbines play a fundamental role, constituting nodes of the distribution network in which the transformation and sorting of energy is carried out. Depending on the function performed, a cabin can be defined as: transformer or distribution cabin. The transformer cabin is an electrical system connected to a medium voltage line (MV) and a low voltage line (LV) and consist of the set of conductors, equipment and devices designed to transform the voltage supplied by medium-voltage distribution lines (e.g., 20 kV) into voltage values suitable for supplying low-voltage lines (e.g., 220 380V).

Then there are the distribution booths that allow to derive from one or more lines of MT a greater number of lines still in MT, without operating any transformation. In general, the cabins perform both transmission and sorting functions. In addition, the cabins can be divided into public and private. The public cabins are pertaining to the electricity distribution company and power private users in single-phase alternating current at 230V or three-phase at 400V.

The private cabins are owned by the user and can power both civil and industrial users with supply from the public network in MT. For the purpose of connection to the medium-voltage network, the user must provide two rooms, one for delivery where only access to e-distribution personnel is allowed and one for energy measurement, in addition, another room may be included at the user's sole disposal, where the transformation of electricity can take place. For the plant in question, the delivery booth is equipped with power switches and disconnectors, as well as adequate TA and TV for protection and measurement; a transformer is also provided to operate the auxiliary services. The amperometric (TA) and voltametric (TV) measuring transformers are electromagnetic signal conditioners that, inserted on systems operating in alternating current, allow to reproduce the quantity of interest (voltage or current), according to a certain scale factor and without appreciable phase deviation.

Inverters are necessary for the transformation from direct current to output from alternating current photovoltaic modules necessary to enter the power produced into the national electricity grid are required inverters. The values of the input voltage and current of this equipment must therefore be compatible with those of the photovoltaic field to which it is connected, while the values of the output voltage and frequency must be compatible with those of the network of the distributor to which they are connected. Inverters for the conversion of direct current into alternating current are provided inside the skids. The skid configuration consists of a structure including:

• LV/MV transformer: necessary to raise the voltage level in the photovoltaic field in order to reduce losses due to the Joule effect during the transport of the energy produced to the delivery booth

• MV electrical panel: necessary to have the possibility to disconnect and disconnect one or more parts of the electrical system in case of failure or maintenance. The electrical panel is also used in an in-out configuration in such a way as to minimize the length of the MT lines that connect the various skids present in the system.

*Figure* 66: Skid configuration

In the following figure we can see the typical behavior of the inverter as the temperature changes; it can be seen that when the inverter exceeds 35 ° C the inverter has a decay of performance that then becomes unsustainable when exceeding 50 ° C.

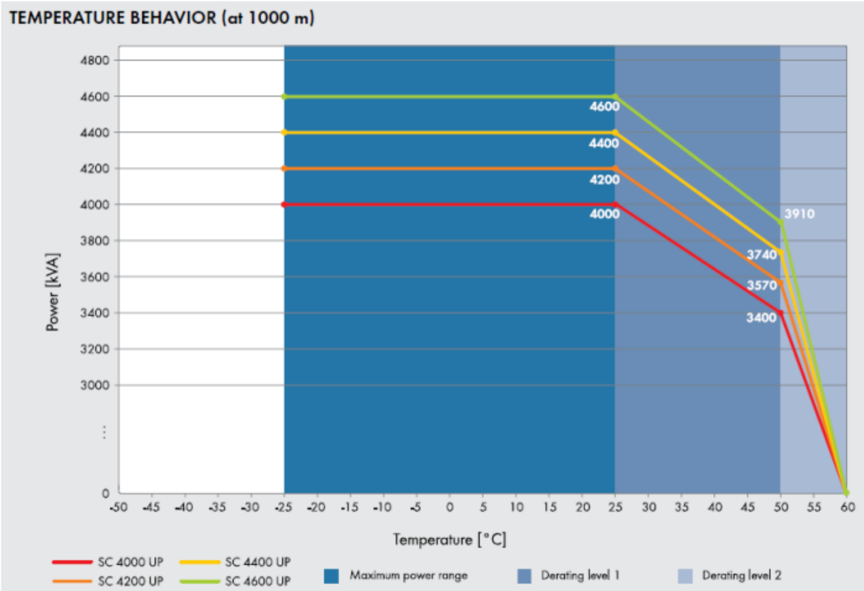



*Figure* 67: Inverter performance as temperature changes

In order to avoid overheating of the skid, the transformer is optionally equipped with a cooling system. In this text, oil-cooled transformers are considered rather than air-cooled. The compliance with the containment requirements of the oils referred to in point 3, title 2 of the DM 15/07/2014 in the skid structure is prepared a collection tank large enough to cope with damage to the transformer that can cause the leakage of all the oil.

The strings of the modules, which put in series the modules of each tracker, are connected to the inverters through combiner boxes positioned between the skids and the photovoltaic field. The electrical system of the photovoltaic system will be composed of the following main elements:

- Double-sided photovoltaic modules;
- Skid (composed of inverter, MV/LV transformer and MV panels)
- Combiner box (Low voltage electrical panels);
- User cabins
- Delivery booths;
- BT/MT lines;

The characteristic curve of the output power varies depending on the voltage value used as visible in *figure* 68.

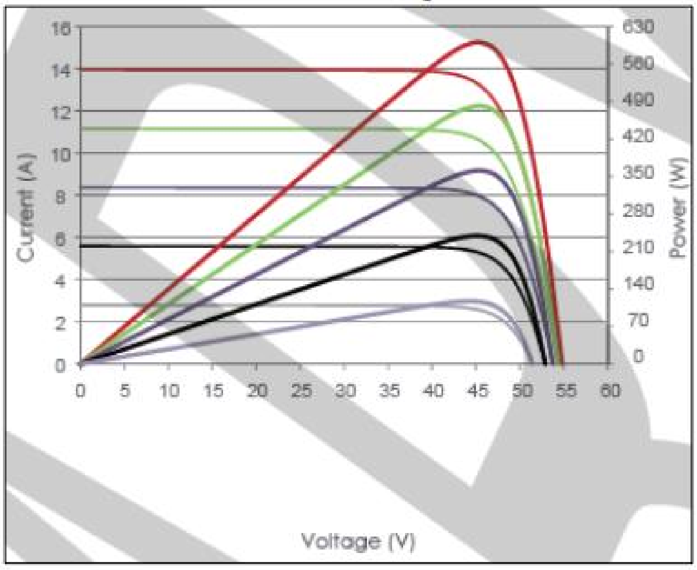



*Figure:* 68 characteristic curve of the output power variation

The photovoltaic cell works at maximum power only at a specific voltage value, losing power as soon as the real value deviates from the ideal one. However, radiation and temperature values can also influence the behavior of the photovoltaic cell. We therefore need a control system called MPPT (maximum power point tracker) which, by measuring the values of temperature and incident radiation, is able to calculate the voltage value necessary to obtain the maximum power from the photovoltaic cell.

The BT cables, used for the transport of energy from the string switchboards to the skids, take into account the fact that each section of cable has a section such that its flow rate is always higher than the current of use associated with it, so as not to have a loss of useful life of the cable itself. In addition, it must be verified that the voltage drop relative to the longest path is less than 2%. For THE BT connections, a unipolar cable designed specifically for solar applications is used, which has a compact rope conductive core with aluminum wires in accordance with IEC 60228, class 2 and insulated with cross-linked polyethylene and protected by a special ST2 quality PVC sheath. The operating temperature of this type of cables in ordinary conditions is about 90 ° C, but in case of short circuit they can also reach 250 ° C. As for the wiring of the MV network, it is verified that each stretch of cable has a section such that its flow rate is always higher than the current of use associated with it, so as not to have a loss of useful life of the cable itself. In addition, it must be verified that the voltage drop relative to the longest path is less than 2%. The agrivoltaic plant will be connected to the national electricity grid by virtue of the STMG proposed by e-distribuzione (Traceability Code T0737659).

The photovoltaic modules, if they are not installed on special fixed structures, will be held in position and orientation by suitable hot-dip galvanized steel structures, which, through servomechanisms, will allow the "pursuit" of the sun throughout its path in the vault of the sky. These are mono-axial tracking systems, so-called roll; this type of tracker, which makes a maximum rotation of +/-55°, is particularly suitable for countries such as Italy characterized by low latitudes, since in them the apparent path of the Sun is wider.

Among the different configurations taken into consideration, it was evaluated that, in order to avoid the problem of mutual shading that with chasing rows would occur at dawn and dusk, the technique of backtracking will be used: the modules will follow the movement of the Sun only in the central hours of the day, reversing the movement close to sunrise and sunset, when they reach a perfectly horizontal alignment. With the backtracking the energy production increase of about the 15%. The negative aspect of the backtracking is that early in the morning and late in the afternoon, when the sun is near the horizon line, the movement induced by the backtracking system will generate a loss of the perpendicular radiation on the modules.

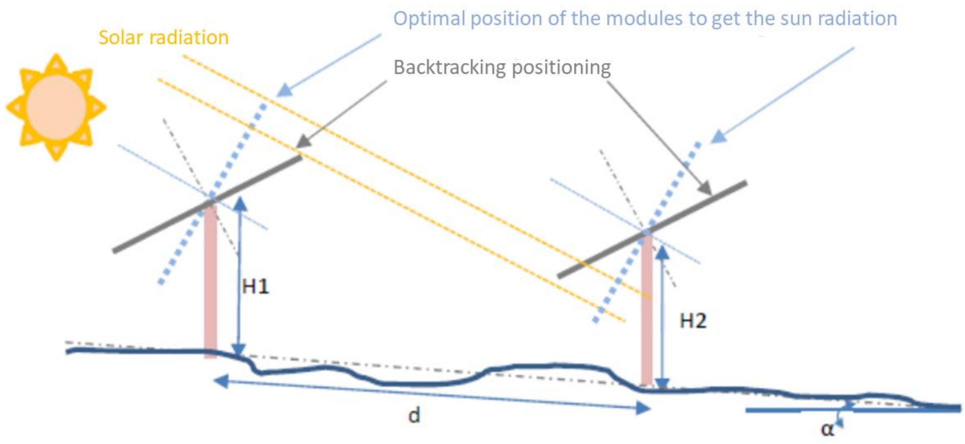



*Figure:* 69 How backtracking works

The support structure is connected to the ground through the motorized pole. The theoretical increase in energy production offered by these pursuers is around 15-20% compared to plants with fixed structures. The operational settings in the rotation of the photovoltaic modules also allow the movement for inspection and maintenance and the movements for washing the modules.

The SCADA (Supervisory Control And Data Acquisition) system is used to carry out a constant supervision of the system and is essentially made up of: a set of sensors and / or converters, which make measurements and / or variations of physical quantities (for example voltage and current of the photovoltaic generator, power output from the conversion group, temperature of the modules and radiation); a set of microcontrollers (Programmable Logic Controller or real their own computers) make measurements through the sensors to which they are connected and store the measured values in a local memory; one or more supervising computers that periodically collect data from microcontrollers, process them, store them and possibly trigger an alarm. The SCADA is therefore necessary for data acquisition; the presentation of the data; the sterilization of the data; the provision of alarms; interaction with higher-level systems.

The construction of the photovoltaic system involves the execution of civil works related to the construction and maintenance needs of the photovoltaic system itself. Reference is made to the execution of underground and above-ground artefacts, to the execution of earthmoving works as well as works in reinforced concrete. Civil works are therefore planned for the realization of:

1. Equipment for the construction phase
2. Service tracks
3. Fences
4. Cable ducts
5. Hydraulic regimentation works
6. Skids and pitches
7. User cabin and delivery booth

It should be noted that the installation of tracking systems does not involve the execution of earthmoving works consisting of excavation excavations. The tracking systems will be fixed in the ground, without the need to carry out excavations and works in cement conglomerate.

With regard to the environmental mitigation interventions of the area subject to intervention, the implementation of a perimeter mitigation band with a minimum width of 10 meters is envisaged, consisting of a shrub and tree belt with species contained in the list of species of the Ecologically Homogeneous Areas attached to the Regional Forest Plan.

### 5.1.2 Technical analysis of the agricultural activity

For the agrivoltaic application illustrated in this work, it has been chosen an olive production cultivation. Super intensive plantations need flat or slightly sloping soils (maximum 15%), which are deep and well drained. They require good water availability and reduced risks of frost damage. The super intensive olive plantations provide for the installation of more than 1500 trees for each hectare of cultivated land [36]. Given the high planting density of the super intensive model, the most responsive cultivars are those characterized by low vigor, compact foliage, self-fertility (self-pollination), early entry into production, high productivity and oil yield, uniform (concentrated) ripening of the fruits. At the present time, there are few varieties that meet such requirements.

