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INDUSTRIAL PLANTS II

Chapter nine (part 1): Solar photovoltaic systems

DOUBLE DEGREE MASTER IN

“PRODUCTION ENGINEERING AND MANAGEMENT”

CAMPUS OF PORDENONE

UNIVERSITY OF TRIESTE

Solar photovoltaic systems

Generality

It defines a **solar photovoltaic plant** or **system** for the production of electrical energy by direct conversion of solar radiation through the photovoltaic effect, which is the ability to have some semiconductor materials, suitably treated, to generate electricity when exposed to light radiation.

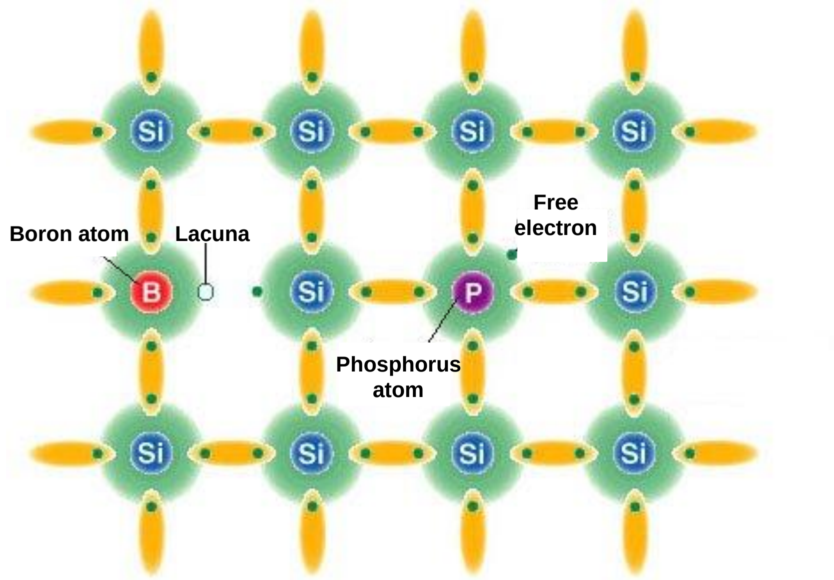
The core around which develops a photovoltaic system is the **photovoltaic cell**, in which takes place the conversion of solar radiation into electrical current. The device consists of a thin layer (between 0.2 and 0.35 mm) of semiconductor material (usually silicon) suitably treated, which consists of a series of chemical processes which are known as "**doping**". The photovoltaic cell is basically a diode, that is, a p-n junction between two semiconductors, one p-doped and the other n-doped.

Generality

The silicon has 14 electrons of which 4, the outermost ones, are of valence, that is available to bind a couple with valence electrons of other atoms, both of silicon, and to other elements, by means of covalent bonds, which can be broken with a amount of energy that allows for an electron to move to a higher energy level, in practice from the valence band to the conduction band, exceeding the prohibited band (Eg - energy gap). The energy required to perform this jump can be supplied to the electrons or by thermal excitation or absorption of photons of appropriate energy. For the silicon atom this energy Eg is 1.08 eV.

Generality

Inserting in the crystal structure of a semiconductor of impurities (**doping process**), which in the case of silicon is made with the introduction of phosphorus atoms, is obtained by the formation of n-type silicon having a concentration of negative charges greater than silicon intrinsic. Introducing boron atoms, is obtained by the formation of p-type silicon having a higher concentration of positive charges (Figure)



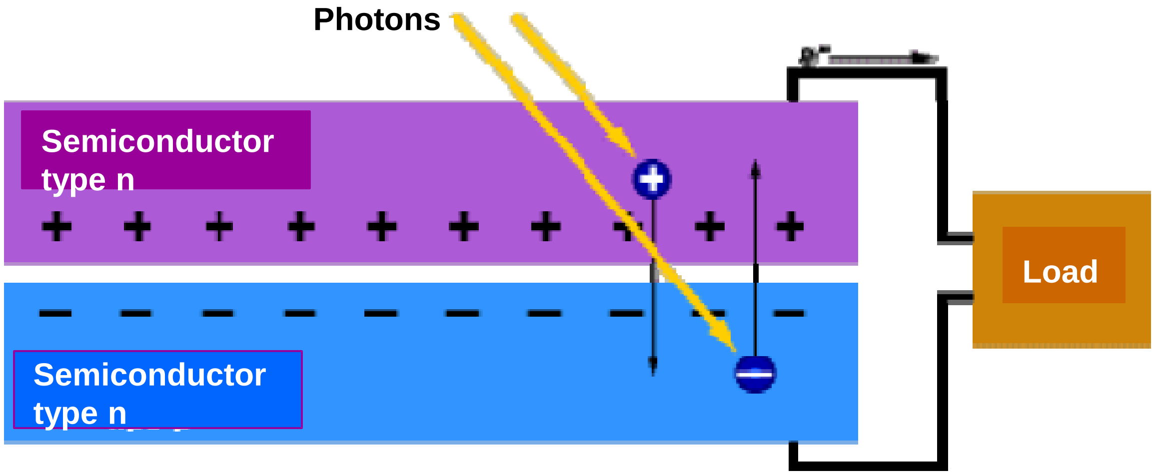
Generality

To generate an electric field and, consequently, an electric current, there must be contact of two layers of silicon pen (pn junction), which activates an electronic flow from zone n to zone p; reached the point of electrostatic equilibrium, determines an excess of positive charge in the area n, due to the phosphorus atoms with one electron less, and an excess of negative charge in the area p, due to the electrons migrate from the area n. The electrons present in the n-type silicon are spread for a short distance in the silicon p-type: the n-type silicon is charged positively, one of type p is negatively charged and it creates a region intermediate said **depletion area**. The result is an internal electric field to the device the amplitude of a few micrometers.

Solar photovoltaic systems

<u>Generality</u>

The technique of the silicon doping together with the bombardment of photons constituting the sunlight generates the photovoltaic effect (figure)



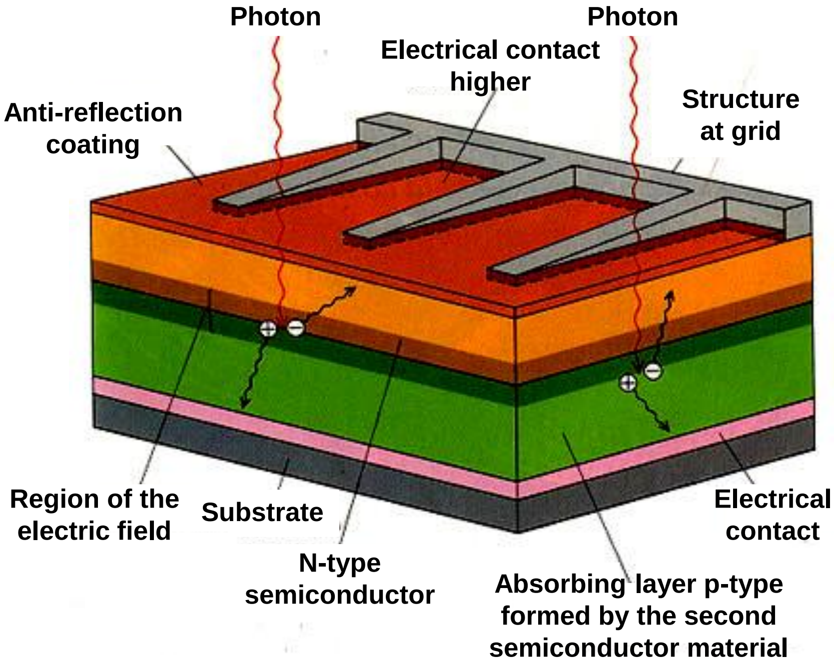
Generality

The reasons for this low efficiency are:

- **reflection**: not all of the photons, which affect the cell, penetrate it, given that in part are reflected from the surface of the cell and in part affect the metal grid of the contacts;
- **photons little energetic**: to break the bond between electron and nucleus requires some energy, and not all incident photons have enough energy;
- **recombination**: not all the electron-hole pairs generated are collected by the electric field of the junction and sent to the external load, given that in the path from the point of generation can meet and recombine charges of opposite sign;
- **parasitic resistances**: the metal contacts on the front and on the back of the cell have a resistance that causes power dissipation.

Generality

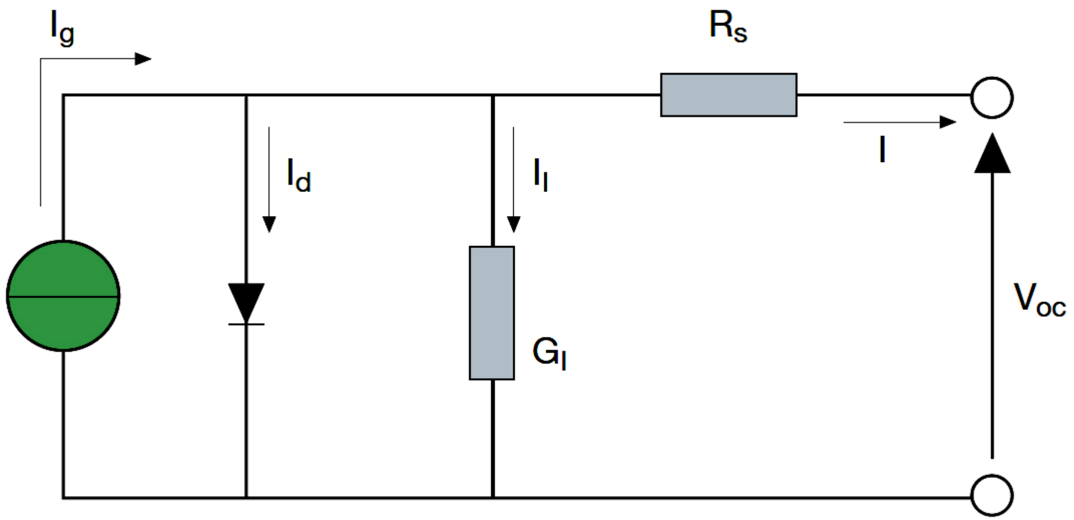
The ratio between the maximum output power of the cell and the solar irradiation in standard conditions is called **conversion efficiency**. In order to increase the efficiency, the photovoltaic cell is treated with an antireflective coating formed by the deposition of a thin layer of titanium oxide (TiO_2) can reduce the reflected solar component (figure)



Generality

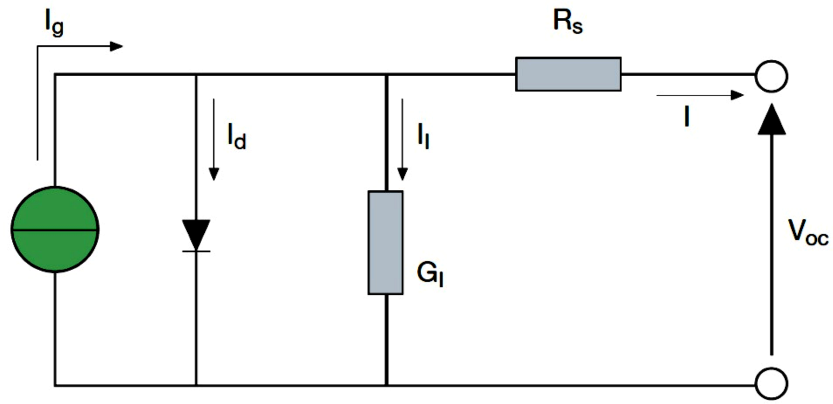
The electrical flow generated within the cell is conveyed outside by means of a metal grid front of collection and a rear contact, applied by electrodeposition.

