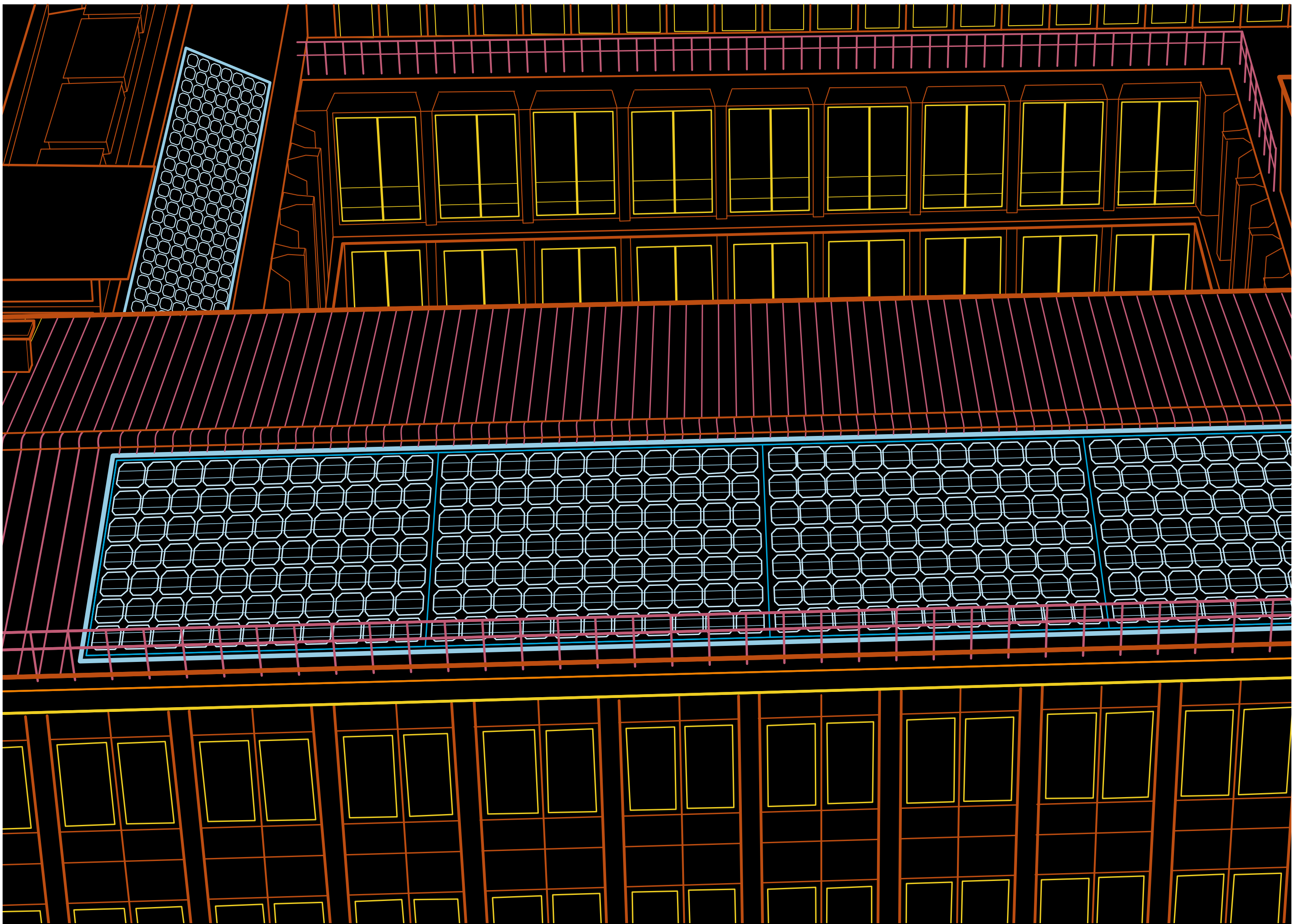

Technical Application Papers No.10
Photovoltaic plants

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Introduction

In the present global energy and environmental context, the aim of reducing the emissions of greenhouse gases and polluting substances (also further to the Kyoto protocol), also by exploiting alternative and renewable energy sources which are put side by side to and reduce the use of fossil fuels, doomed to run out due to the great consumption of them in several countries, has become of primary importance.

The Sun is certainly a renewable energy source with great potential and it is possible to turn to it in the full respect of the environment. It is sufficient to think that instant by instant the surface of the terrestrial hemisphere exposed to the Sun gets a power exceeding 50 thousand TW; therefore the quantity of solar energy which reaches the terrestrial soil is enormous, about 10 thousand times the energy used all over the world.

Among the different systems using renewable energy sources, photovoltaics is promising due to the intrinsic qualities of the system itself: it has very reduced service costs (the fuel is free of charge) and limited maintenance requirements, it is reliable, noiseless and quite easy to install. Moreover, photovoltaics, in some stand-alone applications, is definitely convenient in comparison with other energy sources, especially in those places which are difficult and uneconomic to reach with traditional electric lines.

In the Italian scenario, photovoltaics is strongly increasing thanks to the Feed-in Tariff policy, that is a mechanism to finance the PV sector, providing the remuneration, through incentives granted by the GSE (Electrical Utilities Administrator), of the electric power produced by plants connected to the grid.

This Technical Paper is aimed at analyzing the problems and the basic concepts faced when realizing a photovoltaic plant; starting from a general description regarding the modalities of exploiting solar energy through PV plants, a short description is given of the methods of connection to the grid, of protection against overcurrents, overvoltages and indirect contact, so as to guide to the proper selection of the operating and protection devices for the different components of plants.