*Figure:* 70 Example of a traditional super-intensive olive grove entirely mechanized

The cultivation that give the best results are the Arbequina olive tree. The plants used for very high-density plants are obtained by self-rooting from cuttings, are bred in small pots (7×7× 10 cm) and are planted at an age of 6-8 months, when they have a height of 40-60 cm. The planting of the seedlings can be carried out manually or mechanically with transplanters capable of planting 5,000-8,000 plants / day.

The height of the plants can reach levels above 3 m as long as the last stretch is represented by flexible vegetation that therefore does not break when the excavator passes. Taken together, the plants form a wall of continuous vegetation starting from the 2nd-4th year after planting. In the first 2-3 years, the ramifications in the basal 60-70 cm of the stem must be eliminated, in order to allow the closure of the interception system of the fruits of the excavating machines. The dimensions of the plants to allow easy use of the excavators is 2.5-3.5 m in height and 1.0-1.5 m in width.

At the end of the 2-3rd year it is important to start eliminating the lateral branches of relatively large diameter. In the following years it will be necessary to continue to ensure the renewal of the lateral ramifications in order to avoid the formation of large diameter branches. At the 4th-6th year a passage should be made with a mechanical pruner to cut the highest part (topping) at a height of 2-3 m to contain the development of the trees and therefore allow an easier action of the machine for the execution of the harvest. Subsequently, when the foliage reaches a volume of about 10,000 m3 / ha (5 ° -7 ° year), more intense pruning interventions are necessary to ensure conditions of good lighting and aeration of the foliage. Overall, with mechanical and manual interventions, the development of the foliage in height and width must be contained within the limits required by the excavator machine and promote good lighting of the vegetation and PV modules.

### 5.1.3 Financial analysis of the agrivoltaic activity

The cost analysis for the agrivoltaic plant has been performed using the discounted cash flow method (DCF). The Discounted cash flow is an evaluation method used to estimate the value of an investment basing on its expected future cash flows. DCF analysis attempts to figure out the value of an investment today, relying on projections of how much money it will generate in the future. The investment results convenient if at the end of the analysis the revenues are bigger than the costs. The expenditures of the activity can be divided in CAPEX and OPEX. The CAPEX (CAPital EXpenditure) is a cash flow that a company employs to purchase, maintain or implement its operating fixed assets, such as buildings, land, plant or equipment. The OPEX (OPerational EXpenditure) is the cost necessary to manage a product, a business or a system otherwise called O&M (Operation and Maintenance) costs or operating and management costs. The most important results of the analysis are the net present value, the internal rate of return, the payback period and the return-on-investment ratio.

The NPV is the most widely used criterion in the economic evaluation of investment projects as it is very flexible and user-friendly. The NPV of the investment is the algebraic sum of all discounted cash flows, generated by the project under consideration. NPV represents the incremental wealth generated by a project, expressed as if it were immediately available. If the NPV were to assume negative values, instead of generating value it would destroy it and therefore the investment would not be profitable. On the other hand, a positive NPV testifies to the ability of a project to free up flows of sufficient size to repay the disbursement, remunerate the capital used in the operation, and still leave residual resources.

The NPV can be computed as follows:

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \tag{40}$$

Where:

- $R_t$ is the net cash inflow-outflows during a single time step
- $t$ is the time step considered in the analysis

- $i$ is the interest rate charged to commercial banks and other financial institutions

The internal rate of return (IRR) is a parameter used in financial analysis to estimate the profitability of potential investments. The IRR can be defined as a discount rate that makes the NPVV of all cash flows equal to zero in a discounted cash flow analysis. IRR calculations rely on the same formula as NPV does, but the is not the actual money value of the project, it is the annual return that makes the NPV equal to zero. The higher an internal rate of return is, the more convenient an investment is considered.

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1 + IRR)^t} - C_0 \tag{41}$$

Where:

- $C_t$ is the net cashflow during the period t
- $C_0$ is the total initial investment cost
- $IRR$ is the internal rate of return
- $t$ is the number of time periods

When comparing investment options with other similar characteristics, the investment with the highest IRR probably would be considered the best.

The Pay Back Period is a method that is frequently used by companies for its simplicity of calculation; allows you to calculate the time within which the capital invested in the purchase of a medium-long cycle of use production factor is recovered through the net financial flows generated.

$$PB = \frac{C_{out}}{C_{in}} \tag{42}$$

Where:

- PB is the payback period
- $C_{out}$ is the total expenditure
- $C_{in}$is the net cashflow

Among alternative investments, the one with a shorter "recovery period" will be chosen, as from that moment on, the instrumental asset will contribute to the formation of gross profits.

The Return on Investment (ROI) is the trace of return on the total investments of a company. It is one of the most frequently used balance sheet indices in profitability analysis. It is obtained by making the ratio between the operating result and the total net operating invested capital. The numerator is the result of the characteristic operations, excluding income and expenses related to extraordinary operations; the denominator is the sum used only in the investments characteristic of the business activity net of the respective amortization funds and any provisions.

$$ROI = \frac{inv}{C_{out}} \tag{43}$$

Where:

- $inv$ is the total investment gain

ROI is an indicator of efficiency in the use of the resources available to the company to produce profits through its characteristic activity.

In order to perform the financial analysis, here below are reported the costs for the photovoltaic and the agricultural activity.

*Table 6* cost analysis of the photovoltaic activity

| Category | Item | Price | Unit |
|---|---|---|---|
| MODULE | PV module | 138 | €/piece |
| | Tracking system | 2'000 | €/piece |
| INVERTER | SKID | 40 | €/W (inverter) |
| OTHER COMPONENTS | Other items | 48'800 | € |
| INSTALLATION COSTS | MT cable | 1'500 | € |
| | Delivery cabin | 7'000 | € |
| | Arriving/Departing line | 35'000 | € |
| | MT positioning | 318'866 | € |
| LAND COSTS | Cables | 20'096 | €/ha |
| | Fencing | 3'782 | €/ha |
| | Building Site | 7'000 | €/ha |
| | Regimentation | 1'183 | €/ha |
| | Interference | 4'600 | €/ha |

| | | | |
|---|---|---|---|
| | Lighting | 378 | €/ha |
| | Video Surveillance | 5'000 | €/ha |
| | Mitigation | 5'600 | €/ha |
| | Other Expenditure | 28'724 | €/ha |

*Table 7* cost analysis for the olive plant per hectare

| **Item** | **Quantity** | **Unit** |
|---|---|---|
| Cost of trees | 1611 | €/ha |
| Soil preparation | 300 | €/ha |
| Fertilization | 250 | €/ha |
| Tree supports | 200 | €/ha |
| Irrigation plant | 1000 | €/ha |
| Manpower | 600 | €/ha |
| Total plant cost | 4461 | €/ha |

The olive production starts at the third year since the first 2 years the trees are too young to produce fruits. The production of the trees increases from year 3 to year 6 when the regime production is matched.

*Table 8* olive production per hectare

| | **Year 3** | **Year 4** | **Year 5** | **Year 6** |
|---|---|---|---|---|
| Tree production capacity (%) | 0.5 | 0.8 | 0.9 | 1 |
| Olive production (kg) | 4585 | 7336 | 8253 | 9170 |
| Oil production (l) | 677.2155 | 1123.676 | 1309.283 | 1504.923 |

*Table 9* olive production cost per hectare

| Olive production costs | Year 3 | Year 4 | Year 5 | Year 6 |
|---|---|---|---|---|
| Agricultural operations (€/ha) | 225 | 300 | 375 | 450 |
| pesticides and fertilizers (€/ha) | 350 | 350 | 350 | 350 |
| Irrigation (€/ha) | 350 | 350 | 350 | 350 |
| Pruning and harvesting (€/ha) | 1000 | 1000 | 1000 | 1000 |
| Total Production cost(€/ha) | 1925 | 2000 | 2075 | 2150 |

Total production cost year 1 and 2 925

*Table 10* oil production cost per hectare

| Oil production costs | Year 3 | Year 4 | Year 5 | Year 6 |
|---|---|---|---|---|
| Total transformation cost (€/ha) | 550.2 | 880.32 | 990.36 | 1100.4 |

The revenues of the AV plant are computed considering the production of electricity and oil/olive. The selling cost of the electricity considered in this work is 0.5 € cents per kWh. About the agricultural activity, the olives are sold at 0.5 €/kg and the oil at 5.5 €/l.

# Chapter 6

# 6 Case Study in Southern Italy

## 6.1 Description of the AV plant

The agrivoltaic plant presented in this analysis is located in Southern Italy. The layout of the photovoltaic part of this system is the result of a comparative study between different configurations. In order to find the best possible configuration of the plant, there have been considered 2 variables: the distance among the PV strings, and the technology of the modules (tracking or fixed). About the distance, there have been considered two configurations, called from here on CONF#A and CONF#B, characterized respectively by a pitch distance, of 6m and 7.5m.

For the comparison of fixed module technology and tracking modules technology, it has been used the CONF#B as reference case. While for the comparison of configuration Conf#A and CONF#B, the tracking modules technology has been used. These comparisons will be deepened in the following paragraphs, since it is not enough to consider only the manufacturability of the photovoltaic system to decree the best configuration, but it is necessary to consider the effect that a denser layout of modules has on agricultural production, compared to a layout with modules separated by greater distances.

As far as the photovoltaic system is concerned, the module considered is the same for each configuration and each technology. Bifacial N-type double-sided photovoltaic modules are used in this AV application. N-type modules allow the achievement of greater efficiency than the most common P-type cells. N-type cells are constructed with the negatively charged side as the base of the solar cell. The most powerful solar cells currently available on the market are the n-type ones due to the fact that the land n-type cells are also less subject to the metal impurities of silicon, but above all due to the absence of the boron-oxygen combination. In the presence of boron-doped silico, oxygen forms an area of recombination, known as a defect due to the combination of boron-oxygen, which damages its efficiency. Using n-type cells doped with phosphorus, this defect disappears.

The photovoltaic module used in the AV plant of this work, has the technical specifications listed in the table 11 both for CONF#A and CONF#B or tracking and fixed system.

*Table 11* Technical specifications photovoltaic module

| FEATURE | QUANTITY | UNIT |
|---|---|---|
| Type of double-sided module Power | 610 | W |
| Number of cells | 2x78 | |
| Dimensions (L x H x S) | 2465 x 1134 x 35 | mm |
| Weight | 34 | kg |
| Maximum power (Pmax) | 610 | Wp |
| Voltage at maximum power (Vmp) | 45.73 | V |
| Current at maximum power (Imp) | 13.17 | A |
| Open circuit voltage (Voc) | 55,04 | V |
| Short circuit current (Isc) | 14.11 | A |
| Module efficiency | 21.82% | |
| Temperature coefficient Pmax | -0,3 | %/°C |
| Temperature coefficient of Voc | -0,28 | %/°C |
| Temperature coefficient of Isc | 0.048 | %/°C |

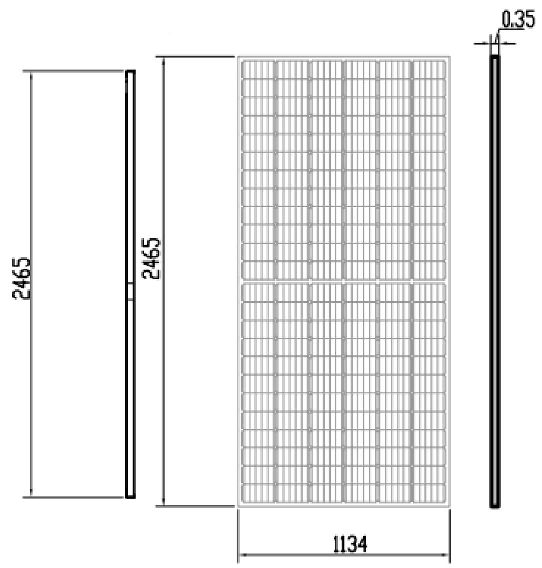



*Figure* 71: representation of the selected module

In the #A configuration (CONF#A), the pitch distance is 6 m, while in CONF#B, the distance is 7.5 m. These numbers are calculated to ensure a minimum safety distance of about 1m for the harvesting machine to work on the tree lines. The dimension of harvesting machine has been chosen considering the *figure 72*.