A photovoltaic cell can be considered as a current generator and can be represented by the equivalent circuit of Figure



Generality

The current at the output terminals I is equal to the current generated by the photovoltaic effect from the I_g ideal current source, minus the diode current I_d and the leakage current I_l. The resistance R_S is the internal resistance to the flow of current generated and depends on the thickness of the p-n junction, the impurities and the contact resistances. The conductance of dispersion G_l takes account of the current to ground in the normal operation. The conversion efficiency of the photovoltaic cell suffers from a very small change in the R_S, while it is much less affected by a variation of G_l.



Generality

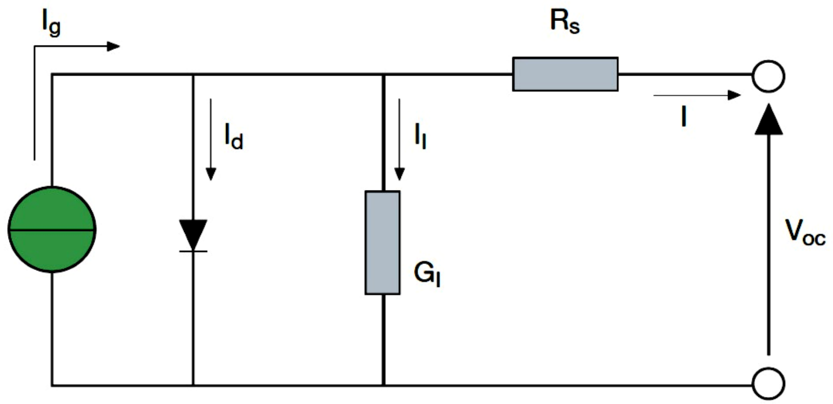
The open circuit voltage V_{OC} occurs when the load does not absorb current (I = 0) and is given by the relation:

$$V_{OC} = \frac{I_I}{G_I}$$

The current of diode is supplied from the classic expression of direct current:

$$I_d = I_D \cdot \left[e^{\left(\frac{Q \cdot V_{OC}}{A \cdot k \cdot T}\right)} - 1 \right]$$

where ID is the saturation current of the diode, Q is the electron charge, A is the identity factor of the diode and depends on the recombination factors inside the diode itself, k is the Boltzmann constant and T is the absolute temperature.

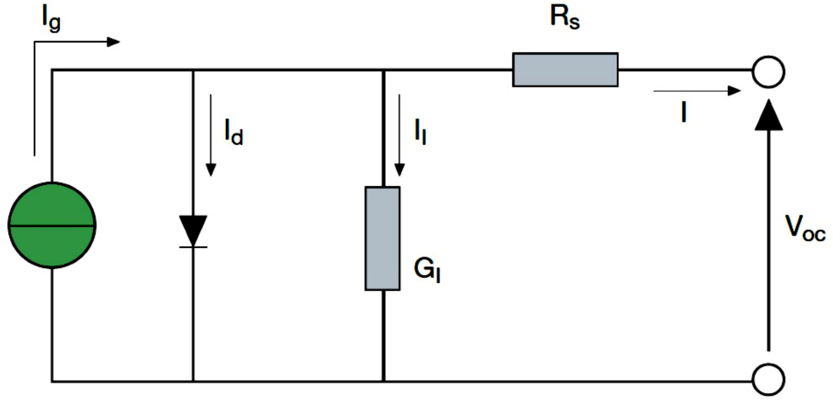


Generality

The current supplied to the load is therefore given by the expression:

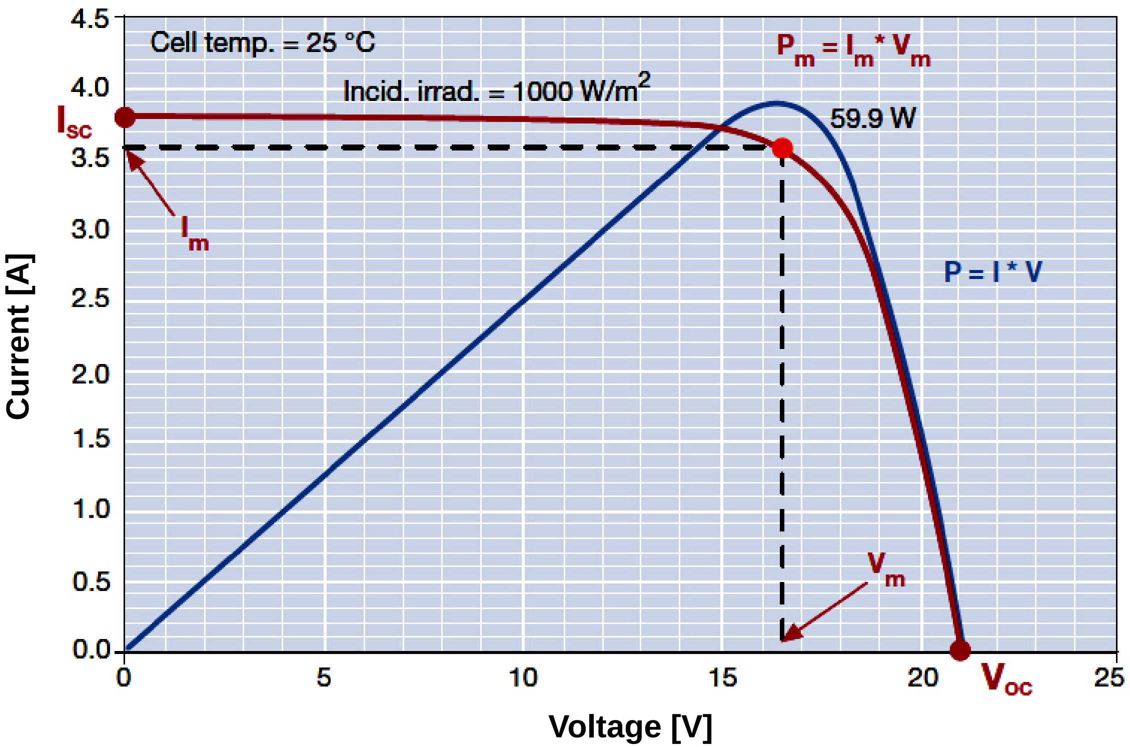
$$I = I_g - I_d - I_I = I_g - I_D \cdot \left[e^{\left(\frac{Q \cdot V_{OC}}{A \cdot k \cdot T}\right)} - 1 \right] - G_I \cdot V_{OC}$$

The last term, the leakage current to earth I_l, in the usual cells is negligible compared to the other two currents. The saturation current of the diode may therefore be determined experimentally by applying the open circuit voltage V_{OC} in a cell is not lit and measuring the current flowing within the cell.



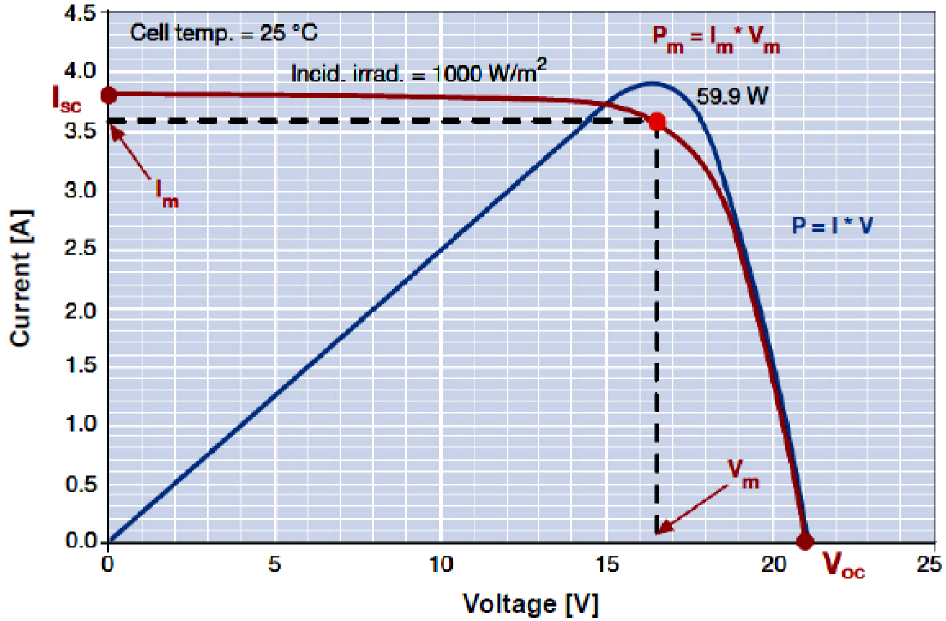
Generality

The voltage-current characteristic of a photovoltaic cell is shown in figure



Generality

In short circuit conditions the current generated is maximum I_{SC}, while in conditions of open circuit voltage V_{OC} is maximum. In these two conditions the electrical power produced by the cell is zero, while in all the other, when the supply voltage increases the power produced, first reaching the maximum power point P_m and then decreasing abruptly in the vicinity of the load voltage.