This Technical Paper is divided into three parts: the first part, which is more general and includes the first three chapters, describes the operating principle of PV plants, their typology, the main components, the installation methods and the different configurations. Besides, it offers an analysis of the production of energy in a plant and illustrates how it varies as a function of determined quantities. The second part (including the chapters from four to eight) deals with the methods of connection to the grid, with the protection systems, with the description of the Feed-in Tariff system and with a simple economical analysis of the investment necessary to erect a PV plant, making particular reference to the Italian context and to the Standards, to the resolutions and the decrees in force at the moment of the drawing up of this Technical Paper. Finally, in the third part (which includes Chapter 9) the solutions offered by ABB for photovoltaic applications are described.

To complete this Technical Paper, there are three annexes offering:

- a description of the new technologies for the realization of solar panels and for solar concentration as a method to increase the solar radiation on panels;
- a description of the other renewable energy sources and an analysis of the Italian situation as regards energy; an example for the dimensioning of a 3kWp PV plant for detached house and of a 60kWp plant for an artisan manufacturing industry.

1 Generalities on photovoltaic (PV) plants

1.1 Operating principle

A photovoltaic (PV) plant transforms directly and instantaneously solar energy into electrical energy without using any fuels. As a matter of fact, the photovoltaic (PV) technology exploits the photoelectric effect, through which some semiconductors suitably "doped" generate electricity when exposed to solar radiation.

The main advantages of photovoltaic (PV) plants can be summarized as follows:
- distribuited generation where needed;
- no emission of polluting materials;
- saving of fossil fuels;
- reliability of the plants since they do not have moving parts (useful life usually over 20 years);
- reduced operating and maintenance costs;
- system modularity (to increase the plant power it is sufficient to raise the number of panels) according to the real requirements of users.

However, the initial cost for the development of a PV plant is quite high due to a market which has not reached its full maturity from a technical and economical point of view. Moreover the generation of power is erratic due to the variability of the solar energy source.

The annual electrical power output of a PV plant depends on different factors. Among them:
- solar radiation incident on the installation site;
- inclination and orientation of the panels;
- presence or not of shading;
- technical performances of the plant components (mainly modules and inverters).

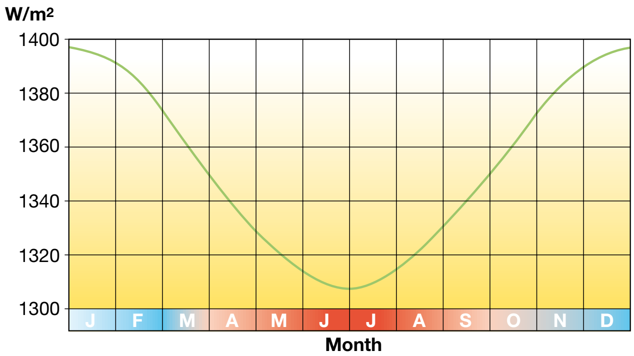
The main applications of PV plants are:
1. installations (with storage systems) for users isolated from the grid;
2. installations for users connected to the LV grid;
3. solar PV power plants, usually connected to the MV grid. Feed-in Tariff incentives are granted only for the applications of type 2 and 3, in plants with rated power not lower than 1 kW.

A PV plant is essentially constituted by a generator (PV panels), by a supporting frame to mount the panels on the ground, on a building or on any building structure, by a system for power control and conditioning, by a possible energy storage system, by electrical switchboards and switchgear assemblies housing the switching and protection equipment and by the connection cables.

1.2 Energy from the Sun

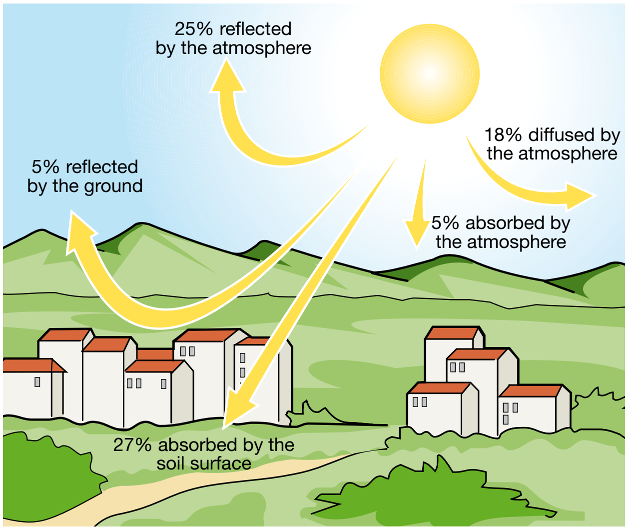
In the solar core thermonuclear fusion reactions occur unceasingly at millions of degrees; they release huge quantities of energy in the form of electromagnetic radiations. A part of this energy reaches the outer area of the Earth's atmosphere with an average irradiance (solar constant) of about 1,367 W/m^2 ± 3%, a value which varies as a function of the Earth-to-Sun distance (Figure 1.1)[1] and of the solar activity (sunspots).

Figure 1.1 - Extra-atmospheric radiation



With ***solar irradiance*** we mean the intensity of the solar electromagnetic radiation incident on a surface of 1 square meter [kW/m^2]. Such intensity is equal to the integral of the power associated to each value of the frequency of the solar radiation spectrum.
When passing through the atmosphere, the solar radiation diminishes in intensity because it is partially reflected and absorbed (above all by the water vapor and by the other atmospheric gases). The radiation which passes through is partially diffused by the air and by the solid particles suspended in the air (Figure 1.2).