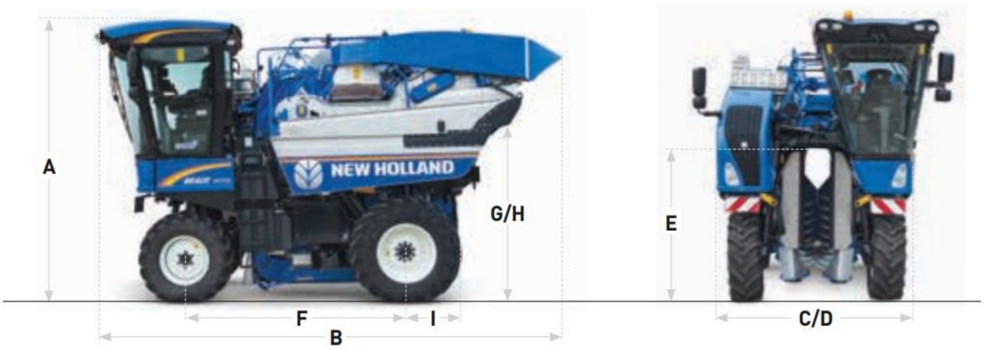



*Figure* 72: Harvesting Machine

| | 9070M | 9050L | 9050L Plus | 9070L | 9070L Plus | 9090L Plus |
|---|---|---|---|---|---|---|
| Front tire | 340-85R24 / 400-80R24 / 420-70R24 | 340-85R24 / 420-70R24 / 400-80R24 | 420-70R24 / 400-80R24 | 340-85R24 / 420-70R24 / 400-80R24 | 420-70R24 / 400-80R24 | 400-80R24 |
| Rear tire | 440-80R28 / 480-70R28 | 440-80R28 / 480-70R28 / 540-65R28 / 600-65R28 | 440-80R28 / 480-70R28 / 540-65R28 / 600-65R28 | 440-80R28 / 480-70R28 / 540-65R28 / 600-65R28 | 440-80R28 / 480-70R28 / 540-65R28 / 600-65R28 | 440-80R28 / 480-70R28 / 540-65R28 / 600-65R28 |
| **A** [m] | 3,69 | 3,69 | 3,93 | 3,69 | 3,93 | 3,93 |
| **B** [m] | 6,0 | 6,0 | 6,0 | 6,0 | 6,0 | 6,0 |
| **C** [m] | 2,79 | 2,99 | 2,99 | 2,99 | 2,99 | 2,99 |
| **D** [m] | 2,30 | 2,53 | 2,53 | 2,53 | 2,53 | 2,69 |
| **E** [m] | 2,00 2,60 | 2.00 2,60 | 2,20 2,97 | 2,00 2,60 | 2,20 2,97 | 2,20 2,97 |
| **F** [m] | 2,93 | 2,93 | 3,05 | 2,93 | 3,05 | 3,05 |
| **G** [m] | 2,70 | 2,70 | 3,10 | 2,70 | 3,10 | 3,10 |
| **H** [m] | 2,88 | 2,88 | 3,28 | 2,88 | 3,28 | 3,28 |
| **I** [m] | 650 | 650 | 650 | 650 | 650 | 650 |

*Figure* 73: Harvesting machine datasheet

The values C and D represent the minimum and maximum size, in which it changes the position of the harvesting box: lateral or posterior. The distance needed by the harvester is minimum 2.3 m and maximum 2.99 m. In CONF#A the harvesting machine can pass through the trees leaving 1m or more distance from the modules only if the structures are temporary set in vertical position. On the other hand, in CONF#B the harvester can pass through the trees lines even if the modules are at 0°. Since the CONF#A need to be modified during the harvesting phase, the fixed modules are applied only to the CONF#B.

Both configurations have been considered with horizontal axis and a maximum rotating angle of 55°.

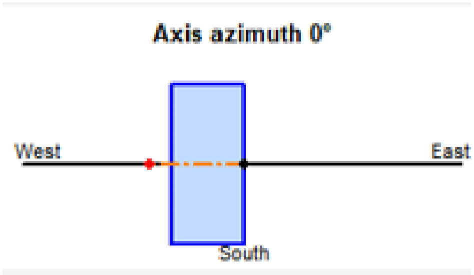



*Figure* 74: axis of the modules

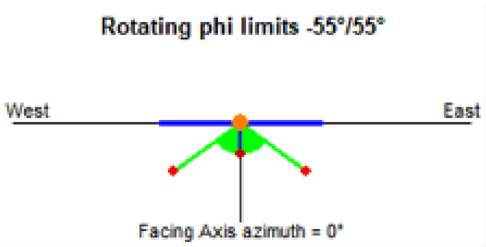



*Figure* 75: rotating angle of the modules

A clear representation of the line-to-line distance is illustrated in figures 76 and figure 77.

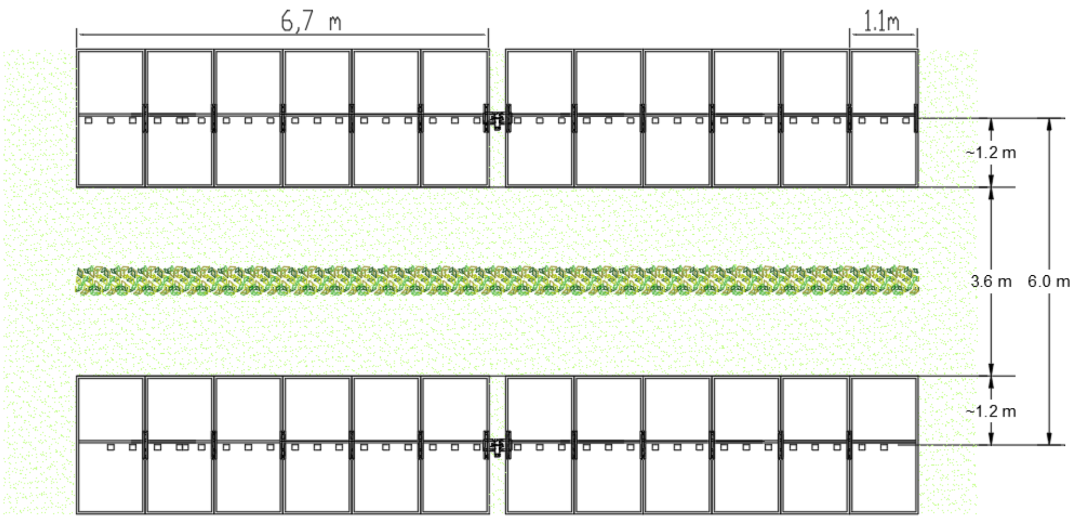



*Figure* 76: aerial view of the CONF#A with modules at 0°

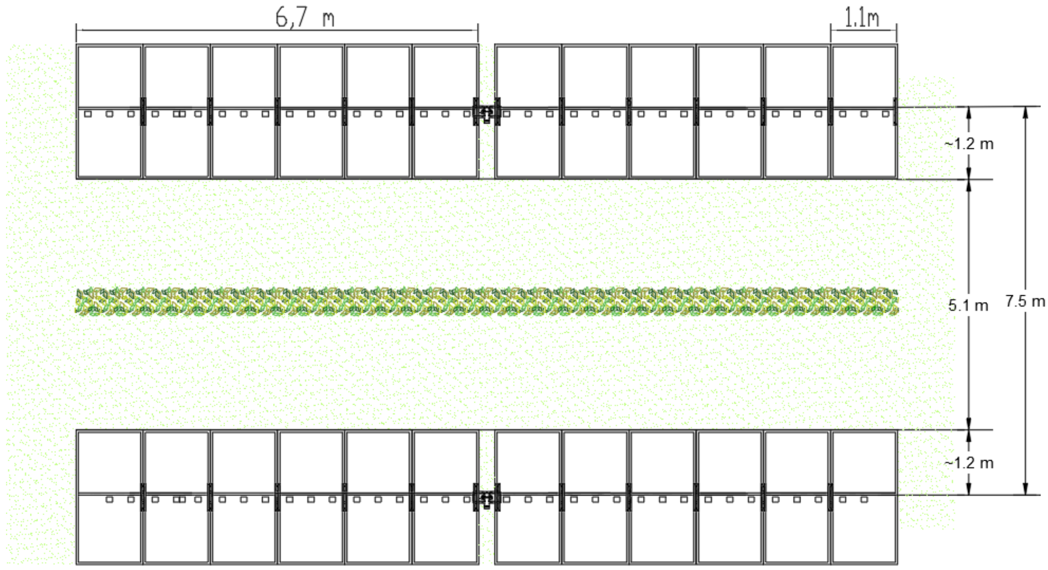



*Figure* 77: aerial view of the CONF#B with modules at 0°

The agrivoltaic plant is illustrated in figures from 75 to 77, but the main technical features are also listed in the table below.

*Table* 12 AV plant configurations technical features

| | CONF#A tracking | CONF#B tracking | CONF#B fixed |
|---|---|---|---|
| Maximum module height | 4.0 m | 4.0 m | 3.8 m |
| Shaft height | 3.0 m | 3.0 m | 3.0 m |
| Minimum module height | 2.0 m | 2.0 m | 2.4 m |
| Tree-shaft distance | ~ 2.5 m | ~ 3.3 m | ~ 3.3 m |
| Tree-module distance | ~ 1.8 m | ~ 2.6 m | ~ 2.25 m |
| Pitch distance | 6.0 m | 7.5 m | 7.5 m |
| Tilt angle | ±55° | ±55° | 30° |

The tracking system considered is mono-axial horizontal solar tracker with a rotation angle equal to ± 55 ° and configuration 1P. There are 24 modules in series for each tracker. The soil below the trackers must have a steepness up to 17% N-S; and any slope E-O. The fixed modules are in series of 24 and are tilted of 30°, since the PV plant is situated in the southern Italy at a latitude of about 40°.