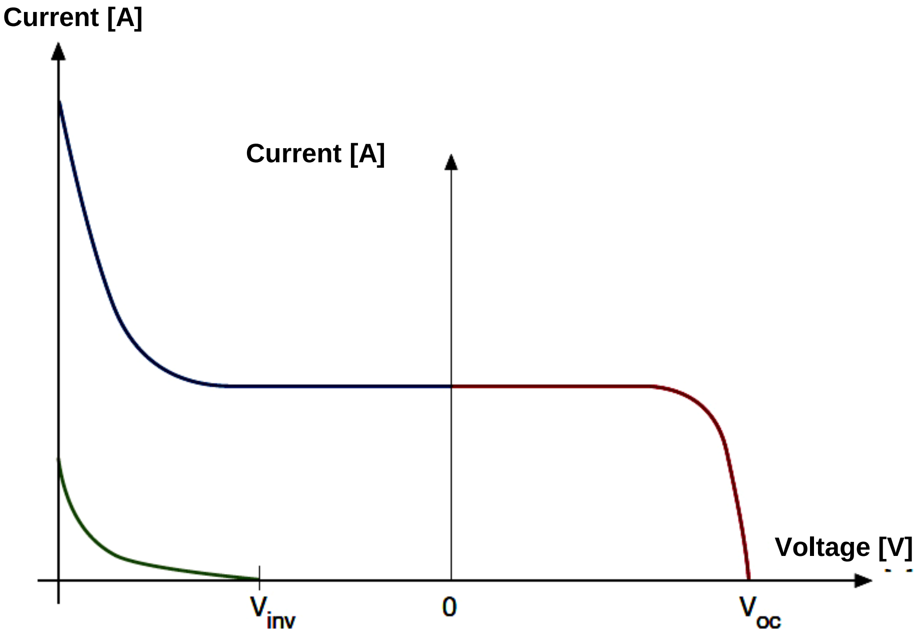
Generality

Therefore the data characteristic of a solar cell are:

- I_{SC} short-circuit current;
- V_{OC} open circuit voltage;
- P_m maximum power produced under standard conditions;
- I_m current produced in the maximum power point;
- V_m voltage at the point of maximum power;
- FF fill factor: is a parameter that determines the shape of the characteristic curve V-I and the ratio between the maximum power and the product ($V_{OC} \cdot I_{SC}$) of the load voltage for the short-circuit current.

Generality

If the photovoltaic cell voltage is applied to the exterior in the opposite direction compared to that of normal operation (figure), the current produced remains constant and the power is absorbed by the cell. Beyond a certain value of reverse voltage (break down voltage), the p-n junction you perforated and the current reaches a high value damaging the cell. In the absence of light, the current generated is nothing for reverse voltage to the voltage break down, then it has a discharge current similar to the conditions of illumination



Generality

Since the power of a photovoltaic cell varies as a function of temperature and solar radiation incident, in order to compare the characteristics of the different photovoltaic cells, have been defined standard conditions imposed by international standards (Standard Test Conditions): **incident radiation: 1000 W/m^2, module temperature: 25°C and wind: 0 m/s**.

Another parameter that is often used is the nominal operating temperature of a cell NOCT (Nominal Operating Cell Temperature), which provides the thermal behavior of the modules and is referred to the following operating conditions: the incident radiation: 1000 W/m^2, air temperature: 20°C and the wind: 1 m / s.

The power that a typical cell is capable of delivering under Standard Test Conditions is called **peak power** (W_p).

Solar photovoltaic systems

Generality

A photovoltaic system to the traditional fixed panel is in any case the concentration system is more convenient for insolation levels beyond 1350 kWh/m^2, with an efficiency of nearly 23%. Concentration technology is rapidly developing, but it is unlikely to go to replace fixed installations, at least not those small and medium size that make them easy to install a strength.

The photovoltaic modules on the market, to be able to access funding of government incentives, will be tested and verified by laboratories according to UNI CEI EN ISO/IEC 17025, in addition to the crystalline silicon modules referenced particular CEI EN 61215 (CEI 82-8) for the design qualification and type approval.

Solar photovoltaic systems

Generality

The production of 1 kWh of electricity from solar energy, when compared to the production from fossil fuels in the production mix Italian, avoids the emission of 0.53 kg of carbon dioxide and all other types of pollution, such as nitrogen oxides, carbon monoxide, sulfur dioxide etc. (table)

Electricity and atmospheric emissions						
Atmospheric emissions	Unit of measure	Coal plant	Fuel oil plant	Natural gas plant	Gas plant to combined cycle	Photovoltaic system
Carbon dioxide	Kg/kWh	1,02	0,75	0,48	0,35	0,00
Nitrogen oxides	g/kWh	0,83	0,56	0,50	0,33	0,00
Sulfur dioxide	g/kWh	1,66	1,12	negligible	negligible	0,00
Dust	g/kWh	0,21	0,14	0,01	0,01	0,00

Generality

The amount of avoided emissions is a function of the annual production of the plant, the installed capacity and the average yield of the panels, as well as insolation of installation locations. You can thus calculate the emissions avoided per year for each kW installed photovoltaic are, for northern Italy, 804 kg of carbon dioxide and, falling to the south, you get to 1,120 kg.

But we must not neglect the environmental impact on the production of photovoltaic panels (extraction and processing of silicon for the production of cells and assembly into panels, machining of the various components of the same panel, the installation of the plant and disposal end of life); in fact the only silicon processing involves a pollutant emission of 11-75 g/kWh of CO_2 and from 0.04 to 0.3 g/kWh depending on the type of cell (amorphous silicon 2010 - monocrystalline 1997).

Generality

The analysis of environmental impacts due to the photovoltaic technology highlights that the production of the same entails an energy cost is not zero, it becomes crucial to this **analysis of the energy payback time** (**EPT**). The cumulative energy input, which is the primary energy input throughout the life cycle of the modules, is estimated at 10-20% of the energy produced by the same throughout the life of the plant, according to technology considered.

Energy Payback Time (EPT) is the energy payback time, ie the time necessary for a plant to produce an amount of energy equal to that which was needed to construct it. It is also equivalent to the financial concept of "payback time", where after they have recovered the money invested, everything that comes in is more profit.

Generality

A further analysis of considerable importance from an economic point of view is the **analysis of energy-EROEI**, **energy return on energy investment**, this criterion that allows to evaluate the relationship between the energy that a plant will produce during its active life and the energy required to build, maintain and then dismantle the plant. If a plant brings a return will have a useful EROEI greater than 1. Despite the rules, a full analysis of EROEI is not easy and depends a lot on some sizes that can be estimated as best as possible, but you can not accurately determine

Generality

Below the values of gray energy needed to complete cycle of production of the module, extraction of raw materials, transport and end of processing, the energy pay back time and of EROEI, comparing the values for the various technologies to silicon (table)

Greatness	Unit	Silicon monocrystalline	Silicon polycrystalline	Silicon amorphous
Gray energy	kWh/kW_p	5,0 – 8,0	3,5 – 7,0	2,5 – 4,0
Energy pay back time	Years	2,1 – 3,3	3,9 – 6,6	1,0
EROEI	-	4,0 – 9,0	4,0 – 9,0	25,0 – 50,0

Generality

High cost and low performance are the real limitations that penalize the advantages of simplicity, reliability and durability of photovoltaic systems. The production cost of a kWh still oscillates between minimum of 0,20 € to over € 0.50 for plants not connected to the network; the values that depend on the irradiation conditions of the installation site, but which are well above production costs of fossil fuels (from 0.04 to 0.07 €) or the cost of wind energy, which fell to values of the order of 0.06 to 0.09 € per kWh.
At the beginning of 2007 the price estimated by the European Photovoltaic Industry Association (EPIA) for a turnkey system is € 6,000.00/kW_p, with forecasts of further declines in the next two years. The learning curve budget estimate for this technology reduces costs by 20% every time you double the cumulative installed capacity.

Solar photovoltaic systems

Generality

The incentive mechanism provided the capital funding up to 75% of the investment, bestowed the Ministry of Environment and the Regions. The mechanism has been far from effective, due to the difficult management by the Regions.

By Ministerial Decree of 28 July 2005, was also introduced in Italy the mechanism or feed-in tariff, thus replicating the German experience and setting targets and mechanisms that are subsequently amended and supplemented by the Ministerial Decree of 6 February 2006 with the most recent on 19 February 2007; with the latter are revised incentives in favor of building integrated plants.

Solar photovoltaic systems

Generality

As early as 2005, the incentive is not a capital funding, or reimburses a portion of the initial investment, but rather a system that pays for twenty years, the electricity produced and therefore obliges managers kept operational and efficiency in the plants themselves.

With the new method has given a boost to the development of photovoltaics and the incentive that depends on the correct installation of the system. In fact, only after you have installed and put into operation the plant can apply for incentive based on the size and level of architectural integration. It is just a strict compliance and adjustment due to the technical and procedural requirements to be sure of obtaining the loan.

Generality

It also introduces a differentiation of the plants according to the level of architectural integration, with the tendency to reward the small integrated plant rather than that the large solar field to ground. The new tariffs are those given in the table

Nominal power of plant	Plant not integrated	Plant partially integrated	Plant architecturally integrated
kWp	€/kWh	€/kWh	€/kWh
1≤P≤3	0,40	0,44	0,49
3≤P≤20	0,38	0,42	0,46
P>20	0,36	0,40	0,44

Generality

The new rates will remain in force until 31 December 2008, only to be cut by 2% per year until 2010, the year in which there is a further review.
The decree n. 387/2003 provides for the promotion of all the energy produced, allowing you to write off a medium-sized facility in about ten years and made for an excellent economic performance. Stimulating the energy produced is obtained, in fact, a double saving: on the one hand, it encourages all the energy produced, consumed or not it; other producing energy you avoid having to withdraw from the network, resulting in a net saving in the bill. In practice the self-consumed energy is remunerated dall'incentivo as self-produced energy, getting to be paid for the energy that is consumed.