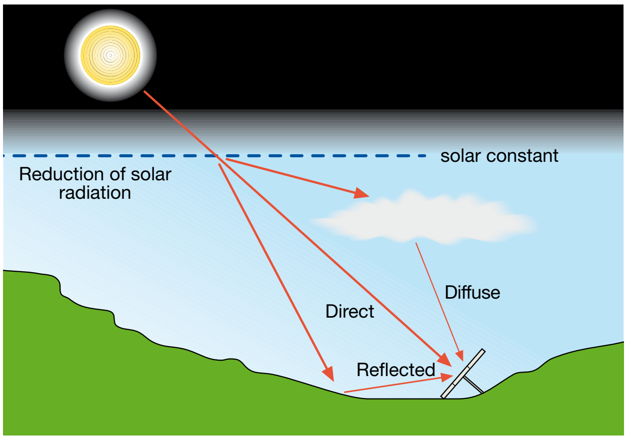
Figure 1.2 - Energy flow between the sun, the atmosphere and the ground



[1] *Due to its elliptical orbit the Earth is at its least distance from the Sun (perihelion) in December and January and at its greatest distance (aphelion) in June and July.*

With ***solar irradiation*** we mean the integral of the solar irradiance over a specified period of time [kWh/m²]. Therefore the radiation falling on a horizontal surface is constituted by a direct radiation, associated to the direct irradiance on the surface, by a diffuse radiation which strikes the surface from the whole sky and not from a specific part of it and by a radiation reflected on a given surface by the ground and by the surrounding environment (Figure 1.3). In winter the sky is overcast and the diffuse component is greater than the direct one.

Figure 1.3 - Components of solar radiation



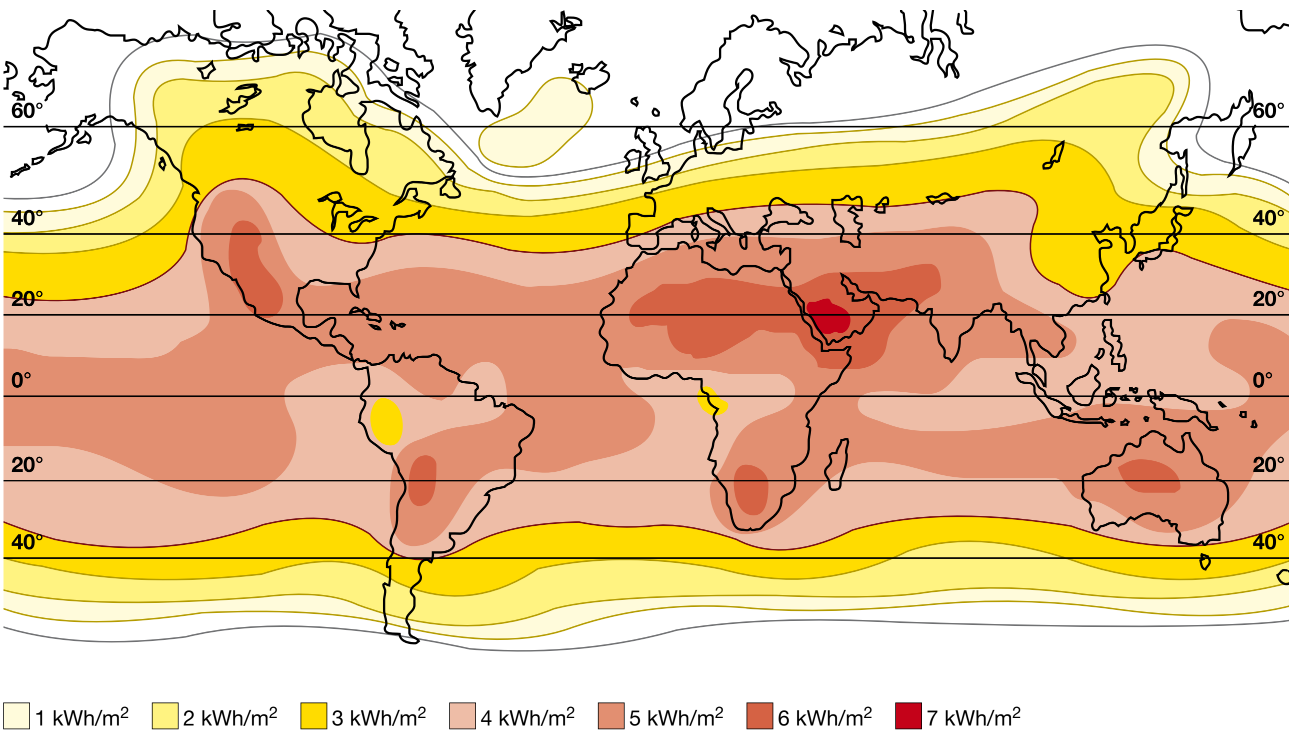
The reflected radiation depends on the capability of a surface to reflect the solar radiation and it is measured by the albedo coefficient calculated for each material (figure 1.4).

Figure 1.4 - Reflected radiation

Surface type	albedo
Dirt roads	0.04
Aqueous surfaces	0.07
Coniferous forest in winter	0.07
Worn asphalt	0.10
Bitumen roofs and terraces	0.13
Soil (clay, marl)	0.14
Dry grass	0.20
Rubble	0.20
Worn concrete	0.22
Forest in autumn / fields	0.26
Green grass	0.26
Dark surfaces of buildings	0.27
Dead leaves	0.30
Bright surfaces of buildings	0.60
Fresh snow	0.75