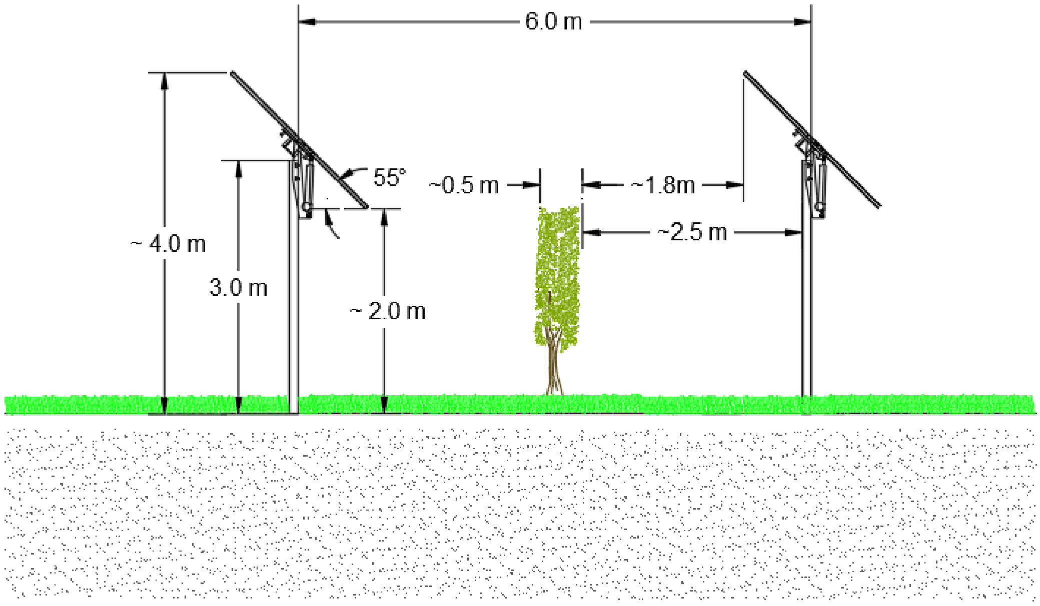



*Figure* 78: AV plant in CONF#A with tracking system

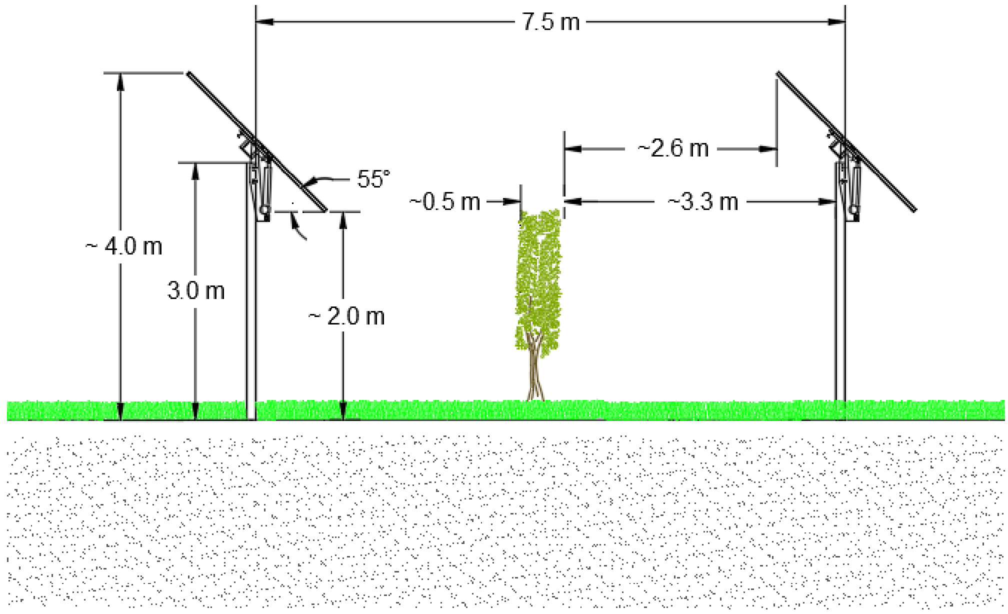



*Figure* 79: AV plant in CONF#B with tracking system

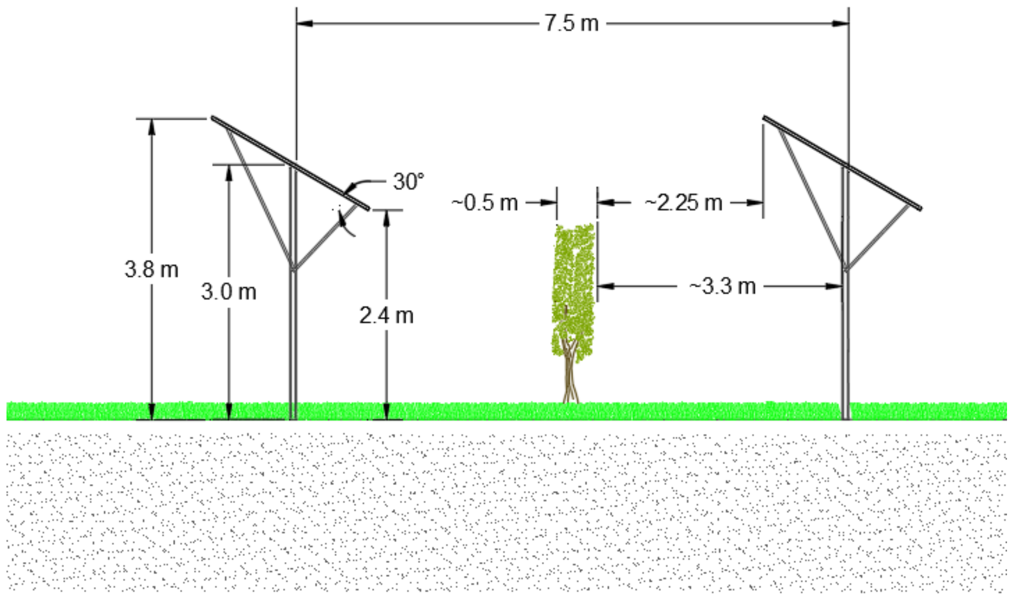



*Figure* 80: AV plant in CONF#B with fixed system

Both configurations have central inverters with a skid system, including MV switchboards, transformers and low-voltage cabinet. In CONF#A, the nominal power of the photovoltaic field is 7.13 MW. The number of modules is 11688 and each string includes 24 modules connected in series, with a nominal voltage of 43 V per module reaching the total voltage of 1032 V for each string.

For CONF#A it is planned to install 2 inverters, the first 4200 kW and the second 2500 kW. The values of the input voltage and current of this equipment must be compatible with those of the photovoltaic field to which it is connected, while the values of the output voltage and frequency must be compatible with those of the network of the distributor to which they are connected. In particular, the inverters intended to be used have the following characteristics:

*Table 13* Inverter 2500 kW technical features

| General features | | |
|---|---|---|
| Nominal Power | 2500 | Kva |
| Dimensions (W / H / D) | 2780 / 2318 / 1588 | mm |
| Weight | <3400 | Kg |
| Losses (max / average / standby) | < 8100 / < 1800 / < 2000 W | |
| Temperature of use | From -25 to +60 | °C |

| | | |
|---|---|---|
| Efficiency (max / European / CEC) | 98.8% / 98.3% / 98.0% | |
| DC side | | |
| Degree of protection of electronics | IP65 | |
| Lightning protection | Level 3 | |
| Noise emissions | 67 | Db |
| Minimum voltage | 778 | V |
| Maximum voltage | 1500 | V |
| Maximum current (at 35 °C) | 3200 | A |
| Maximum short circuit current | 6400 | A |
| Number of inputs | 24 | |
| AC side | | |
| Rated current | 2624 | A |
| THD at rated power | < 3 % | |
| Nominal voltage | 600 | V |
| Voltage range | From 440 to 660 | V |
| Frequency | 50 | Hz |
| Frequency range | From 47 to 53 | Hz |
| Power factor | 0.8 in overexcitation to 0.8 in sub excitation | |

In CONF#B the nominal power of the generator is 5.68 MW. There are 9312 modules, each string has 24 modules, and there are 194 strings for both the two converters, each one with nominal power of 2750 kW. The technical features of the inverter are reported in the following table.

*Table 14* 2750 kW inverter technical features

| General features | | |
|---|---|---|
| Nominal Power | 2750 | Kva |
| Dimensions (W / H / D) | 2780 / 2318 / 1588 | mm |
| Weight | <3400 | Kg |
| Losses (max / average / standby) | < 8100 / < 1800 / < 2000 W | |
| Temperature of use | From -25 to +60 | °C |
| Efficiency (max / European / CEC) | 98.8% / 98.3% / 98.0% | |
| DC side | | |
| Degree of protection of electronics | IP65 | |
| Lightning protection | Level 3 | |
| Noise emissions | 67 | Db |

| | | |
|---|---|---|
| Minimum voltage | 778 | V |
| Maximum voltage | 1500 | V |
| Maximum current (at 35 °C) | 3200 | A |
| Maximum short circuit current | 6400 | A |
| Number of inputs | 24 | |
| AC side | | |
| Rated current | 2624 | A |
| THD at rated power | < 3 % | |
| Nominal voltage | 600 | V |
| Voltage range | From 440 to 660 | V |
| Frequency | 50 | Hz |
| Frequency range | From 47 to 53 | Hz |
| Power factor | 0.8 in overexcitation to 0.8 in sub excitation | |

In each configuration, after the inverter it is installed a proper transformer in order to bring the voltage to MT levels (1KV to 35 kV) to decrease the amount of losses in the transmission line.

In the present work, the analysis of the shadow effects on crop production is performed for Arbequina plants, which produce olives and olive oil. This variety of olives, native from Spain, are suitable for intensive and super-intensive cultivation. The growth of these plants goes from the first two years, when the plant does not produce fruits, to the $6^{th}$ year, when the complete production is reached. The production rises from $3^{rd}$ to the $6^{th}$ year; then, it is constant for all the life of the tree. The sizes of the tree are 2.5÷3.5 m in width, and ≈6 m in height (not pruned) [19]. For the application described in this analysis, the tree would be pruned at 2/2.5 m, avoiding any shadows on the PV modules since the modules are at 3 m above the ground. During the harvesting phase, the machine moves between the string passing on the olive trees through the brushes located in the lower part of the vehicle, as shown in *figure 81*.

*Figure* 81: Example of harvesting phase [36]

For this AV application the trees are set side by side with the PV strings. In a hectare, there are 83 rows of plants of different lengths; each olive tree is 1.2 m far from the following one, and the trunks are at more than 2.5 m from the edges of the PV modules, so at more than 5 meters from the parallel line of trees.

## 6.2 Analysis of the crop production

The crop production of the Arbequina trees follows a development path from the year 1 to the year 5. For the first 2 years the trees do not produce any fruits, from year 3 to year 5 the productivity increases from 50% to 90%, finally in the sixth year the olive production reaches its nominal rate. The evolution of the production through the years is represented in the table below:

*Table 15* agricultural nominal production for CONF#A and #B

| | m=0 | | | | | |
|---|---|---|---|---|---|---|
| Year | 1 | 2 | 3 | 4 | 5 | 6 |
| olive [kg] | 0.0 | 0.0 | 4585.0 | 7336.0 | 8253.0 | 9170.0 |
| olio [l] | 0.0 | 0.0 | 677.2 | 1123.7 | 1309.3 | 1504.9 |

The crop disposition in the two configurations does not change since in CONF#A there is only a row of trees more than in CONF#B, leading to a nominal production that actually is the same. What changes from a configuration to another is the shadowing of the modules on the crops. This effect is higher if there are more modules and tighter, so in the CONF#A.

The model described in the paragraph 5.3 was applied to the olive and oil production from Arbequina trees of the plant described in the chapter 7. The parameter “global radiation on ground” is given by PVsyst® and is computed in the model as a fraction of the radiation on ground without any obstacles/modules: for the CONF#A the ground radiation is the 48%; for the CONF#B is 58%. For the CONF#A the pitch distance is 6m, so the shadowing contribution on the crops is higher than in the CONF#B where the pitch distance is 7.5m. Since there is not any agronomic study about the shadow sensibility of the Arbequina trees, the cases taken into account in the model, are the following: m=0 (no sensitivity to shadowing), m=0.5 (average sensitivity to shadowing), and m=1 (maximum sensitivity to shadowing).Considering the effect of shadowing the production is modified as follow:

*Table* 16 agricultural production when the shadowing effect medium affecting the crops

| | CONF#A : m=0.5 | | | | | |
|---|---|---|---|---|---|---|
| Year | 1 | 2 | 3 | 4 | 5 | 6 |
| olive [kg] | 0.0 | 0.0 | 3382.9 | 5412.6 | 6089.1 | 6765.7 |
| olio [l] | 0.0 | 0.0 | 499.7 | 829.1 | 966.0 | 1110.3 |

| | CONF#B: m=0.5 | | | | | |
|---|---|---|---|---|---|---|
| Year | 1 | 2 | 3 | 4 | 5 | 6 |
| olive [kg] | 0.0 | 0.0 | 3612.0 | 5779.1 | 6501.5 | 7223.9 |
| olio [l] | 0.0 | 0.0 | 533.5 | 885.2 | 1031.4 | 1185.5 |

*Table 17* agricultural production when the shadowing effect affect the most the crops

| | CONF#A: m=1 | | | | | |
|---|---|---|---|---|---|---|
| Year | 1 | 2 | 3 | 4 | 5 | 6 |
| olive [kg] | 0.0 | 0.0 | 2180.7 | 3489.1 | 3925.3 | 4361.4 |
| olio [l] | 0.0 | 0.0 | 322.1 | 534.4 | 622.7 | 715.8 |

| | CONF#B: m=1 | | | | | |
|---|---|---|---|---|---|---|
| Year | 1 | 2 | 3 | 4 | 5 | 6 |
| olive [kg] | 0.0 | 0.0 | 2638.9 | 4222.3 | 4750.1 | 5277.9 |
| olio [l] | 0.0 | 0.0 | 389.8 | 646.7 | 753.6 | 866.2 |

*Table 18* olive and olive oil production per unit of hectare as a function of configuration and shadowing sensitivity

| | Configuration | *m*=0 | *m*=0.5 | *m*=1 |
|---|---|---|---|---|
| Olive tons (tons) | CONF#A | 92 | 68 | 44 |
| | CONF#B | 92 | 72 | 52 |
| Oil (kilo-liters) | CONF#A | 15 | 11 | 7 |
| | CONF#B | 15 | 12 | 9 |

Both CONF#A and CONF#B exhibit a linearly decreasing trend for olive production. The reference production at m=0 is about 92 tons for each configuration; it is the same in both configurations, because the shadows from PV modules on the trees lead to a negligible effect on the crop. With m=0.5, the olive production in CONF#A decreases by 26%; if m=1, production is halved with respect to the case without shadowing (m=0). With a longer distance among rows (CONF#B) and m=0.5, the production is slightly higher (relative difference is ≈6%) with respect to CONF#A. Finally, with m=1, CONF#B production is 18% higher (relative difference). In the case of oil production, the shadowing has a slightly non-linear effect. In CONF#A, an intermediate shadowing sensitivity m=0.5 leads to a relative lower production (-7%) with respect to CONF#B. Finally, with m=1, CONF#B production is 18% higher.