Solar photovoltaic systems

Generality

The plants of nominal power above 20 kW, as in the preliminary project analyzed, it is expected the trade regime in place (make a balance between the annual electricity fed into the grid from the plant and the electricity drawn from user). It follows that all the energy is fed into the grid is not self-consumed and purchased from the Single to the administered price, or sold on the free market.

Solar photovoltaic systems

Generality

The decree of 12.02.2007 on the new energy bill also provides the ability to associate the incentive on production to any other regional incentives for the promotion of alternative sources. In Friuli Venezia Giulia, for example, there are regional and provincial laws aimed at the development of photovoltaic systems, such as the contract to encourage capital to businesses that want to install photovoltaic plants with capacities above 10 kW. These capital funding, as provided in the decree, be combined with the energy bill as long as they do not exceed the rate of 20% of capital invested, or risk losing the right to the incentive state production.

Generality

For the years 2014, 2015 and 2016, GSE (Energy Services Manager) indicates the percentage reductions to be applied to tariffs of the previous semester.

Incentives Photovoltaic Solar Plants: 1st half 2014: 13% reduction, 2nd half 2014: 13% reduction, 1st half 2015: 15% reduction, 2nd half 2015: 15% reduction, 1st half 2016: 30% reduction and 2nd haf 2016: 30% reduction

Incentives Photovoltaic Innovative Plants: 1st half 2014: 4% reduction and 2° half 2014: 4% reduction

Incentives Concentration Photovoltaic Plants: 1° half 2014: 4% reduction and 2nd half 2014: 4% reduction

Types of photovoltaic cells

Most of the photovoltaic cells on the market is constituted by silicon semiconductors. The main reason for this choice is due to the fact that silicon, unlike other semiconductors, is available in nature in virtually unlimited amount.

In addition, silicon is widely used in the electronics industry that has facilitated the development of existing methods of refining, processing and doping. In addition, the scraps of the electronic components can be recycled in photovoltaic industry that tolerates products with lower degree of purity.

Types of photovoltaic cells

The processes of production of photovoltaic cells are different depending on the type of cell that is to be realized. The major differences in the formation of the silicon wafer, referred to as "**wafer**", which is the main structure on which various treatments are performed, especially of a chemical nature, which will lead to its creation.

The cells most valuable, that offer the best performance are those of **monocrystalline silicon**, which is obtained by a process, said **melting**, from silicon crystals of high purity which, when melted, are solidified in contact with a crystal seed. The cooling process leads to the formation of a cylindrical ingot formed of a single crystal with a diameter of 13-20 cm and a length that can reach 200 cm. The ingot is then cut into thin blades; the thickness of the wafers which are obtained is 250-300 μm.

Types of photovoltaic cells

For cells less valuable, some years you are also using the **polycrystalline silicon**. The wafer of multi-crystal is obtained by melting and subsequent recrystallization of the silicon scrap electronics industry. The polycrystalline silicon has lower production costs and the recrystallization does not take place in an orderly manner as is the case for the monocrystalline silicon, since the molten bath originate more crystals that grow at the same time, to form a 'bread' that will then be cut in the shape of a parallelepiped. The growth is faster than that of monocrystalline silicon and requires less energy. The efficiency of these cells is lower than the first, the yields vary between 12% and 14%.

Types of photovoltaic cells

A different type of cells, said thin film, used for particular applications, is the one that exploits the **amorphous silicon**, which differs substantially from the products in the crystal since the production process. In this type of cell the active material is available in the form of gas deposited on different types of support surfaces. The film that is deposited reaches a thickness of a few μm, which allows interesting applications where the technology of the lens is inhibited due to the rigidity of the structure. The efficiency of amorphous silicon cells, with yields up to 10% of the cells is less crystalline and, even if the costs remain quite high, are used for installation on flexible structures, of special shape or on panels rollable.

Types of photovoltaic cells

One other technology of construction of the thin-film solar cells involves the use of **gallium arsenide** (GaAs) instead of silicon. This technology, albeit with very high costs, yields very high returns, with peaks of 35%, almost double the yield obtained with the single-crystal silicon, making these cells particularly suitable for use aerospace. Other solutions such as thin-film **modules CIS** (copper indium diselinide) are promising from the economic point of view but needs to be further developments regarding the efficiency and performance is maintained over time, weakness of the thin film.

Types of photovoltaic cells

The thin film technology can solve the problem of supply of basic material, as, leading to a very limited consumption of material, equal to about 1/200 of that required for crystalline silicon technology could allow the development of production processes dedicated, that does not depend from the electronics industry. Potentially thin films have a lower cost than the crystalline silicon, and for the greater simplicity of the process, due to the lower the energy payback time (EPT). As for the **crystalline silicon cells the EPT time corresponds to 3.2 years for thin-film cells is approximately 1.5 years**.

Harnessing the sun's energy to produce electricity has clear and indisputable advantages.

Solar photovoltaic systems

Types of photovoltaic cells

During the operating phase, a photovoltaic system does not involve any type of harmful emissions and allows to avoid the emission of many pollutants. It is estimated that in the life cycle 1 kWh of photovoltaic will avoid about 20 tons of CO_2. In order to make a more careful and detailed, it must however take into account the production and installation of a photovoltaic module is not zero emission, but involves the consumption of energy. In particular, the environmental costs are attributable to the consumption of raw materials and energy as well as waste production and disposal and recycling plant at the end of its useful life.

Types of photovoltaic cells

The environmental impact assessment of a product or system, in order to provide meaningful results, it needs to consider the entire life cycle of the same. An operational tool that allows you to conduct this assessment is the Life Cycle Assessment (LCA), which by definition is a process that allows to assess the environmental impacts associated with a product, process or activity by identifying and quantifying consumption matter and energy, and emissions into the environment and the identification and evaluation of opportunities to reduce these impacts. The analysis covers the whole life cycle of the product or process, from its beginning to its end, the extraction and processing of raw materials, production, transport and distribution of the product, its use, reuse and maintenance, up to recycling and final disposal.

Solar photovoltaic systems

Types of photovoltaic cells

The environmental impact on the production of photovoltaic panels is due to the extraction phases of silicon, the same processing for the production of photovoltaic cells and assembly into panels, you must also consider all the stages of processing of the various components of the panel itself the commissioning of the plant and disposal at end of life.

Types of photovoltaic cells

Consider that in the production phase of the solar panels the environmental impact is similar to that of a chemical plant. In fact, in the production process are used toxic substances that require the presence of adequate security systems. In case of malfunction, however, pollution concerns only the production site without major contamination of the surrounding environment. The risks in case of accident will be different according to the different type of panel worked. The production of crystalline silicon cells involves the working of chemicals such as trichlorosilane, phosphorus ossicloridrico and hydrochloric acid; for amorphous silicon using substances such as silane, phosphine and diborane. Finally in the production of the CIS (Copper, Indium e Selenide) stands selenurio hydrogen and that of cadmium in CdTe modules, high toxicity and impact on health.

Solar photovoltaic systems

Types of photovoltaic cells

The environmental impact for the photovoltaic production is similar to that of an industrial production process and as such, the experience and the technological evolution covers an important role in limiting consumption and environmental repercussions.

A solar panel has a useful life of 30 years, during which produces no emissions, but at the end of these will turn into a special waste to be treated appropriately. The photovoltaic module is composed of many elements, many of which are toxic and the separation and recovery of these appears to be a process is not simple. It is very likely, however, that in the coming years with the expansion of the market for money laundering offenses receive investments by the manufacturers themselves so that we can recover some of the metals needed for new productions.

Solar photovoltaic systems

Types of photovoltaic cells

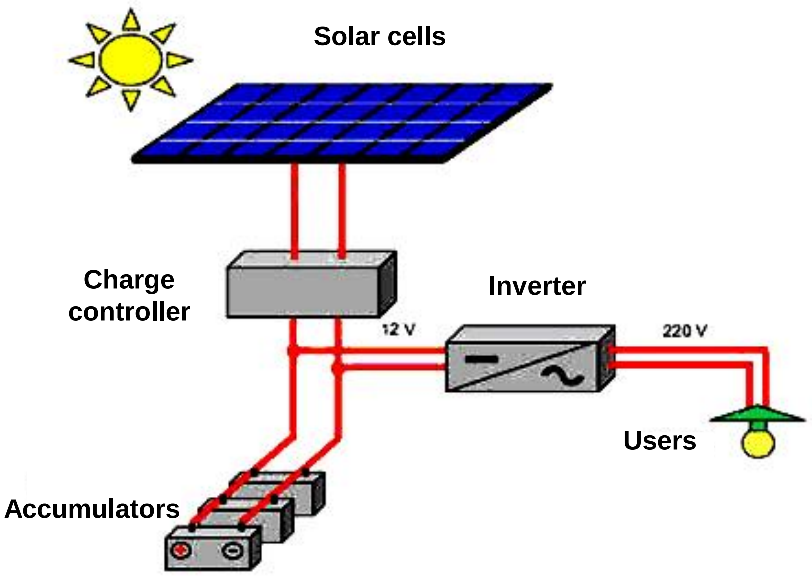
Of other nature, but no less important, is the environmental impact to be landscaped. The installation of large solar power plants require the occupation of space is vast, although apparently indifferent in terms of emissions, can interfere with the landscape and human activity. For this, more so, the tendency is to favor the creation of small systems installed on the roofs of buildings and homes in urban centers without affecting rural areas.

Photovoltaic systems

The photovoltaic system is composed of a set of electrical, electronic and mechanical devices capable of receiving and converting solar energy into electric energy, up to make it available for use by the user. Depending on their use the systems are classified into:

a) isolated systems (stand-alone)

They provide energy directly to the user during the hours of sunshine, while the excess energy is stored in batteries, making it available in the periods when the photovoltaic array is not in a position to provide it.



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a) isolated systems (stand-alone)

A photovoltaic plant consists of the following elements:

- **solar cell**: used for the transformation of solar energy into electrical energy;
- **charge regulator**: electronic device that regulates the charging and discharging of the batteries with the possibility of programming and control system;
- **storage batteries**, usually lead: are the systems of energy storage of a photovoltaic plant and provide electricity when the modules are not able to produce, for lack of solar radiation;

Solar photovoltaic systems

Photovoltaic systems

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a) isolated systems (stand-alone)

A photovoltaic plant consists of the following elements:

- **inverter or converter**: converts the direct current from the modules and/or accumulators into alternating current at 230 V single-phase or three-phase 400 V;
- **utilities**: appliances powered by photovoltaic.