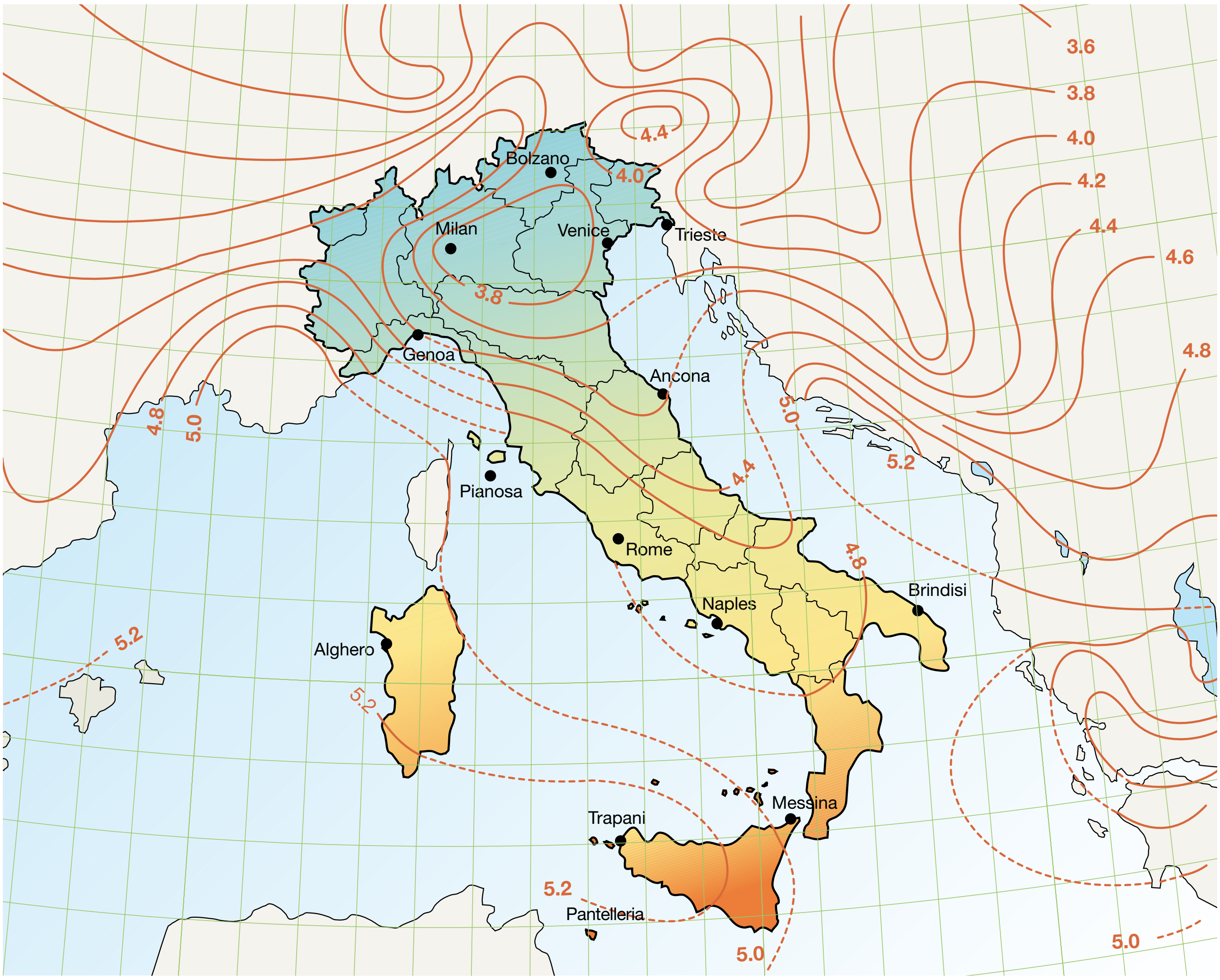
Figure 1.5 shows the world atlas of the average solar irradiance on an inclined plan 30° South [kWh/m²/day]

Figure 1.5 - Solar Atlas



In Italy the average annual irradiance varies from the 3.6 kWh/m^2 a day of the Po Valley to the 4.7 kWh/m^2 a day in the South-Centre and the 5.4 kWh/m^2/day of Sicily (Figure 1.6).
Therefore, in the favorable regions it is possible to draw about 2 MWh (5.4 · 365) per year from each square meter, that is the energetic equivalent of 1.5 petroleum barrels for each square meter, whereas the rest of Italy ranges from the 1750 kWh/m^2 of the Tyrrhenian strip and the 1300 kWh/m^2 of the Po Valley.

Figure 1.6 - Daily global irradiation in kWh/m^2



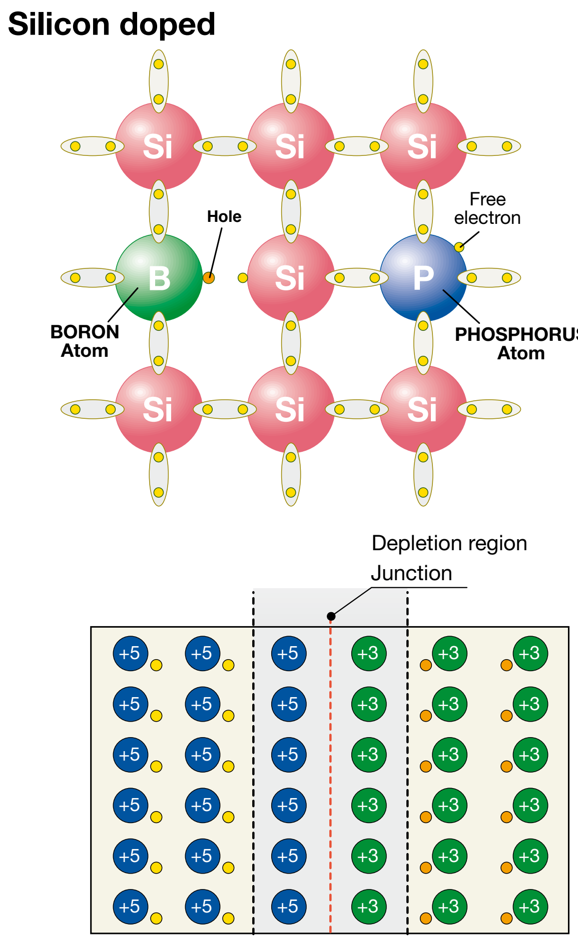
1.3 Main components of a photovoltaic plants

1.3.1 Photovoltaic generator

The elementary component of a PV generator is the photovoltaic cell where the conversion of the solar radiation into electric current is carried out. The cell is constituted by a thin layer of semiconductor material, generally silicon properly treated, with a thickness of about 0.3 mm and a surface from 100 to 225 cm^2.