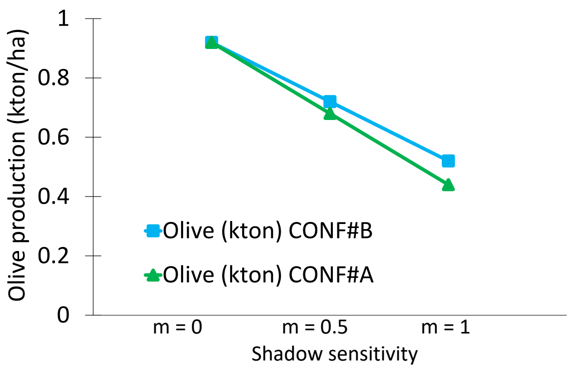



*Figure* 82 Olive production as function of the configuration and shadowing sensibility

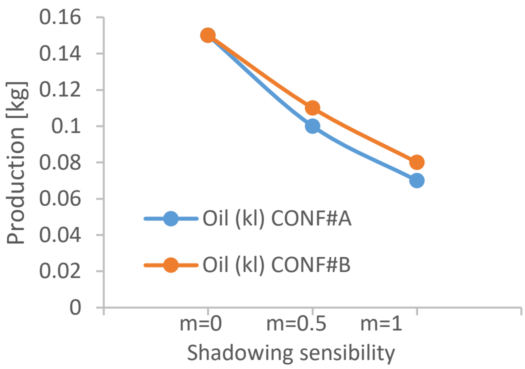



*Figure* 83 Oil production as function of the configuration and shadowing sensibility

## 6.3 Analysis of energy production

This analysis takes into account the three configurations of the agrivoltaic plant, CONF#A, CONF#B, and the traditional photovoltaic one. In the present work, the traditional PV generator used as reference has the same tracking structure as the AV systems, but the rows are installed with a minimal distance of 5 m. For the CONF#B there are 3 variations: with fixed structures; with tracking structures; with tracking structures without the backtracking.

The disposition of modules for the plant descripted in this work is represented in *figure* 84.

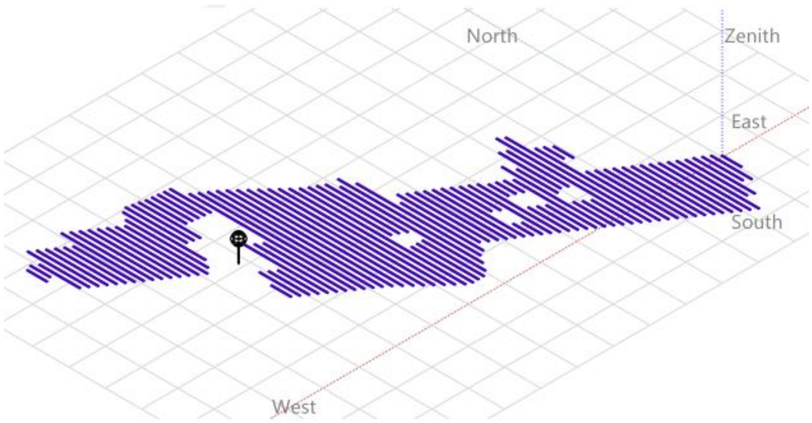



*Figure* 84: module disposition

This is a multimegawatt power plant and there is a high number of modules, so it is represented only one disposition independently from the configuration considered since the variations would not be appreciable.

**Fixed structures (CONF#B)**

The fixed structure layout is characterized as follow:

- 388 strings of 24 modules in series, for a total number of 9312
- Inclination of 30°
- Nominal module power: Pnom = 610 Wp
- Nominal power of the array: Pnom array = 5680 kWp,
- Area of the modules: A = 26030 m²
- Power of the inverter: 2750 kWa
- Number of inverters: 2 units for a total power of 5500 kW

The main results of the simulation of this plant are the following:

*Table 19* main system results for fixed structures

| | **GlobHor** | **DiffHor** | **T_Amb** | **GlobInc** | **GlobEff** | **EArray** | **E_Grid** | **PR** |
|---|---|---|---|---|---|---|---|---|
| | kWh/m² | kWh/m² | °C | kWh/m² | kWh/m² | MWh | MWh | ratio |
| **January** | 66.9 | 31.61 | 7.07 | 91.8 | 80.4 | 441 | 426 | 0.817 |
| **February** | 93.2 | 39.16 | 8.1 | 129.3 | 114.4 | 624 | 604 | 0.823 |
| **March** | 114.4 | 56.93 | 8.64 | 148.6 | 133.8 | 722 | 699 | 0.828 |
| **April** | 168.7 | 65.69 | 12.57 | 224.9 | 206.5 | 1092 | 1059 | 0.829 |
| **May** | 202 | 73.69 | 15.76 | 267.5 | 247.3 | 1288 | 1250 | 0.823 |
| **June** | 215.3 | 72.01 | 21.99 | 285.8 | 264.5 | 1347 | 1309 | 0.806 |
| **July** | 215.5 | 72.92 | 24.63 | 298.3 | 275.6 | 1397 | 1358 | 0.801 |
| **August** | 184.9 | 68.05 | 24.82 | 255.8 | 234.5 | 1188 | 1155 | 0.795 |
| **September** | 154.8 | 58.71 | 20.33 | 212.1 | 193 | 999 | 971 | 0.806 |
| **October** | 103.5 | 49.39 | 16.29 | 139.6 | 125.1 | 663 | 643 | 0.811 |
| **November** | 75.9 | 36.05 | 13.12 | 107.1 | 93.2 | 502 | 486 | 0.799 |
| **December** | 65.9 | 31.39 | 8.38 | 95.1 | 81.4 | 447 | 431 | 0.798 |
| **Year** | 1661.1 | 655.61 | 15.18 | 2256 | 2049.8 | 10710 | 10390 | 0.811 |

Where:

-GloHor: global horizontal radiation

-DiffHor: Horizontal diffuse radiation

-T_Amb: ambient temperature

-GlonInc: global incident in collector plane

-GlobEff: effective global radiation

-Earray: effective energy at the output of the array

-Egrid: energy injected into the grid

-PR: performance Ratio that is an estimation of the expected efficiency for the PV, it is calculated as described in [37] and reported in the paragraph 2.8 :

$$PR = \frac{E_{AC}}{H_g \cdot S_{PV} \cdot \eta_{STC}} \tag{44}$$

Where:

- EAC is the electricity production in the period under analysis (i.e., one year)
- Hg is the irradiation on the plane of array in the same period (kWh/m2)
- SPV is the total surface of the PV generator
- $\eta_{STC}$ is the nominal efficiency of the modules at Standard Test Condition [38].

**Tracking structures (CONF#B)**

The CONF#B with tracking system has the following features:

- 388 strings of 24 modules in series, for a total number of 9312
- Tracking structures
- Nominal module power: Pnom = 610 Wp
- Nominal power of the array: Pnom array = 5680 kWp,
- Area of the modules (front side): A = 26030 m²
- Power of the inverter: 2750 kWa
- Number of inverters: 2 units for a total power of 5500 kW

The tracking structures are simulated with and without the backtracking technology, to have a correct comparison with the fixed modules. When the backtracking is activated, the module is set as bifacial.

The main results of the simulation of this plant are in the following tables :

*Table 20* main system results for tracking CONF#B without backtracking

| | GlobHor | DiffHor | T_Amb | GlobInc | GlobEff | EArray | E_Grid | PR |
|---|---|---|---|---|---|---|---|---|
| | kWh/m² | kWh/m² | °C | kWh/m² | kWh/m² | MWh | MWh | ratio |
| **January** | 66.9 | 31.61 | 7.07 | 91.8 | 80.4 | 442 | 426 | 0.817 |
| **February** | 93.2 | 39.16 | 8.1 | 129.3 | 114.5 | 624 | 605 | 0.823 |
| **March** | 114.4 | 56.93 | 8.64 | 148.6 | 133.9 | 722 | 699 | 0.828 |
| **April** | 168.7 | 65.69 | 12.57 | 224.9 | 206.6 | 1092 | 1060 | 0.829 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **May** | 202 | 73.69 | 15.76 | 267.5 | 247.4 | 1288 | 1250 | 0.823 |
| **June** | 215.3 | 72.01 | 21.99 | 285.8 | 264.6 | 1348 | 1309 | 0.806 |
| **July** | 215.5 | 72.92 | 24.63 | 298.3 | 275.7 | 1397 | 1358 | 0.802 |
| **August** | 184.9 | 68.05 | 24.82 | 255.8 | 234.6 | 1189 | 1155 | 0.795 |
| **September** | 154.8 | 58.71 | 20.33 | 212.1 | 193 | 1000 | 971 | 0.806 |
| **October** | 103.5 | 49.39 | 16.29 | 139.6 | 125.2 | 664 | 643 | 0.811 |
| **November** | 75.9 | 36.05 | 13.12 | 107.1 | 93.2 | 503 | 486 | 0.799 |
| **December** | 65.9 | 31.39 | 8.38 | 95.1 | 81.4 | 447 | 432 | 0.799 |
| **Year** | 1661.1 | 655.61 | 15.18 | 2256 | 2050.7 | 10715 | 10395 | 0.811 |

In the moths of November and December the PR is low because the shadowing during the early morning and the late afternoon causes severe losses. Using the backtracking would reduce this loss as visible in the following table.

*Table 21* main system results for tracking CONF#B with backtracking

| | **GlobHor** | **DiffHor** | **T_Amb** | **GlobInc** | **GlobEff** | **EArray** | **E_Grid** | **PR** |
|---|---|---|---|---|---|---|---|---|
| | kWh/m² | kWh/m² | °C | kWh/m² | kWh/m² | MWh | MWh | ratio |
| **January** | 66.9 | 31.61 | 7.07 | 88 | 81.1 | 483 | 466 | 0.933 |
| **February** | 93.2 | 39.16 | 8.1 | 124.3 | 116 | 681 | 660 | 0.935 |
| **March** | 114.4 | 56.93 | 8.64 | 144.1 | 135.1 | 792 | 767 | 0.937 |
| **April** | 168.7 | 65.69 | 12.57 | 219.8 | 208.2 | 1182 | 1147 | 0.918 |
| **May** | 202 | 73.69 | 15.76 | 262.1 | 249 | 1391 | 1349 | 0.906 |
| **June** | 215.3 | 72.01 | 21.99 | 280.2 | 266.5 | 1455 | 1412 | 0.887 |
| **July** | 215.5 | 72.92 | 24.63 | 291.4 | 277.3 | 1499 | 1457 | 0.88 |
| **August** | 184.9 | 68.05 | 24.82 | 248.3 | 235.6 | 1277 | 1240 | 0.879 |
| **September** | 154.8 | 58.71 | 20.33 | 205.6 | 194.4 | 1080 | 1048 | 0.898 |
| **October** | 103.5 | 49.39 | 16.29 | 134.9 | 126.3 | 723 | 701 | 0.916 |
| **November** | 75.9 | 36.05 | 13.12 | 102.2 | 94.5 | 550 | 532 | 0.916 |
| **December** | 65.9 | 31.39 | 8.38 | 89.5 | 81.9 | 485 | 469 | 0.923 |
| **Year** | 1661.1 | 655.61 | 15.18 | 2190.4 | 2065.9 | 11597 | 11249 | 0.904 |

### Tracking structures (CONF#A)

The CONF#A has the following features:

- 487 strings of 24 modules in series, for a total number of 11688
- Tracking structures
- Nominal module power: Pnom = 610 Wp
- Nominal power of the array: Pnom array = 7130 kWp,
- Area of the modules (front side): A = 32671 m²
- Power of the inverter: 4200/2500 kWa
- Number of inverters: 1 unit of each for a total power of 6700 kW

The main results for the CONF#A are in the table 22. CONF#A with backtracking and bifacial modules was considered in this simulation.