Photovoltaic systems

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a) isolated systems (stand-alone)

When it is necessary that the voltage at the load has a constant value are used of circuits and voltage regulators, which maximize the performance of the PV system making it work with the voltage and current optimal (devices Maximum Power Point Cracker or MPPT - trackers maximum power point)

Photovoltaic systems

The photovoltaic system is composed of a set of electrical, electronic and mechanical devices capable of receiving and converting solar energy into electric energy, up to make it available for use by the user. Depending on their use the systems are classified into:

b) plants connected to the network (grid-connected)

Are permanently connected to the electricity distribution network. In the hours in which the plant is not capable of producing sufficient energy to meet the demands of users, the electricity network delivers energy to the user by operating in parallel to the photovoltaic plant, while in those in which the plant produces more energy than it is used, the excess is fed back into the national grid, which acts as a storage time for the PV system. These systems require very little maintenance as they have no moving parts and installations of energy storage.

Photovoltaic systems

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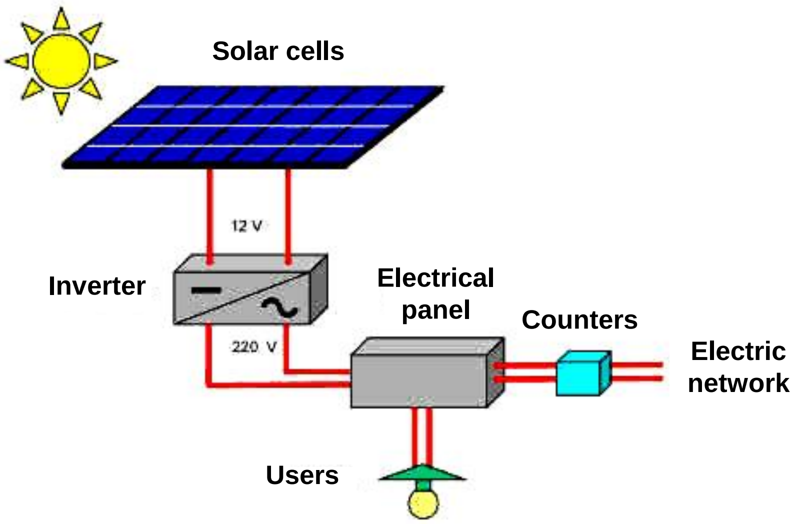
b) plants connected to the network (grid-connected)

A photovoltaic plant to grid-connect is mainly composed of the following components:



Photovoltaic systems

The photovoltaic system is composed of a set of electrical, electronic and mechanical devices capable of receiving and converting solar energy into electric energy, up to make it available for use by the user. Depending on their use the systems are classified into:

b) plants connected to the network (grid-connected)

A photovoltaic plant to grid-connect is mainly composed of the following components:

- **solar cell**: for the transformation of solar energy into electrical energy;
- **inverter**: transforms the direct current coming from the modules of the conventional alternating current at 230 V single-phase or three-phase 400 V, necessary for the proper operation of the connected and the power of the network;

Photovoltaic systems

The photovoltaic system is composed of a set of electrical, electronic and mechanical devices capable of receiving and converting solar energy into electric energy, up to make it available for use by the user. Depending on their use the systems are classified into:

b) plants connected to the network (grid-connected)

A photovoltaic plant to grid-connect is mainly composed of the following components:

- **electric network**: where is the distribution of energy;
- **network**: connection to the public network of the utility;
- **users**: appliances powered photovoltaic system.

Photovoltaic systems

The photovoltaic system is composed of a set of electrical, electronic and mechanical devices capable of receiving and converting solar energy into electric energy, up to make it available for use by the user. Depending on their use the systems are classified into:

b) plants connected to the network (grid-connected)

These plants offer the advantage of distributed generation, rather than centralized, as the energy produced in the vicinity of the use has a value greater than that provided by traditional large power plants, they are limited transmission losses and reduce the economic burden of the big electrical transmission and dispatching. Moreover, the production of energy in the hours of sunshine can reduce the demand to the network during the day, just when there is a greater demand

Photovoltaic systems

From the constructive point of view, as regards the choice of modules, you can choose between different technologies:

a) crystalline silicon modules

They can be in monocrystalline or polycrystalline, recognizable by observing the purity of the surface, but also the shaping of the cells, which has cut corners for those in monocrystalline and polycrystalline right angles to those. The corresponding modules are constructed from cells of dark blue color, adjacent to one another encapsulated in a laminate of glass and plastic film. They offer a good conversion efficiency of solar energy into electrical energy, respectively, between 14% -17% and 12% -14%, which is associated with high durability and maintenance characteristics over time.

Photovoltaic systems

From the constructive point of view, as regards the choice of modules, you can choose between different technologies:

b) thin-film modules

Composed of semiconductor material deposited, generally as a mixture of gases, on supports such as glass, polymers and aluminum, which give physical consistency to the mixture. The materials used are amorphous silicon, cadmium telluride-cadmium sulfide (CdTeS), gallium arsenide (GaAs) and based alloys selinurio double copper and iridium (CIS, CIGS, CIGSS).

The amorphous silicon modules are cost-effective, but they offer a less energetic performance than other types, with a yield of cells that worsens over time, and are used when you need to minimize the weight of the panel and adapted to curved surfaces of industrial warehouses.

Photovoltaic systems

From the constructive point of view, as regards the choice of modules, you can choose between different technologies:

b) thin-film modules

The modules in CdTeS have the advantage of being realized with simple processes and with performance equal to 10% -11% in the case of irradiation, exposure and inclination are not optimal. The disadvantage is related to an environmental problem: cadmium telluride contained in the cell can become a problem if not properly disposed of or recycled.

The modules in GaAs are the most interesting from the point of view of efficiency obtained, more than 25% -30%, but the production of these cells is limited by the high cost and scarcity of the material used and are mainly used for space applications, where are important weight and small size.

Photovoltaic systems

From the constructive point of view, as regards the choice of modules, you can choose between different technologies:

b) thin-film modules

The modules with films in CIS, CIGC and CIGSS are promising for the performance (reaching 13%), but they have limitations due to lack of availability, toxicity of some components and high production costs. The advantages are reflected in less use of semiconductor material, as well as the lower cost of production processes and the possibility of having transparent modules for roofs and facades. The thin film is less efficient, but has the advantage of better tolerate shading and be less affected by temperature.

Photovoltaic systems

The requirements to be considered in the choice of a photovoltaic module are:

- **efficiency**, to be considered at the same power, but also of module size and performance even at low radiation;
- **power tolerance**, which should preferably be positive;
- temperature coefficients of power (as is lower, the greater the overall yield and efficiency);
- **type of frame**, preferably free from empty chamber to eliminate the problems associated with ice in winter;
- **provision of the junction box**, to be preferred raised from the module to ensure maximum ventilation to the diodes by-pass and to the cells;
- **guarantees on the product in terms of power over time and guarantees**;
- **presence of a certification**.

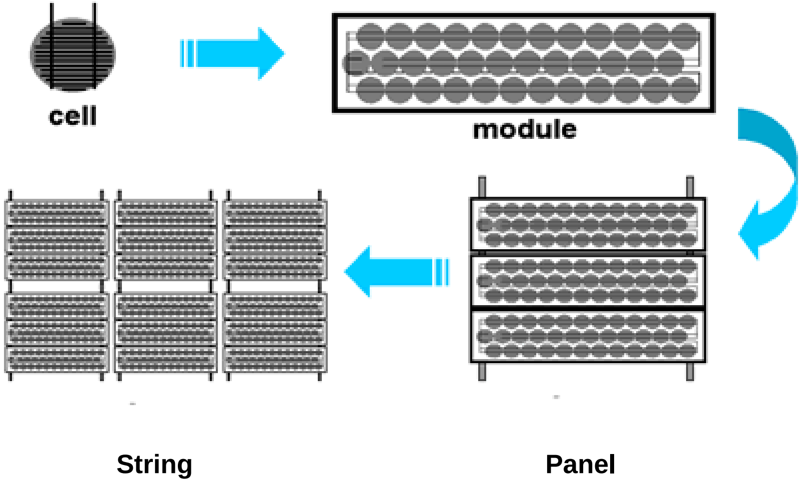
Photovoltaic systems

To gain access to the incentives of the Energy Bill, the PV modules must have specific certifications that attest to their quality and durability. The main rule for crystalline silicon modules is IEC 61215, which must necessarily accompany each module to be used for a photovoltaic system connected to the network. That for thin-film modules is IEC 61646, which includes many tests also included in IEC 61215, but also prescribes specific to this technology.

The "Energy Bill" is the decree establishing an incentive for 20 years for individuals, companies and government agencies that install a solar photovoltaic (ie a plant that generates electricity from solar energy) connected to the mains. The incentive is proportional to the electricity produced

Photovoltaic systems

The **photovoltaic field** is a set of photovoltaic modules suitably connected in series or in parallel so as to achieve the desired operating conditions.
More modules mechanically assembled together to form the panel, while modules or panels are electrically connected in series.
To obtain the nominal voltage generation, they form the string.
The electrical connection of several strings in parallel constitutes the field.



Photovoltaic systems

A fundamental choice in the design phase is surely that of the series-parallel configuration of the modules that make up the field, which determines the electrical characteristics of the photovoltaic generator, that are not those due to the series-parallel sum of the individual modules, since between them intervenes an effect of not perfect coupling (mismatch), due to the inhomogeneity of their electrical characteristics.

This phenomenon causes power losses that can reach 10%; for an appropriate series-parallel configuration of the field, in addition to a reduced loss, can increase the reliability of the field itself, limiting the effects caused by the failure of the individual modules.

Solar photovoltaic systems

Photovoltaic systems

The **inverter** is a static converter for converting direct current into alternating current (DC/AC converter). Despite having the same principle of operation of the electric motors, inverters dedicated to Photovoltaic systems have special characteristics such that manufacturers have had to specialize in the field with the right products.