Silicon, which has four valence electrons (tetravalent), is "doped" by adding trivalent atoms (e.g. boron – P doping) on one "layer" and quantities of pentavalent atoms (e.g. phosphorus – N doping) on the other one. The P-type region has an excess of holes, whereas the N-type region has an excess of electrons (Figure 1.7).

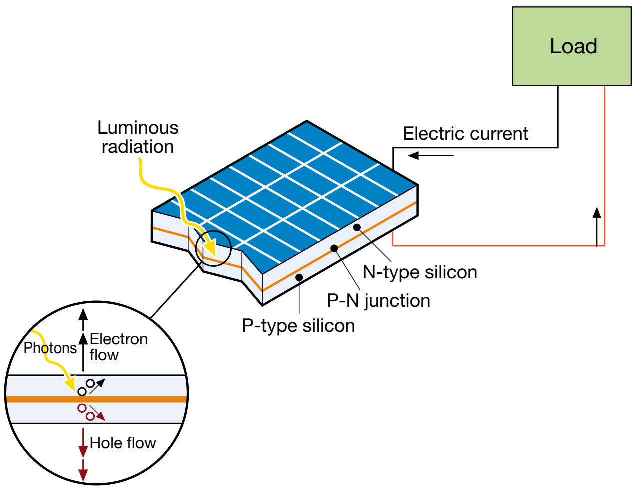
Figure 1.7 - The photovoltaic cell



In the contact area between the two layers differently doped (P-N junction), the electrons tend to move from the electron rich half (N) to the electron poor half (P), thus generating an accumulation of negative charge in the P region. A dual phenomenon occurs for the electron holes, with an accumulation of positive charge in the region N. Therefore an electric field is created across the junction and it opposes the further diffusion of electric charges. By applying a voltage from the outside, the junction allows the current to flow in one direction only (diode functioning).

When the cell is exposed to light, due to the photovoltaic effect[2] some electron-hole couples arise both in the N region as well as in the P region. The internal electric field allows the excess electrons (derived from the absorption of the photons from part of the material) to be separated from the holes and pushes them in opposite directions in relation one to another. As a consequence, once the electrons have passed the depletion region they cannot move back since the field prevents them from flowing in the reverse direction. By connecting the junction with an external conductor, a closed circuit is obtained, in which the current flows from the layer N, having higher potential, to the layer N, having lower potential, as long as the cell is illuminated (Figure 1.8).

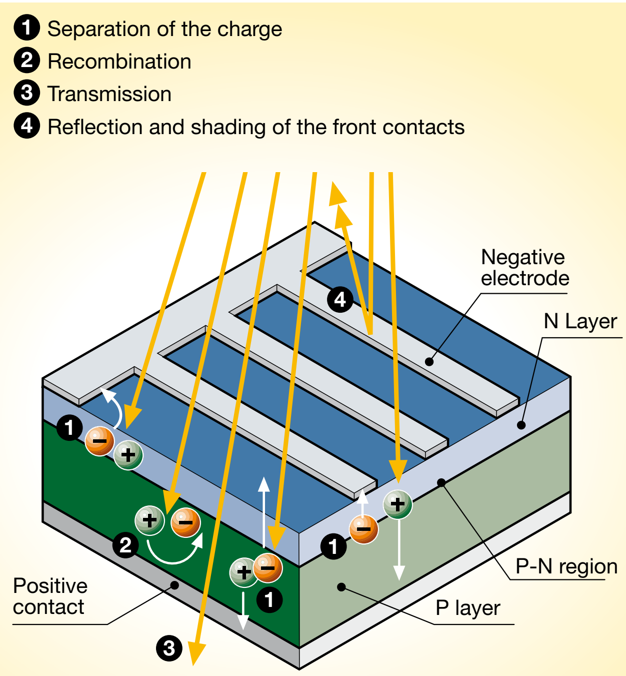
Figure 1.8 - How a photovoltaic cell works



[2] *The photovoltaic effect occurs when an electron in the valence band of a material (generally a semiconductor) is promoted to the conduction band due to the absorption of one sufficiently energetic photon (quantum of electromagnetic radiation) incident on the material. In fact, in the semiconductor materials, as for insulating materials, the valence electrons cannot move freely, but comparing semiconductor with insulating materials the energy gap between the valence band and the conduction band (typical of conducting materials) is small, so that the electrons can easily move to the conduction band when they receive energy from the outside. Such energy can be supplied by the luminous radiation, hence the photovoltaic effect.*

The silicon region which contributes to supply the current is the area surrounding the P-N junction; the electric charges form in the far off areas, but there is not the electric field which makes them move and therefore they recombine. As a consequence it is important that the PV cell has a great surface: the greater the surface, the higher the generated current.
Figure 1.9 represents the photovoltaic effect and the energy balance showing the considerable percentage of incident solar energy which is not converted into electric energy.

Figure 1.9 - Photovoltaic effect



100% of the incident solar energy
- **3%** reflection losses and shading of the front contacts
- **23%** photons with high wavelength, with insufficient energy to free electrons; heat is generated
- **32%** photons with short wavelength, with excess energy (transmission)
- **8.5%** recombination of the free charge carriers
- **20%** electric gradient in the cell, above all in the transition regions
- **0.5%** resistance in series, representing the conduction losses

= **13%** usable electric energy

Under standard operating conditions (1W/m^2 irradiance at a temperature of 25° C) a PV cell generates a current of about 3A with a voltage of 0.5V and a peak power equal to 1.5-1.7Wp.

On the market there are photovoltaic modules for sale constituted by an assembly of cells. The most common ones comprise 36 cells in 4 parallel rows connected in series, with an area ranging from 0.5 to 1m^2.
Several modules mechanically and electrically connected form a panel, that is a common structure which can be anchored to the ground or to a building (Figure 1.10).

Figure 1.10

Several panels electrically connected in series constitute an array and several arrays, electrically connected in parallel to generate the required power, constitute the generator or photovoltaic field (Figures 1.11 and 1.12).