*Table 22* main system results for tracking CONF#A

| | GlobHor | DiffHor | T_Amb | GlobInc | GlobEff | EArray | E_Grid | PR |
|---|---|---|---|---|---|---|---|---|
| | kWh/m² | kWh/m² | °C | kWh/m² | kWh/m² | MWh | MWh | ratio |
| **January** | 66.9 | 31.61 | 7.07 | 86.3 | 79 | 586 | 567 | 0.921 |
| **February** | 93.2 | 39.16 | 8.1 | 120.7 | 112 | 822 | 798 | 0.927 |
| **March** | 114.4 | 56.93 | 8.64 | 141.6 | 131.9 | 964 | 935 | 0.927 |
| **April** | 168.7 | 65.69 | 12.57 | 215.8 | 203.5 | 1444 | 1402 | 0.911 |
| **May** | 202 | 73.69 | 15.76 | 258.5 | 244.6 | 1705 | 1656 | 0.898 |
| **June** | 215.3 | 72.01 | 21.99 | 276.8 | 262.2 | 1786 | 1735 | 0.879 |
| **July** | 215.5 | 72.92 | 24.63 | 287.2 | 272.1 | 1837 | 1786 | 0.872 |
| **August** | 184.9 | 68.05 | 24.82 | 243.1 | 229.7 | 1555 | 1511 | 0.872 |
| **September** | 154.8 | 58.71 | 20.33 | 201.3 | 189.5 | 1315 | 1278 | 0.89 |
| **October** | 103.5 | 49.39 | 16.29 | 132.3 | 123.1 | 880 | 854 | 0.905 |
| **November** | 75.9 | 36.05 | 13.12 | 99.3 | 91.2 | 663 | 642 | 0.907 |
| **December** | 65.9 | 31.39 | 8.38 | 86.8 | 78.8 | 582 | 564 | 0.912 |
| **Year** | 1661.1 | 655.61 | 15.18 | 2149.7 | 2017.4 | 14138 | 13728 | 0.896 |

**Tracking structures (traditional solution)**

The traditional PV field has the following features:

- 579 strings of 24 modules in series, for a total number of 13896
- Tracking structures
- Nominal module power: Pnom = 610 Wp
- Nominal power of the array: Pnom array = 8477 kWp,
- Area of the modules (front side): A = 38846 m²
- Power of the inverter: 4000 kWa
- Number of inverters: 2 units for a total power of 8000 kWa

The main results for the traditional configuration are in the table 23. CONF#A with backtracking and bifacial modules was considered in this simulation.

*Table 23* main system results for tracking traditional solution

| | GlobHor | DiffHor | T_Amb | GlobInc | GlobEff | EArray | E_Grid | PR |
|---|---|---|---|---|---|---|---|---|
| | kWh/m² | kWh/m² | °C | kWh/m² | kWh/m² | MWh | MWh | ratio |
| **January** | 66.9 | 31.61 | 7.07 | 84 | 76.1 | 601 | 553 | 0.776 |
| **February** | 93.2 | 39.16 | 8.1 | 118.3 | 108.8 | 853 | 839 | 0.836 |
| **March** | 114.4 | 56.93 | 8.64 | 138.7 | 128.1 | 994 | 955 | 0.812 |
| **April** | 168.7 | 65.69 | 12.57 | 212.3 | 198.8 | 1511 | 1485 | 0.825 |
| **May** | 202 | 73.69 | 15.76 | 254 | 238.8 | 1787 | 1757 | 0.816 |
| **June** | 215.3 | 72.01 | 21.99 | 271.9 | 256.1 | 1876 | 1844 | 0.8 |
| **July** | 215.5 | 72.92 | 24.63 | 279.7 | 263.5 | 1921 | 1890 | 0.797 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **August** | 184.9 | 68.05 | 24.82 | 238 | 223.2 | 1626 | 1599 | 0.793 |
| **September** | 154.8 | 58.71 | 20.33 | 197.4 | 184.6 | 1375 | 1317 | 0.787 |
| **October** | 103.5 | 49.39 | 16.29 | 129.4 | 119.4 | 910 | 874 | 0.797 |
| **November** | 75.9 | 36.05 | 13.12 | 96.5 | 87.8 | 681 | 624 | 0.762 |
| **December** | 65.9 | 31.39 | 8.38 | 84.3 | 75.7 | 597 | 586 | 0.821 |
| **Year** | **1661.1** | **655.61** | **15.18** | **2104.5** | **1960.9** | **14733** | **14323** | **0.803** |

The energy production and the performance ration of each configuration is reported in table 24 to have a direct comparison.

*Table 24* Comparison of Monthly Energy Productions and PR Values in Conf#A ,Conf#B and traditional

| | **CONF#A tracking** | | **CONF#B tracking** | | **CONF#B tracking with no backtracking** | | **CONF#B fixed** | | **Traditional** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $E_{grid}$ (MWh/ha) | *PR* | $E_{grid}$ (MWh/ha) | *PR* | $E_{grid}$ (MWh/ha) | *PR* | $E_{grid}$ (MWh/ha) | *PR* | $E_{grid}$ (MWh/ha) | *PR* |
| **January** | 567 | 0.921 | 466 | 0.933 | 442 | 426 | 426 | 0.817 | 553 | 0.776 |
| **February** | 798 | 0.927 | 660 | 0.935 | 624 | 605 | 604 | 0.823 | 839 | 0.836 |
| **March** | 935 | 0.927 | 767 | 0.937 | 722 | 699 | 699 | 0.828 | 955 | 0.812 |
| **April** | 1402 | 0.911 | 1147 | 0.918 | 1092 | 1060 | 1059 | 0.829 | 1485 | 0.825 |
| **May** | 1656 | 0.898 | 1349 | 0.906 | 1288 | 1250 | 1250 | 0.823 | 1757 | 0.816 |
| **June** | 1735 | 0.879 | 1412 | 0.887 | 1348 | 1309 | 1309 | 0.806 | 1844 | 0.8 |
| **July** | 1786 | 0.872 | 1457 | 0.88 | 1397 | 1358 | 1358 | 0.801 | 1890 | 0.797 |
| **August** | 1511 | 0.872 | 1240 | 0.879 | 1189 | 1155 | 1155 | 0.795 | 1599 | 0.793 |
| **September** | 1278 | 0.89 | 1048 | 0.898 | 1000 | 971 | 971 | 0.806 | 1317 | 0.787 |
| **October** | 854 | 0.905 | 701 | 0.916 | 664 | 643 | 643 | 0.811 | 874 | 0.797 |
| **November** | 642 | 0.907 | 532 | 0.916 | 503 | 486 | 486 | 0.799 | 624 | 0.762 |
| **December** | 564 | 0.912 | 469 | 0.923 | 447 | 432 | 431 | 0.798 | 586 | 0.821 |
| **Year** | **13728** | **0.896** | **11249** | **0.904** | **10715** | **10395** | **10390** | **0.811** | **14323** | **0.803** |

Considering the CONF#B with fixed modules as the base case, the yearly energy production is the 32% higher for the CONF#A, the 8% higher in the CONF#B, the 38% in the traditional plant and almost the same as in the fixed system for the configuration B without the backtracking. The production of the plants is illustrated in the *figure 85.*

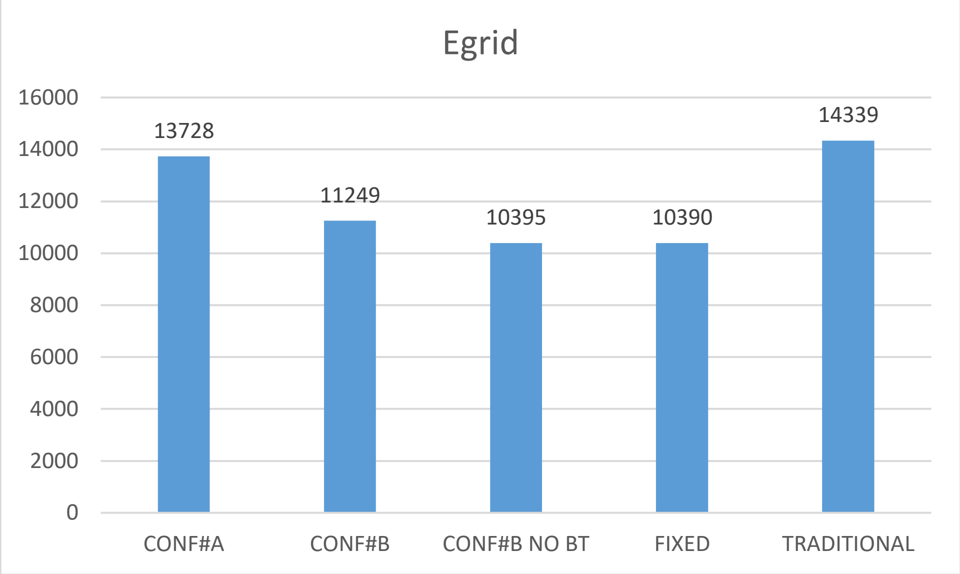



*Figure* 85: Energy production of the different configurations

These results are mostly a consequence of the performance features of the different configurations, the most important of which are reported in the table 25.

*Table* 25 technical losses of the system layouts

| | Fixed | Conf#B no bt | Conf#B | Conf#A | Traditional |
|---|---|---|---|---|---|
| Glo Inc | 35.80% | 35.80% | 31.90% | 29.40% | 35.8% |
| Bifacial | 0 | 0 | 10.60% | 9.70% | 9.1% |
| Temperature loss | 4% | 4% | 4% | 4% | 4% |
| Shading loss | 4.90% | 4.90% | 1.80% | 1.90% | 8.9% |

The incident radiation in the configurations with the backtracking loses the 4%—6% because, when the sun is low respect to the horizon, the modules move in order to avoid each other shading, losing the perpendicularity with the sun rays.

The backtracking technology is equipped with bifacial modules, so there is a certain amount of energy exploited from the indirect radiation, the final contribution of this energy is the 10.6 % for CONF#B, 9.7 % for CONF#A and 9.1 in the traditional layout. In the CONF#B the amount of energy from the back is higher since there is more space among the lines than in the CONF#A and in the traditional, so with the same indirect radiation per unit area, the CONF#B has more area per each module than the others.

The traditional plant has not the best values about the losses, but the energy production is massive because it outnumbers the amount of modules of the other configurations.

The temperature losses are the same for each configuration, since in the simulations of the thermal feature is the same, that is “free standing system with air circulation all around collectors". The effect of temperature on the modules performance is reported if *figure 86.*

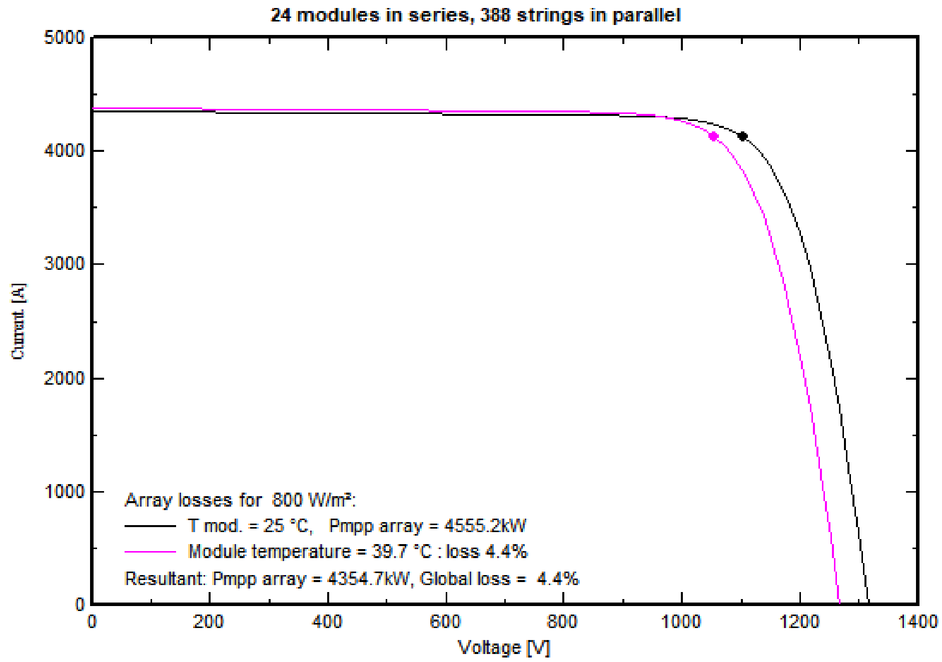



*Figure* 86: temperature effect on the system performance

The temperature of the cell is almost 40°C following the thermal model adopted in PVsyst giving as output a thermal loss equal to the 4.4%. Since the presence of the trees in the area could avoid the correct application of the PVsyst thermal model, for sake of safety an higher temperature will be taken into account.

- The module surface temperature is :$T_{surface} = 65°C$
- Following the module datacheet the reduction of power is: $T_{red\_P} = 0.3\ \%\ /°C$

  So the thermal losses resuls equal to: 10.5%.

Finally, the comparison among the different performance ratio is shown in the figure 87.