Photovoltaic systems

A first distinction between two classes of inverters can be done according to the type of photovoltaic plant:

a) stand-alone plants

The inverters must ensure the supply of electrical energy with characteristics similar to those of the distribution network, and then, in addition to ensuring the necessary continuity, must be able to control the levels of voltage and frequency of the line feed. Must be able to withstand transient overloads (start of electric motors) and provide reactive power loads on power factor correction

Photovoltaic systems

A first distinction between two classes of inverters can be done according to the type of photovoltaic plant:

b) grid-connected plants

The inverters must convert the energy produced by the solar generator into alternating with as efficiently as possible, without having to adjust the voltage and frequency. Typical of these inverters is the ability to adapt to a reference voltage excursions with very pronounced, characteristic of the photovoltaic fields; this capacity is met with a follower circuit of the maximum power point or maximum Power Point Tracking (MPPT) that has the purpose to identify instant by instant that particular point on the characteristic curve of the generator so that it is maximum power transfer

Photovoltaic systems

The inverters must meet the requirements for electromagnetic compatibility which refer to the standards (IEC 50081 and IEC 61000), whose main aspects are the limit electromagnetic disturbance generated in order not to interfere with the operation of other equipment and its level of intrinsic immunity to electromagnetic disturbances.

The device that allows the conversion of the electrical energy is the conversion bridge, a circuit based on the use of diodes of which is controlled with the switching techniques PWM (Pulse Width Modulation - modulation of the pulse width).

Photovoltaic systems

Another central device for the operation of the **transformer**, whose functions are to adapt the voltage level of the primary circuit with the load and the galvanic separation between the PV generator and users.

The **storage system** is a typical component of alone plants and is normally produced with accumulators electrochemical type.

The presence of such a system allows the continuity of the service in case of insufficient irradiation.

The features that most affect the quality of the battery system are efficiency, durability, resistance to thermal excursions, low maintenance and reduced self-discharge.

Photovoltaic systems

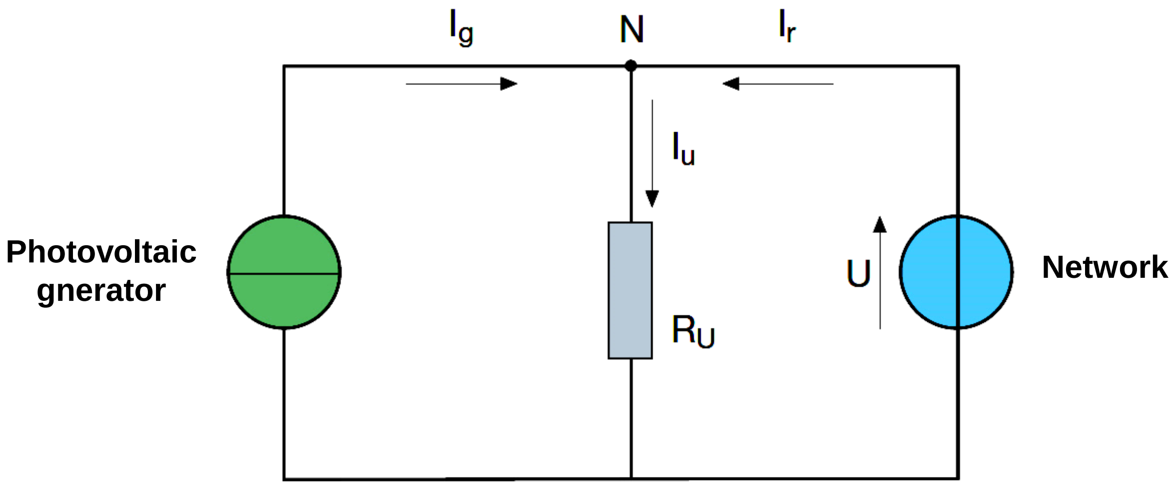
Delicate phase is the choice of **accommodation and the installation of the batteries**, these account for about one third of the cost of the system and their duration depends significantly on the characteristics of the environment in which they are housed. The location most suitable must be at a constant temperature around 25°C and with a moisture content less than 40%, and should be well ventilated since the batteries being charged emit oxygen and hydrogen, the latter may constitute a danger , as with concentrations above 4% will form an explosive mixture. This is why the local storage of a storage system becomes a danger of explosion and should be dimensioned according to current standards (IEC 60079 and IEC 50272).

Photovoltaic systems

The **network interface** is the set of a switching device (counter) with a relay, called the interface device and interface protection. Protection must be accepted by the company that manages the distribution of electricity to which it connects. Regulations (CEI 11-20, Standards for connection DK 5940 Enel S.p.A.) provide for different types of connection depending on the size of the plant and the type of connection offered by the network of distributor. For small plants, the protection interface for connection to the network can be integrated in the inverter. To grow the plant, switching from single-phase connection to the three-phase connection, interface protections and transformer from internal to external inverter, from delivery to delivery low voltage medium voltage. Note that, for the connection medium voltage, if the site is not equipped with its own transformation cabin and delivery, it is necessary to build a special.

Photovoltaic systems

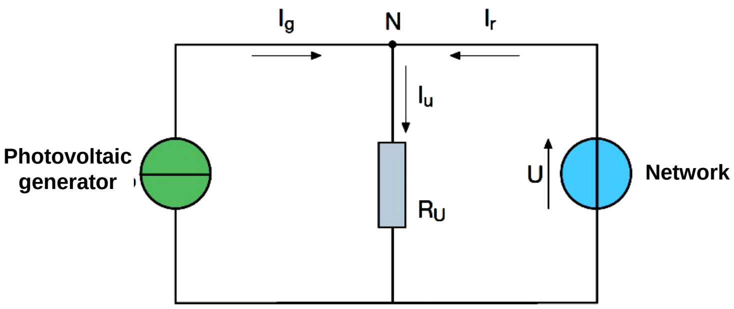
A photovoltaic plant connected to the network and that feeds a user plant can be represented in a simple way through the scheme of Figure



Photovoltaic systems

The supply network submitted to short-circuit power infinite is schematized by means of an ideal voltage source whose value is independent of the load conditions of the user. The photovoltaic generator is otherwise represented by an ideal current source (constant current equal to solar radiation), while the user system by a resistor R_U. In the node N converging currents I_g and I_r, respectively coming from the photovoltaic generator and the grid, and exits the current I_u absorbed by the user:

$$I_u = \frac{U}{R_U}$$



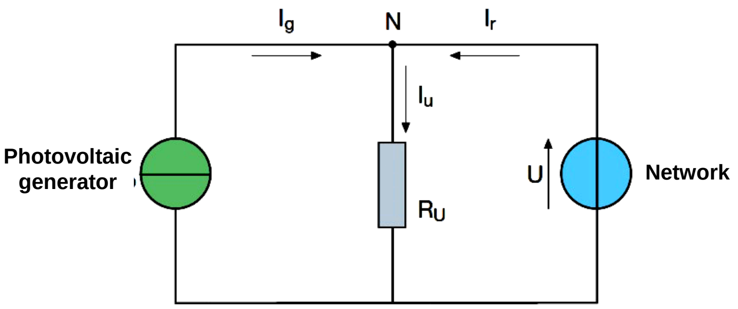
Photovoltaic systems

Since the load current is also the ratio between the voltage U and the resistance of the load itself R_u:

$$I_u = \frac{U}{R_U}$$

the report on the current becomes :

$$I_r = \frac{U}{R_U} - I_g$$



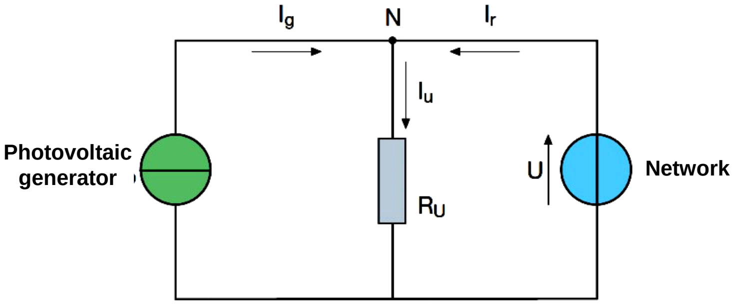
Photovoltaic systems

If the report is placed $I_g = 0$, such as may occur during the night hours, the current that the load absorbs from the network is :

$$I_r = \frac{U}{R_U}$$

Conversely, if all the current generated by the photovoltaic system is absorbed by the user cancels the current supplied by the network and therefore the relationship becomes :

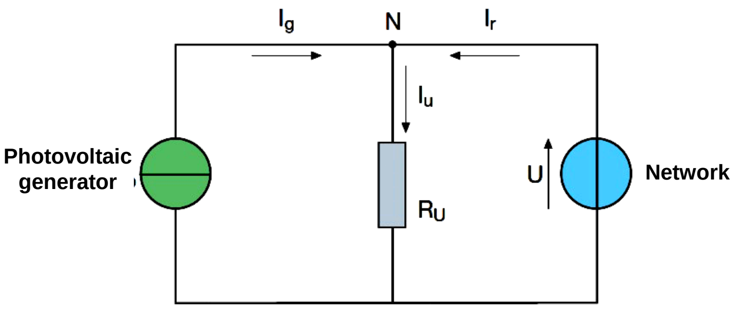
$$I_g = \frac{U}{R_U}$$



Photovoltaic systems

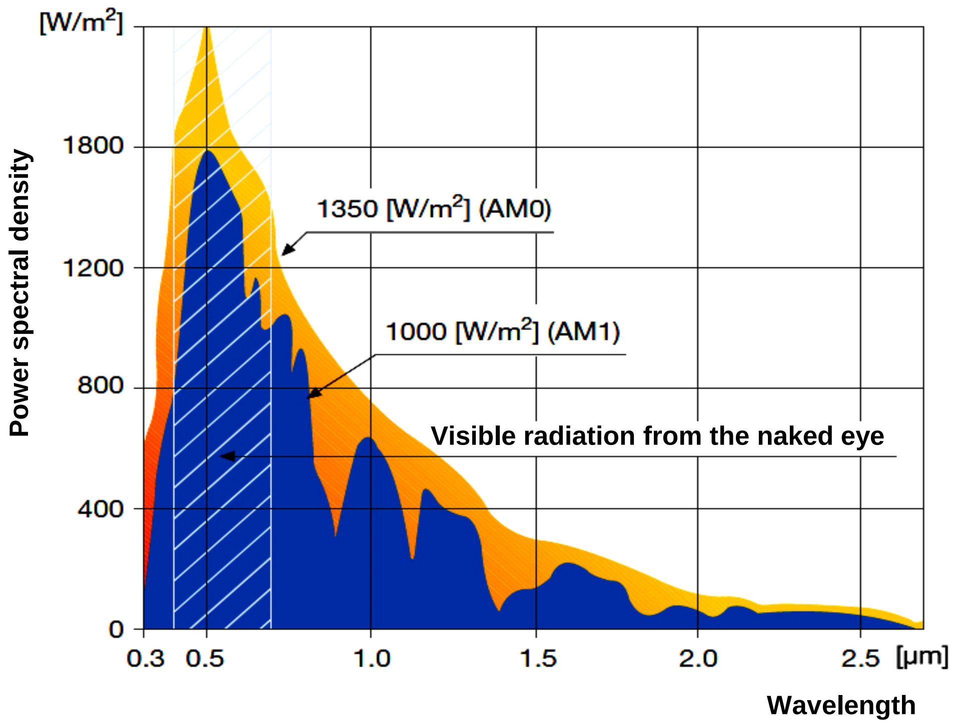
If to grow of the solar radiation the generated current I_g becomes higher than that required by the load I_u, the current I_r becomes negative, i.e. is no longer charged, but fed into the grid.