Figure 1.11

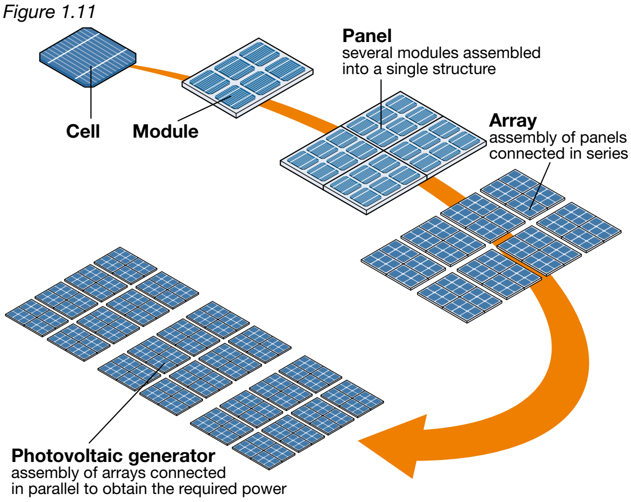


Figure 1.12

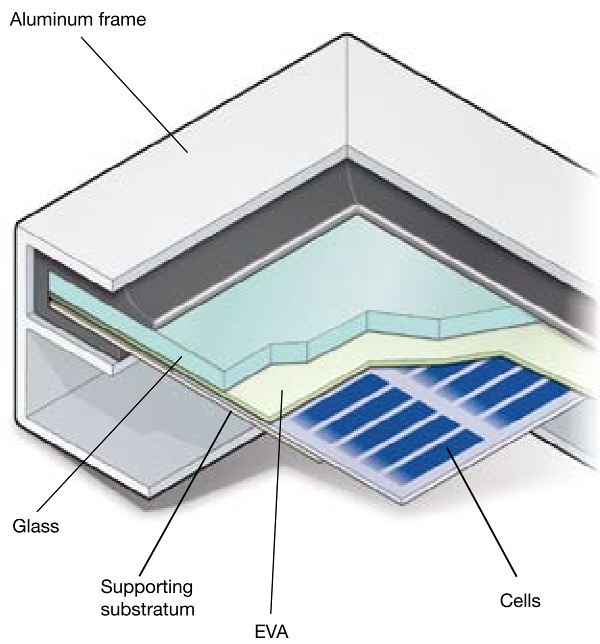
The PV cells in the modules are not exactly alike due to the unavoidable manufacturing deviations; as a consequence, two blocks of cells connected in parallel between them can have not the same voltage. As a consequence, a flowing current is created from the block of cells at higher voltage towards the block at lower voltage. Therefore a part of the power generated by the module is lost within the module itself (mismatch losses).
The inequality of the cells can be determined also by a different solar irradiance, for example when a part of cells are shaded or when they are deteriorated. These cells behave as a diode, blocking the current generated by the other cells. The diode is subject to the voltage of the other cells and it may cause the perforation of the junction with local overheating and damages to the module.
Therefore the modules are equipped with by-pass diodes to limit such phenomenon by short-circuiting the shaded or damaged part of the module. The phenomenon of mismatch arises also between the arrays of the photovoltaic field, due to inequality of modules, different irradiance of the arrays, shadings and faults in an array. To avoid reverse current flowing among the arrays it is possible to insert diodes.
The cells forming the module are encapsulated in an assembly system which:

- electrically insulates the cells towards the outside;
- protects the cells against the atmospheric agents and against the mechanical stresses;
- resists ultra violet rays, at low temperatures, sudden changes of temperature and abrasion;
- gets rid of heat easily to prevent the temperature rise from reducing the power supplied by the module.

Such properties shall remain for the expected lifetime of the module. Figure 1.13 shows the cross-section of a standard module in crystalline silicon, made up by:

- a protective sheet on the upper side exposed to light, characterized by high transparency (the most used material is tempered glass);
- an encapsulation material to avoid the direct contact between glass and cell, to eliminate the interstices due to surface imperfections of the cells and electrically insulate the cell from the rest of the panel; in the processes where the lamination phase is required Ethylene Vinyl Acetate (EVA) is often used;
- a supporting substratum (glass, metal, plastic) on the back;
- a metal frame, usually made of aluminum.

Figure 1.13

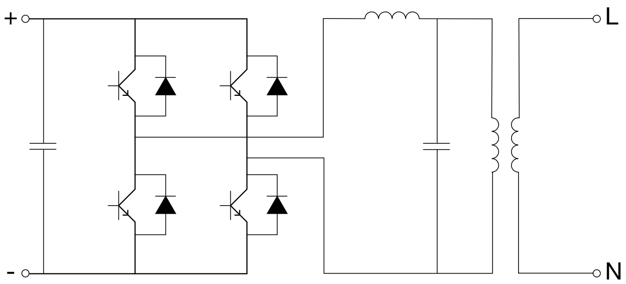


In the crystal silicon modules, to connect the cells, metallic contacts soldered after the construction of the cells are used; in the thin film modules the electrical connection is a part of the manufacturing process of the cells and it is ensured by a layer of transparent metal oxides, such as zinc oxide or tin oxide.