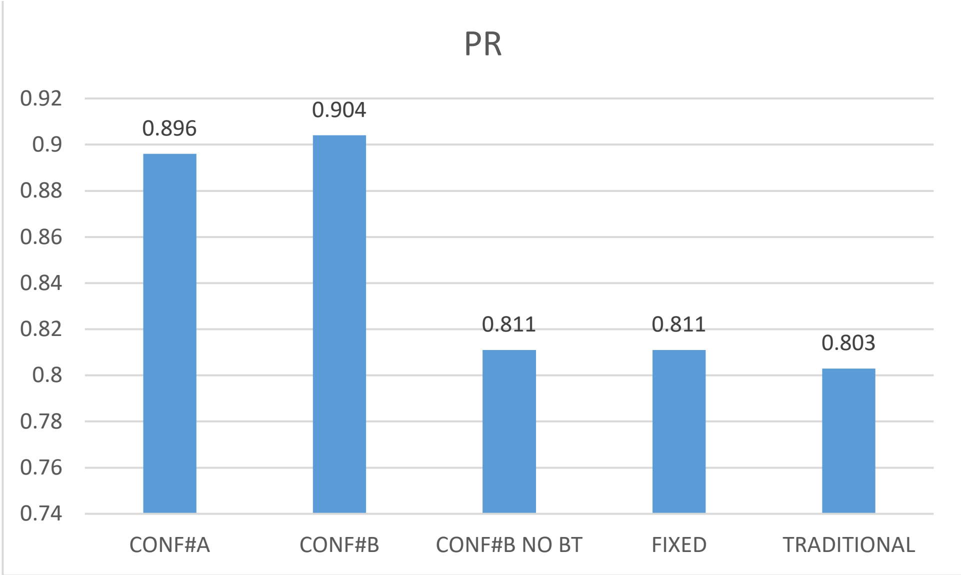



*Figure* 87: PR comparison

It is visible a clear difference among the configurations without the backtracking and those with the backtracking. The backtracking gives an average 8% boost to the PR, leading it to almost 90%, that is a bright result.

The traditional case has low performance ratio because the distance between the strings is low and even with the backtracking the PR cannot go over the 80,3%.

## 6.4 Land use saving due to agrivoltaic concept

The key concept of the AV plants is that their installation is convenient under the point of view of the exploitation of the available land. To prove this, the land use saving analysis is performed.

The results for the energy production from the different layout are deeply analyzed in the previous paragraph, but are synthetically reported here.

| | CONF#A | CONF#B | CONF# NO BT | FIXED | TRADITIONAL |
|---|---|---|---|---|---|
| Energy [$GWh/year/ha$] | 1.3 | 1.1 | 1.0 | 1.0 | 1.4 |

About the traditional and the AV production of the olive and olive oil, following the "crop model" from the paragraph 5.3 the crop yield is affected by the shadowing according to 3 different levels of intensity, that are indicated by the parameter m :

- m=0
- m=0.5
- m=1

When m=0 there is not any influence of the shadowing on the crop yield; on the other hand, if m=1 the influence of the shadowing on the crops is maximum; finally, if m=0.5 there is and average sensibility for the shadowing. Clearly as the shadowing sensitivity increases, the agronomic output decreases.

The traditional production with m=0 is characterized by the data are exposed in table 26:

*Table 26* agricultural production per year

| | | m=0 | | m=0.5 | | m=1 | |
|---|---|---|---|---|---|---|---|
| | Traditional | CONF#A | CONF#B | CONF#A | CONF#B | CONF#A | CONF#B |
| Olive [kg/ha] | 1700 | 917 | 917 | 676 | 722 | 436 | 527 |
| Oil [l/ha] | 279 | 150 | 150 | 111 | 118 | 71 | 86 |

In case of CONF#A and the production of olive oil whose LER results in LERCONF#A, olive=1.45. Thus, the saved land is 0.45 ha per each hectare of the agrivoltaic system, or the 45%. The calculation is the following:

$$LER_{\ CONF\#A,olive} = \frac{1.3GWh/year/ha}{1.4GWh/year/ha} + \frac{9\ ton/ha}{17\ ton/ha}$$

$$LER_{\ CONF\#A,olive} = 0.928 + 0.529 = 1.45$$

Since the oil is a product of the olives, in the LER analysis it will be taken into account only the cultivation of the olives.

The results for the olive and electricity production with a "m" coefficient equal to 0 is shown in Table 27.

*Table 27* Land Saving Calculation for Agrivoltaic Plant with Olive production with no agricultural yield modification due to shadowing

| | CONF#A | CONF#B | CONF# NO BT | FIXED |
|---|---|---|---|---|
| **Energy [MWh/ha/y]** | 1.3 | 1.1 | 1 | 1 |
| **Olive [kg/ha]** | 917 | 917 | 917 | 917 |
| **LER (olive)** | 1.47 | 1.33 | 1.25 | 1.25 |
| **Land saved** | 0.47 | 0.33 | 0.25 | 0.25 |

The results about the land saved are brilliant. In the best case, that is the CONF#A, for producing the same output the agrivoltaic technology saves the 47% of land. The result for the CONF#B are less advantageous than the CONF#A but anyway very optimistic, the is the 33% of land saved. Finally, the fixed and the CONF#B without backtracking produce the same output, that is a 25% of land saving.

The results from the table 27 considers m=0 so the agricultural output is independent from the incidence of shadowing. If the olive production would be characterized by m=0.5, so by an average influence of the shadowing, the results are in table 28.

*Table 28* Land Saving Calculation for Agrivoltaic Plant with Olive production with average agricultural yield modification due to shadowing

| | CONF#A | CONF#B | CONF# NO BT | FIXED |
|---|---|---|---|---|
| **Energy [MWh/ha/y]** | 1.3 | 1.1 | 1 | 1 |
| **Olive [kg/ha]** | 676 | 722 | 722 | 722 |
| **LER (olive)** | 1.33 | 1.21 | 1.14 | 1.14 |
| **Land saved** | 0.33 | 0.21 | 0.14 | 0.14 |

With an average effect of the shadowing on the crop yield there is a reduction of the land saving, but the result are anyway relevant for CONF#A and CONF#B with tracking systems. CONF#A and #B save respectively the 33% and the 21% of the land. The configuration without the backtracking, as well as the fixed one, save the 14% of the land, so less than half of the CONF#A.

If the effect of shadowing on the olive trees is maximum, the "m" coefficient is equal to 1. The relative results are in table 29.

*Table 29* Land Saving Calculation for Agrivoltaic Plant with Olive production with high agricultural yield modification due to shadowing

| | CONF#A | CONF#B | CONF# NO BT | FIXED |
|---|---|---|---|---|
| **Energy [MWh/ha/y]** | 1.3 | 1.1 | 1 | 1 |
| **Olive [kg/ha]** | 436 | 527 | 527 | 527 |
| **LER (olive)** | 1.19 | 1.10 | 1.02 | 1.02 |
| **Land saved** | 0.19 | 0.10 | 0.02 | 0.02 |

With maximum sensibility to shadowing the agrivoltaic application should be avoided for the specific variety of crop, but anyway for the CONF#A the land saved is near the 20%. The result almost halves for the CONF#B and is practically negligible for the configuration without backtracking and fixed. These results find a justification behind the fact that the energetic production in the CONF#A and #B is higher than in the others, so even if the agronomic production sensibly drops sown, the LER is brought up by the ratio of the electricity production.

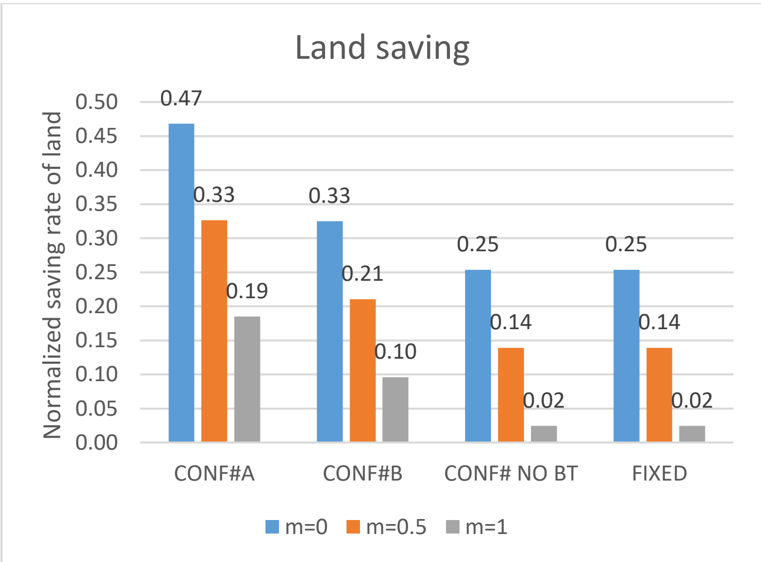



*Figure* 88: Land saving final response

Finally, it is worth to say that the agricultural species with high sensibility to shadowing should be avoided for the agrivoltaic applications. For low or average sensibility to shadowing of the crops, the agrivoltaic system not only can give out an agronomic output enough high for an industrial production, but the advantages in land savings are considerable, ranging from almost 15% for basic PV technology and average sensibility to shadowing, to almost 50% with dense PV field with crops slightly not affected by shadowing.

A final outlook to the results of the analysis is provided by the figure 88, where the land saving for each configuration at different shadowing sensibility is illustrated.

## 6.5 Financial analysis

Even in the financial analysis have been considered three levels of sensitivity to shadowing for the calculation of the yearly incomes of the agricultural side of the plant.

Moreover, the economic output is calculated both for olive and oil selling, considering the financial data described in the paragraph 6.1.3.

The main results of the agronomic production are listed in the tables below:

*Table 30* economic analysis for the olive production

| Production | Layout | Shadow sensibility | ROI per year | Annuity per ha |
|---|---|---|---|---|
| *Olive* | *Config A* | m=0 | 65% | € 2’893 |
| | | m=0.5 | 28% | € 1’232 |
| | | m=1 | 1% | € 30 |
| | *Config B* | m=0 | 65% | € 2’893 |
| | | m=0.5 | 33% | € 1’462 |
| | | m=1 | 11% | € 488 |

*Table* 31 economic analysis for the oil production

| Production | Layout | Shadow sensibility | ROI per year | Annuity per ha |
|---|---|---|---|---|
| Oil | *CONF#A* | m=0 | 113% | € 5'027 |
| | | m=0.5 | 64% | € 2'856 |
| | | m=1 | 15% | € 686 |
| | *CONF#B* | m=0 | 113% | € 5'027 |
| | | m=0.5 | 73% | € 3'270 |
| | | m=1 | 34% | € 1'514 |

When the sensitivity parameter is set to 0, the global revenue is almost 3k€/year for olives and 5 k€/year for olive oil. For each production the revenues are the same in the two configurations (CONF#A and CONF#B) since shadows have no effect on the crops.

If an average sensitivity is set, so m=0.5, the profit is 1 k€/year for the olives and 3 k€/year for the oil in CONF#B, while for CONF#A the values are almost the same for the olives and about 2% less than CONF#B for the oil.

Finally, when the sensitivity is maximum, the effect of shadowing on the profit is high: the incomes for CONF#B are less than 0.5 k€/year for the olives and only 1.5 k€/year for olive oil.

In CONF#A with maximum shadow sensitivity, the incomes are 65% less than in CONF#B for the olives and 13% less for the oil, letting the incomes drastically falling down. The agronomic investment is in any configuration profitable, but there are some observations about the most convenient alternative. As showed in the *graph 7*, the oil activity is more remunerative than the olive one. The oil production generates a return on the investment from the 14% to the 48% higher than the olive production, depending on the configuration and the shadowing sensibility. About the two configurations, the CONF#B is the best for the agricultural activity, since for olives it produces a return the 5% higher than the CONF#A when m=0.5 and the 10% higher if m=1, while for the oil those values reach up the 9% if m=0.5 and 14% when m=0.