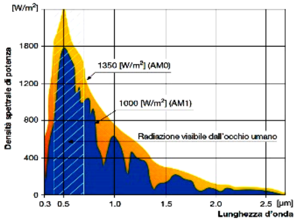
The nominal peak (kWp) is the electrical power that a photovoltaic system is capable of delivering in the standard test conditions (STC): 1 kW/m of radiation perpendicular to the panels, 25°C cell temperature, and the index the air mass (AM) of 1.5.



Photovoltaic systems

The air mass influences the photovoltaic energy production as it is an index of the trend of the power spectral density of the solar radiation, which has a spectrum which also varies as a function of air density (figure).





Photovoltaic systems

The yellow surface of the figure represents the radiation perpendicular to the earth's surface, absorbed by the atmosphere, while the blue surface indicates the solar radiation that actually reaches the earth's surface; the difference of the trend of the two curves gives an indication of the variation of the spectrum due to the air mass. The holes of irradiance correspond to the frequencies of the solar radiation absorbed by water vapor in the atmosphere. The **index of air mass AM** is determined by:

$$AM = \frac{P}{P_o \cdot sen(h)}$$

where:

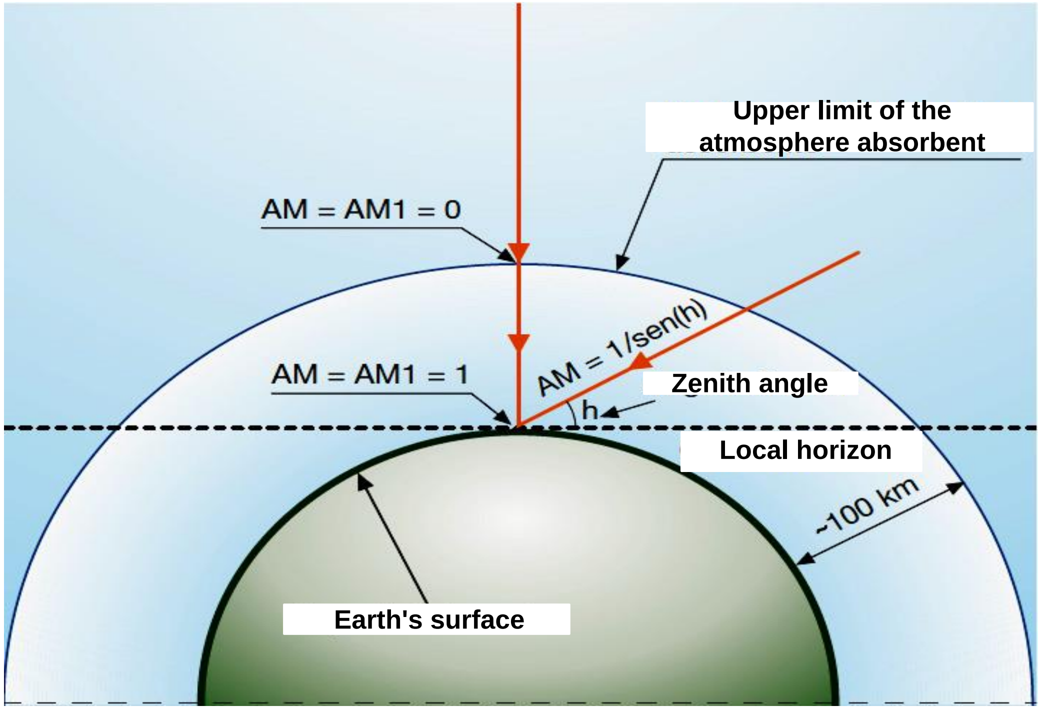
P = atmospheric pressure measured at the point and the instant considered (Pa);

P_o = reference atmospheric pressure at sea level (Pa);

h = zenith angle, i.e. the angle of elevation of the sun above the horizon local instant considered (Figure)

Photovoltaic systems

h = zenith angle, i.e. the angle of elevation of the sun above the horizon local instant considered (Figure)



Solar photovoltaic systems

Photovoltaic systems

Significant values of AM are:

AM = 0 outside the atmosphere where P = 0;

AM = 1 at sea level on a day with clear skies and the sun at its zenith;

AM = 2 at sea level on a beautiful day with the sun at 30° above the horizon.

The maximum output of a solar panel could result if the incidence of sunlight was always 90º. In fact, the incidence of solar radiation varies both with latitude, both during the year with the solar declination.

Photovoltaic systems

If you want to tilt the panels so that they are perpendicular affected by sunlight at noon on the longest day of the year, you have to know the maximum height in degrees that the Sun is above the horizon at this time, using the relationship:

$$\alpha = 90^{o} - \text{lat} + \delta$$

where:

δt = value in degrees of latitude of the site of installation of the panels;

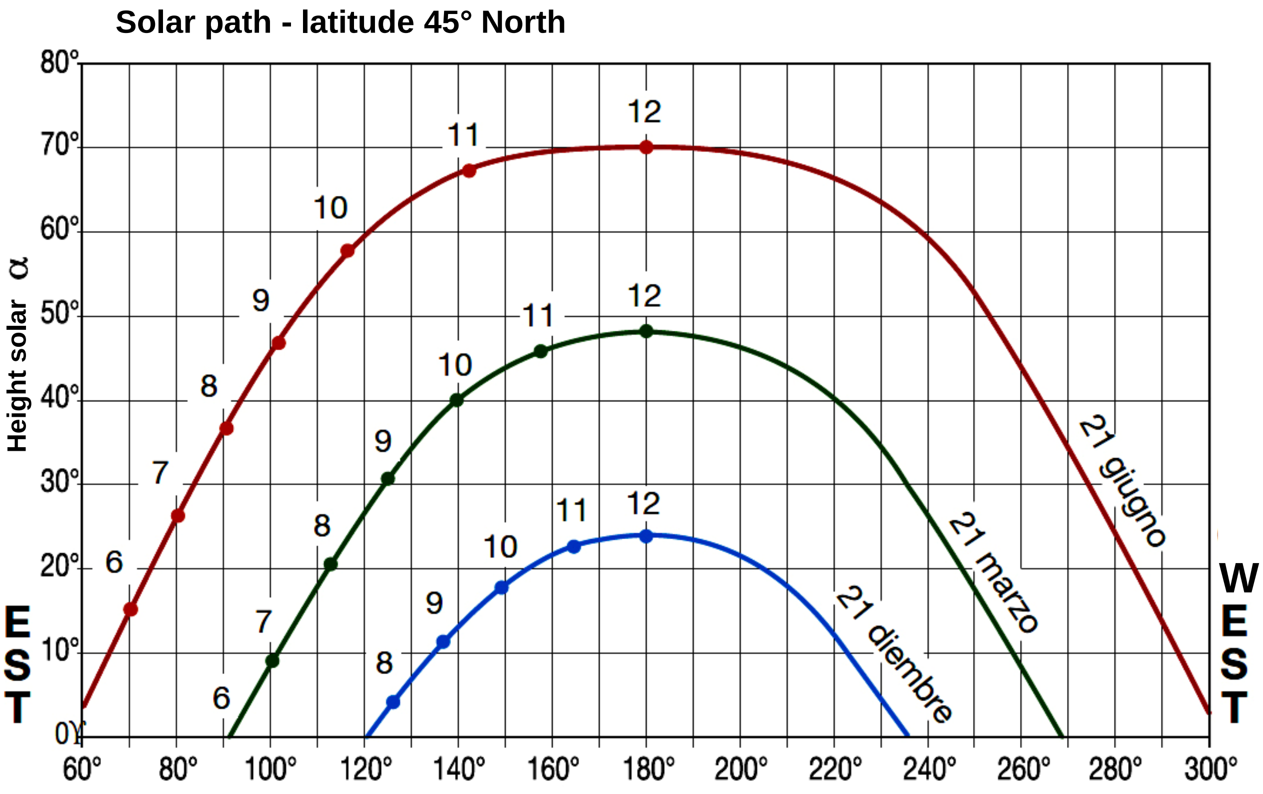
= angle of solar declination (23.45º).

Photovoltaic systems

Taking the complement of the angle α (90º- α), we obtain the angle of inclination, said angle of tilt of tβe panels with respect to the horizontal plane so that they are perpendicularly hit by solar rays in the said time. On pitched roofs the tilt angle is determined by the inclination of the roof itself. However know the angle α is not sufficient to determine the optimum orientation of the panels, but must also take into consideration the solar path in the sky in the different periods of the year, for which the angle of tilt should be mediated by considering all the days year. In Italy the optimum angle is approximately 30º.