1.3.2 Inverter

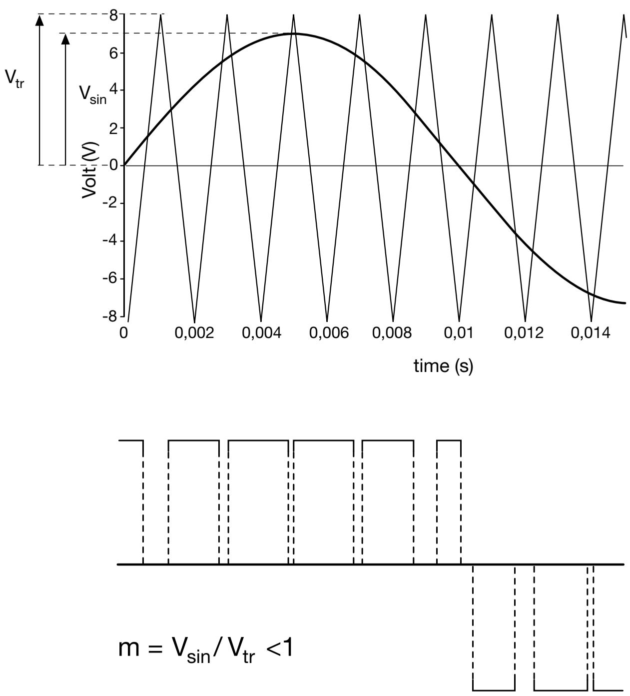
The power conditioning and control system is constituted by an inverter that converts direct current to alternating current and controls the quality of the output power to be delivered to the grid, also by means of an L-C filter inside the inverter itself. Figure 1.14 shows the principle scheme of an inverter. The transistors, used as static switches, are controlled by an opening-closing signal which, in the simplest mode, would result in an output square waveform.

Figure 1.14 – Principle scheme of a single-phase inverter



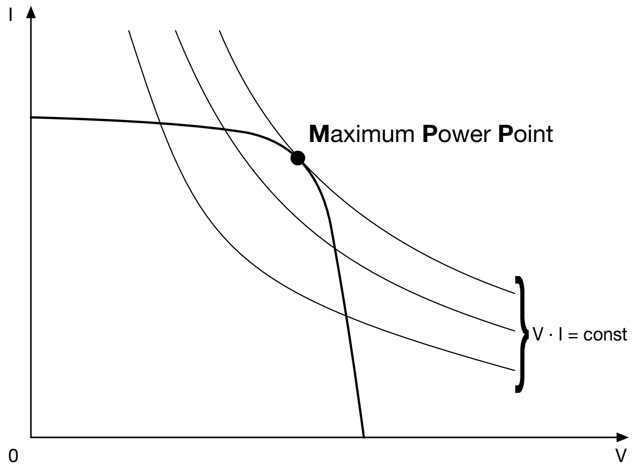
To obtain a waveform as sinusoidal as possible, a more sophisticated technique – Pulse Width Modulation (PWM) – is used; PWM technique allows a regulation to be achieved on the frequency as well as on the r.m.s. value of the output waveform (Figure 1.15).

Figure 1.15 – Operating principle of the PWM technology



The power delivered by a PV generator depends on the point where it operates. In order to maximize the energy supply by the plant, the generator shall adapt to the load, so that the operating point always corresponds to the maximum power point.
To this purpose, a controlled chopper called Maximum Power Point Tracker (MPPT) is used inside the inverter. The MPPT calculates instant by instant the pair of values "voltage-current" of the generator at which the maximum available power is produced. Starting from the I-V curve of the PV generator:

Maximum Power Point (MPP) for a photovoltaic generator



The maximum point of power transfer corresponds to the point of tangency between the I-V characteristic for a given value of solar radiation and the hyperbola of equation $V \cdot I = \text{const}$.
The MPPT systems commercially used identify the maximum power point on the characteristic curve of the generator by causing, at regular intervals, small variations of loads which determine deviations of the voltage-current values and evaluating if the new product I-V is higher or lower then the previous one. In case of a rise, the load conditions are kept varying in the considered direction. Otherwise, the conditions are modified in the opposite direction.

Due to the characteristics of the required performances the inverters for stand-alone plants and for grid-connected plants shall have different characteristics:
- in the stand-alone plants the inverters shall be able to supply a voltage AC side as constant as possible at the varying of the production of the generator and of the load demand;
- in the grid-connected plants the inverters shall reproduce, as exactly as possible, the network voltage and at the same time try to optimize and maximize the energy output of the PV panels.

1.4 Typologies of photovoltaic panels

1.4.1 Crystal silicon panels

For the time being the crystal silicon panels are the most used and are divided into two categories:

- *single crystalline* silicon (Figure 1.16), homogeneous single crystal panels are made of silicon crystal of high purity. The single-crystal silicon ingot has cylindrical form, 13-20 cm diameter and 200 cm length, and is obtained by growth of a filiform crystal in slow rotation. Afterwards, this cylinder is sliced into wafers 200-250 μm thick and the upper surface is treated to obtain "microgrooves" aimed at minimizing the reflection losses.
  The main advantage of these cells is the efficiency (14 to 17%), together with high duration and maintenance of the characteristics in time[3] .
  The cost of these module is about 3.2 to 3.5 €/W and the panels made with this technology are usually characterized by a homogenous dark blue color[4].
- *polycrystalline* silicon panels (Figure 1.17), where the crystals constituting the cells aggregate taking different forms and directions. In fact, the iridescences typical of polycrystalline silicon cells are caused by the different direction of the crystals and the consequent different behavior with respect to light. The polycrystalline silicon ingot is obtained by melting and casting the silicon into a parallelepiped-shaped mould. The wafers thus obtained are square shape and have typical striations of 180-300 μm thickness.
  The efficiency is lower in comparison with single crystalline silicon (12 to 14%), but also the cost, 2.8 to 3.3 €/W. Anyway the duration is high (comparable to single crystalline silicon) and also the maintenance of performances in time (85% of the initial efficiency after 20 years).
  The cells made with such technology can be recognized because of the surface aspect where crystal grains are quite visible.