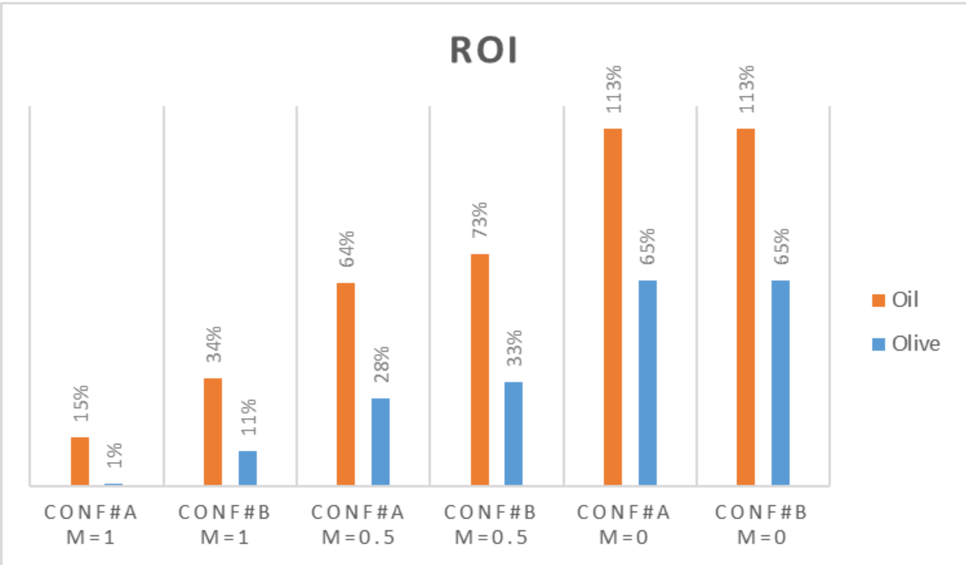



*Figure* 89: ROI comparison for the agronomic activities

The NPV and the payback period with an discount interest of 9% are reported in table 32:

*Table* 32 NPV and payback time for agronomic activity

| Production | Layout | Shadow sensibility | NPV (20 years) | Payback |
|---|---|---|---|---|
| *Olive* | *Config A* | m=0 | €196'527 | 2 |
| | | m=0.5 | €60'213 | 4 |
| | | m=1 | €-38'464 | 149 |
| | *Config B* | m=0 | €196'527 | 2 |
| | | m=0.5 | €62'479 | 4 |
| | | m=1 | €-33'932 | 52 |
| Oil | *CONF#A* | m=0 | €371'627 | 1 |
| | | m=0.5 | €193'489 | 2 |
| | | m=1 | €15'352 | 7 |
| | *CONF#B* | m=0 | €371'627 | 1 |
| | | m=0.5 | €197'580 | 2 |
| | | m=1 | €23'533 | 6 |

The NPV gives a clear picture about the effectiveness of the investment. The olive cultivation with high shadowing sensibility is not profitable since the NPV is negative. The same condition for the olive oil produces a certain return, but the payback period is at 7 years for CONF#A and at 6 years for CONF#B.

The shadowing sensibility has a primary effect on the profitability of the investment, if the crops have a null influence from the shadowing the NPV is very high, more than 370 k€ for the oil production, and 196 k€ for the olive production. But just halving the resistance to the shadowing the NPV decreases of more than the 45% for the oil production, and more than 70 % for the olives.

The response about which configuration should be chosen is taken from the Roi analysis. Since for each hectare the CONF#B produces in average 400€/year more than CONF#A, the CONF#B should be slightly preferred.

As far as the energetic part of the AV plant is considered, the economical evaluation has taken into account two classes of incentive: a maximum incentive case and a minimum incentive case. This classification is due to the fact than the incentives estimation depends on a multitude of factors that cannot be analytically considered. The incentives for the two configurations plus the fixed layout are showed in the table 33.

*Table 33* incentives for each configuration per unit of hectare

| | | CONF#A | CONF#B | Fixed |
|---|---|---|---|---|
| **Energy per ha** | MWh/year | 1’373 | 1’125 | 1’039 |
| **Maximum incentives** | €/year | 17’68 | 1’452 | 1’341 |
| **Minimum incentives** | €/anno | 49 | 40 | 36 |

With maximum incentives the CONF#B has a payback period of 6.3 years, a NPV of 5M€ after 20 years, a ROI of 163 % and a LCOE of 0.017 €/kWh. With minimum incentives the values become 8.7 years for the payback period, 289’811 €/ha for the NPV, 91% for the ROI and a LCOE of 0.032 €/kWh.

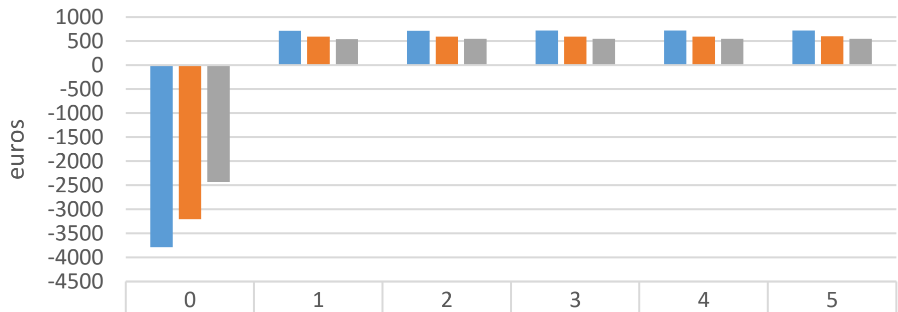
CONF#A with maximum incentives shows a NPV of 10M€ at 20 years of the exercise, a payback period of 5.4 years, a ROI of 274 % and a LCOE of 0.012 €/kWh. On the other hand, with minimum incentives, the NPV becomes 696 k€/ha, the payback period is at 7 years, the ROI is 185% and the LCOE is 0.025 €/kWh.

The fixed plant with maximum incentives has a NPV of 6M€ at 20 years, the payback period is at 4.6 years, the ROI is 258% and the LCOE is 0.012 €/kWh. With minimum incentives the NPV becomes 350 k€/ha, the payback period is 6.6 years, the ROI is 145 % and the LCOE is 0.027 €/kWh.

The incentives are a fundamental element in the evaluation of the quality of the investment. Switching from the maximum to the minimum incentives: the variation in the NPV is more than the 30%, the ROI loses till 91 percentual points, the payback period increases by almost the 40% and the LCOE practically doubles. From now on only the case with the maximum incentive will be taken into account for sake of clarity for the following comparisons.

It is important to specify that under the financial point of view, the main difference between the fixed and the tracker configuration is that the second has higher costs because of the presence of the electric motors that also requires maintenance. In this study the maintenance costs for the fixed structures are 1% of the capex, while for the tracking system are the 3% of the capex.

The three types of plants have different expenditures and incomes, as the figure 90 shows for the first 5 years of the plants. As illustrated, the CONF#A is the most expensive one, but also the most remunerative. The CONF#B and the fixed have similar incomes even if the CONF#B has an initial cost higher than the fixed configuration.




| | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| CONF#A | -3782 | 717 | 718 | 719 | 720 | 721 |
| CONF#B | -3205 | 595 | 596 | 597 | 598 | 599 |
| Fixed | -2427 | 545 | 545 | 546 | 546 | 547 |

Yearly cashflow in k€

CONF#A CONF#B Fixed

*Figure* 90: cash flow for CONF#A, CONF#B and fixed plants

The pivotal point of this financial analysis is to verify if the better performance of the tracking configurations are enough to compare their difference in CAPEX and OPEX costs respect to the fixed structure.

The balance between the initial expenditure and the income of the plant is the net cashflow, that is represented in *figure* 91. As it is possible to see, the CONF#A plant overcomes the net incomes of the fixed configuration between the 7th and the 8th year of the exercise (almost 2 years after the payback of the CONF#A plant). While the CONF#B overcomes the incomes of the fixed plant only in the 16th year. The

CONF#A is the most remunerative layout, as its huge NPV confirms, even if it has the highest initial cost.

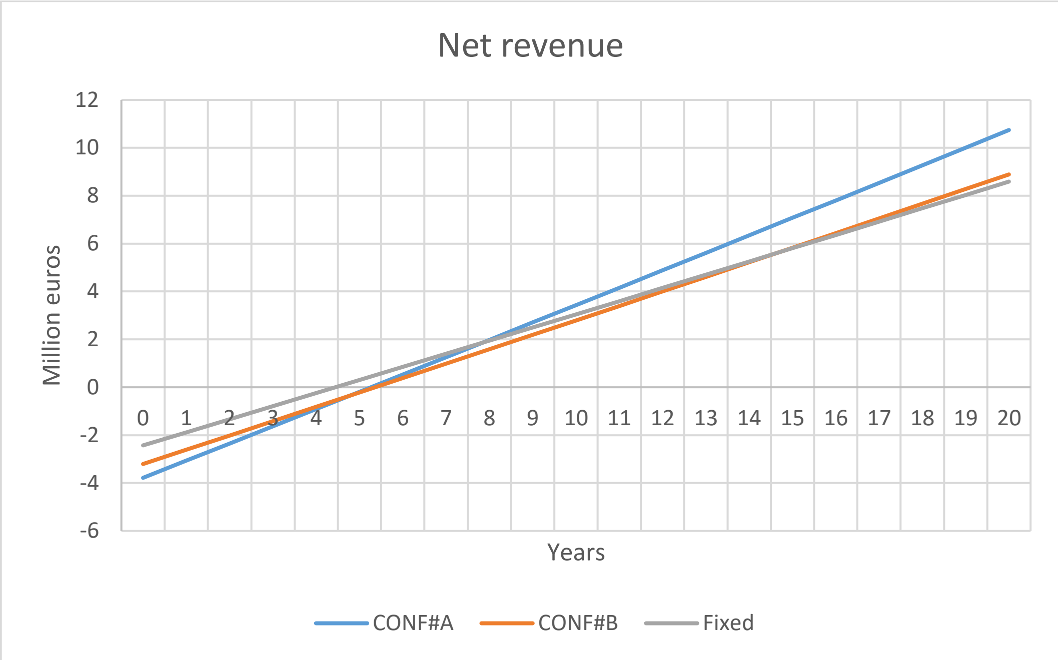



*Figure* 91: Net revenue for CONF#A, CONF#B and fixed plants

The three configurations financial indicators are summed up in table 34, where the NPV, the Payback period, the ROI and the IRR too, have been calculated for the three plants in the condition of maximum incentives.

*Table 34* economic indicators comparison

| | **CONF#A** | **CONF#B** | **Fixed** |
|---|---|---|---|
| **NPV [M€]** | 10 | 5 | 6 |
| **Payback [years]** | 5.4 | 6.3 | 4.6 |
| **ROI** | 274% | 163% | 257.9 |
| **IRR** | 18% | 18% | 22% |
| **LCOE [€/kWh]** | 0.02 | 0.02 | 0.02 |

The CONF#A shows the highest NPV and the best ROI, but the IRR is lower than the fixed configuration. Since the investment is actuated on a time period of 20 years, the uncertainty in the ROI calculation could be inaccurate. So the CONF#A is anyhow a valid alternative, it is the one that eventually would bring the highest incomes according to ROI. On the other hand, the fixed structure layout represent the most secure investment of the group, since the discount rate to take the NPV to is the highest.

The analysis of the AV plant should take into account both agricultural and photovoltaic production, but since energy production generates more revenue, this should be the main parameter for choosing the best layout. The CONF#A is the most profitable, following the results on the photovoltaic activity, so it should be the one selected. In the case of particular attention to agronomic activity, even if its incomes are not comparable to those deriving from energy production, it is advisable to select the CONF#B and, to balance the effect of this choice, fixed modules can be preferred to trackers.

# Chapter 7

# 7 Conclusions

This paper presents the simulation and analysis of the production of an agrivoltaic plant in Southern Italy to generate both energy from the photovoltaic activity and implement an intensive olive cultivation. The goal of this kind of plant is land saving: thus, it may meet the needs of countries with high energy demand and low available areas just like Italy, where wide lands are not largely available since there are lots of agricultural sites.

For both energy and crop production, the models have taken into account the effect of shadows, with particular attention to the shadowing of the models on the crop and the other PV surfaces. By changing the distance among the PV strings, different plant configurations were created, and a sensitivity analysis was carried out, with the comparison on the productions.

In conclusion, this work demonstrates that there are cases in which agrivoltaic technology works well and can be considered a leader technology in the achievement of the national goals, according to the PNRR and PNIEC, and international treaties such as the European Green Deal. This thesis shows that in the agrivoltaic activity the energy production is comparable to traditional plants, the crop production is not omitted, the cost-effectiveness of investment is preserved, and a considerable amount of land can be saved for other purposes.

The yield analysis has enlightened that the AV system with the CONF#A, the configuration in which the distance across the strings is 6m, would produce 1372 MWh per year, that is only the 5% less than a traditional plant. Considering the same configuration, the agronomic activity reaches a level of production of more than 4 tons of olive per hectare in the worst shadowing case, that is the one in which the trees are affected the most by the shadowing.

If the agricultural activity should be the pivotal point of the investment, then the fixed structure with the CONF#B, that is the largest configuration considered, with a distance across the strings of 7.5m, should be considered, giving out almost the 20% more olive than the CONF#A and about 1000 litre of olive oil per hectare. With the fixed structures the energetic activity is anyhow present, generating 1039 MWh/ha each year and more than 500 k€ of incomes, the 40% less than the CONF#A.

The application of the Land Equivalent Ratio method illustrated how the agrivoltaic technology would better exploit the available space, saving up to the 47% of lands if the CONF#A is used and the shadow sensibility of the trees is very low.

In the end, the economic analysis confirmed the validity of the project, reaching high NPV values and profitable results for the ROI and the IRR in all the configurations of the PV side.

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