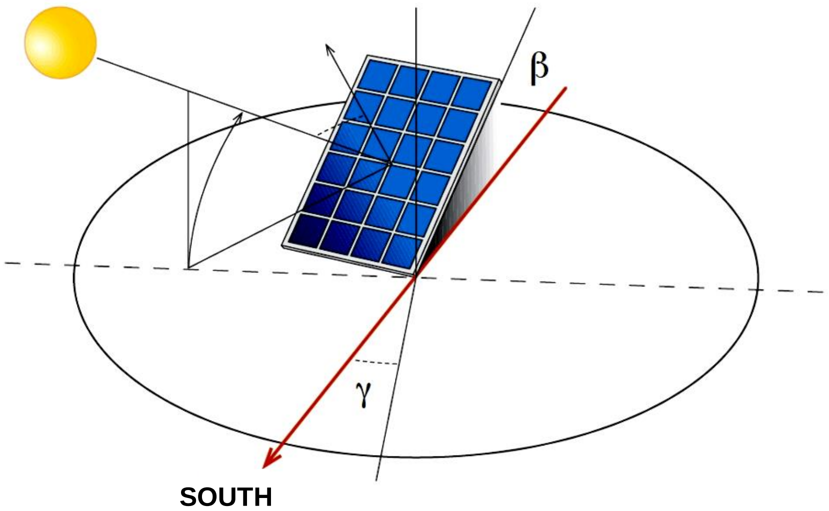
Photovoltaic systems

The paths solar related to the spring equinox and the summer and winter solstices for a latitude of 45° is shown in Figure.



Photovoltaic systems

The orientation of the panels can be indicated with Azimuth angle (γ) of deviation from the optimal direction to the south (for sites in the northern hemisphere) or north (for sites in the Southern Hemisphere). Positive values indicate an azimuth angle of orientation to the west, while negative values an orientation to the east. In the panels installed on the ground, the combination of the inclination and orientation determines the exposure of the panels (Figure)



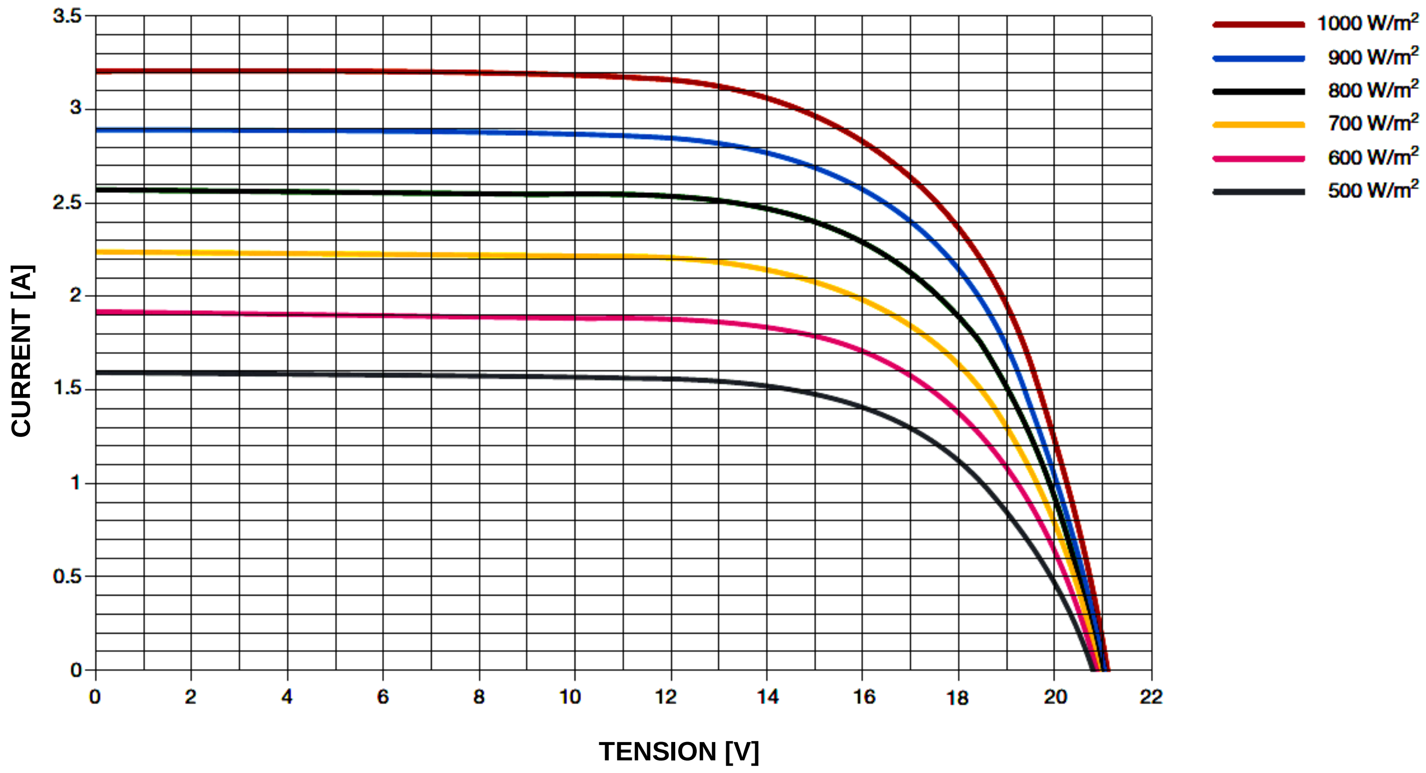
Photovoltaic systems

Viceversa, se i pannelli sono installati sul tetto degli edifici, dell'esposizione stessa è vincolata dall'inclinazione e l'orientamento delle falde del tetto. Deviazioni maggiori possono essere compensati con un leggero allargamento della superficie del collettore.

I principali fattori che influenzano l'energia prodotta da un impianto fotovoltaico sono irraggiamento, temperatura dei moduli e ombreggiamento.

Photovoltaic systems

In function of the **radiation incident on the photovoltaic cells**, the voltage-current characteristic V-I of the same changes as shown in the Figure



Photovoltaic systems

To decrease the radiation decreases proportionally the photovoltaic current generated, while the change of the load voltage is minimum. The conversion efficiency is not affected by the variation of the radiation within the range of normal operation of the cells, which means that the conversion efficiency is the same in both a clear day that cover. The lower power produced with cloudy sky stems therefore, not to a decrease in efficiency, but at a reduced production of current to less radiation.

As the temperature of the PV modules, the current produced remains virtually unchanged, while the voltage decreases and with it there is a reduction of the performance of the panels in terms of electric power produced.

Solar photovoltaic systems

Photovoltaic systems

To avoid excessive performance degradation is appropriate to control the temperature in the exercise trying to give a good ventilation panels that limits the temperature change of the same on them. In doing so it can reduce the energy loss due to the temperature (compared to standard conditions of 25°C) to a value around 7%. The reduction of the yield with the increase in temperature is estimated at 0.4-0.6 for each °C.

Photovoltaic systems

Given the area occupied by the modules of a PV system, it may happen that some of them (one or more cells) is shaded by trees and leaves that are deposited, chimneys or photovoltaic panels installed nearby. In case of shading, a PV cell consists of a pn junction stops producing energy and becomes passive load. The cell behaves like a diode that blocks the current produced by the other cells connected in series with the consequent impairment of the entire production of the module. Furthermore, the diode is subject to the voltage of the other cells which can cause the perforation of the junction with localized overheating and damage to the module. To avoid that one or more shaded cells jeopardize the production in whole string, at the level of the modules are inserted diodes by-pass short-circuiting part of the module in the shade or damaged. In doing so it guarantees the operation of the module even with reduced efficiency.

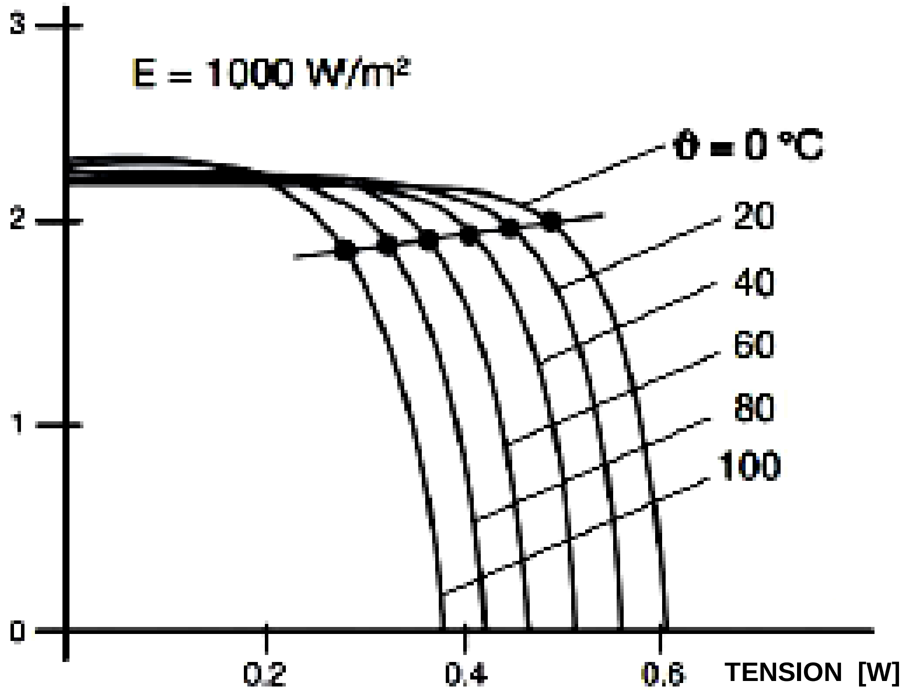
Photovoltaic systems

Theoretically should insert a bypass diode in parallel to each cell, but that would be too expensive in cost/benefit ratio. Therefore usually 2-4 diodes are installed by-pass for the module.

As the temperature of the PV modules, the current produced remains virtually unchanged, while the voltage decreases and with it there is a reduction of the performance of the panels in terms of electric power produced.

Photovoltaic systems

The characteristic of the current and voltage of a photovoltaic module to vary the operating temperature of the cells is shown in Figure



Solar photovoltaic systems

Photovoltaic systems

In order to avoid an excessive reduction in performance is therefore appropriate to keep under control the temperature in the exercise trying to give a good ventilation panels that limits the temperature change of the same on them. In doing so it can reduce the energy loss due to the temperature (compared to standard conditions of 25 degrees) to a value around 7%. The reduction of the yield with the increase in temperature is estimated at 0.4-0.6 for each °C.