Figure 1.16 – Single crystalline silicon panel

Figure 1.17 – Polycrystalline silicon panel

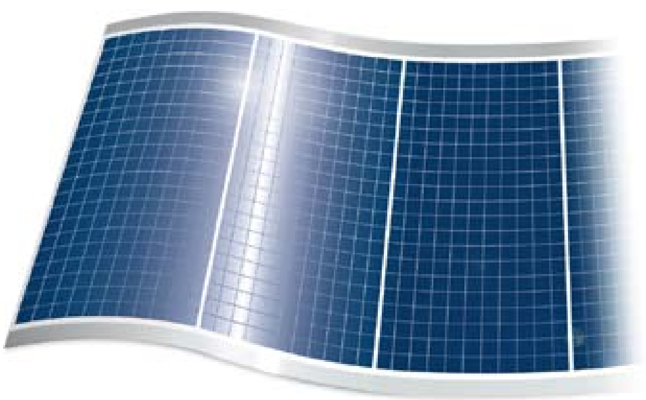
[3] *Some manufacturers guarantee the panels for 20 years with a maximum loss of efficiency of 10% with respect to the nominal value.*
[4] *The dark blue color is due to the titan oxide antireflective coating, which has the purpose of improving the collection of solar radiation.*

Nowadays the market is dominated by crystal silicon technology, which represents about 90% of it. Such technology is ripe in terms of both obtainable efficiency and manufacturing costs and it will probably continue to dominate the market in the short-medium period. Only some slight improvements are expected in terms of efficiency (new industrial products declare 18%, with a laboratory record of 24.7%, which is considered practically insurmountable) and a possible reduction of the costs linked both to the introduction in the industrial processes of bigger and thinner wafers as well as to the economies of scale. Besides, the PV industry based on such technology uses the surplus of silicon intended for the electronics industry but, due to the constant development of the last and to the exponential growth of the PV production at an average rate of 40% in the last six years, the availability on the market of raw material to be used in the photovoltaic sector is becoming more limited.

1.4.2 Thin film panels

Thin film cells are composed by semiconducting material deposited, usually as gas mixtures, on supports as glass, polymers, aluminum, which give physical consistency to the mixture. The semiconductor film layer is a few µm in thickness with respect to crystalline silicon cells which are some hundreds µm. As a consequence, the saving of material is remarkable and the possibility of having a flexible support increases the application field of thin film cells (Figure 1.18).
The used materials are:
- Amorphous Silicon;
- CdTeS (Cadmium Telluride-Cadmium Sulfide);
- GaAs (Gallum Arsenide);
- CIS, CIGS and CIGSS (Copper Iridium Diselenide alloys).

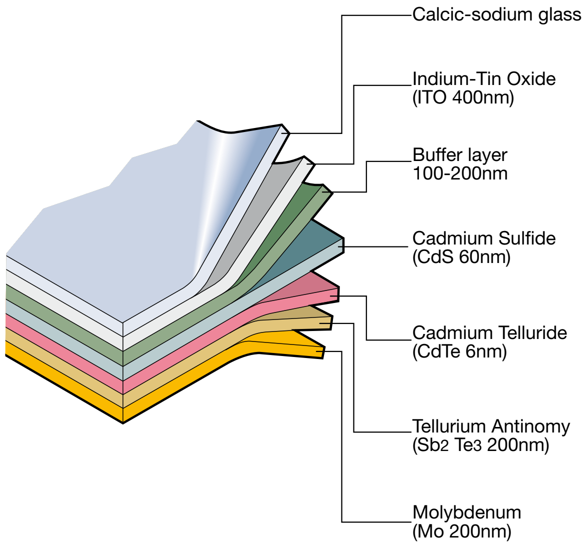
Figure 1.18 – Thin film module



Amorphous Silicon (symbol a-Si) deposited as film on a support (e.g. aluminum) offers the opportunity of having PV technology at reduced costs in comparison with crystalline silicon, but the efficiency of these cells tends to get worse in the time. Amorphous silicon can also be "sprayed" on a thin sheet of plastic or flexible material. It is used above all when it is necessary to reduce maximally the weight of the panel and to adapt it to curved surfaces. The efficiency of a-Si (5% to 6%) is very low due to the many resistances that the electrons have to face in their flux. Also in this case the cell performances tend to get worse in the time. An interesting application of this technology is the "tandem" one, combining an amorphous silicon layer with one or more multi-junction crystalline silicon layers; thanks to the separation of the solar spectrum, each junction positioned in sequence works at its best and guarantees higher levels in terms both of efficiency as well as endurance.

CdTeS solar cells consist of one P-layer (CdTe) and one N-layer (CdS) which form a hetero-junction P-N.
CdTeS cells have higher efficiency than amorphous silicon cells: 10% to 11% for industrial products (15.8% in test laboratories). The production on a large scale of CdTeS technology involves the environmental problem as regards the CdTe contained in the cell: since it is not soluble in water and it is more stable than other compounds containing cadmium, it may become a problem when not properly recycled or used (Figure 1.19). The unit cost of such modules is 1.5 to 2.2 €/W.
Nowadays *GaAs technology* is the most interesting one if considered from the point of view of the obtained efficiency, higher than 25 to 30%, but the production of such cells is limited by the high costs and by the scarcity

Figure 1.19 – Structures of thin film cells based on CdTe-CdS



of the material, which is prevailingly used in the “high speed semiconductors” and optoelectronics industry. In fact, GaAs technology is used mainly for space applications where weights and reduced dimensions play an important role.

CIS/CIGS/CIGSS modules are part of a technology which is still under study and being developed. Silicon is replaced with special alloys such as:

- copper, indium and selenite (CIS);
- copper, indium, gallium and selenite (CIGS);
- copper, indium, gallium, selenite and sulphur (CIGSS).

Nowadays the efficiency is 10 to 11% and the performances remain constant in time; as for single crystalline and polycrystalline silicon a reduction in the production cost is foreseen, for the time being around 2.2-2.5 €/W.

The market share of thin film technologies is still very limited (≈7%), but the solutions with the highest capacities in the medium-long term are being taken into consideration for a substantial price reduction. By depositing the thin film directly on a large scale, more than 5 m^2, the scraps, which are typical of the slicing operation to get crystalline silicon wafers from the initial ingot, are avoided. The deposition techniques are low power consumption processes and consequently the relevant payback time is short, that is only the time for which a PV plant shall be running before the power used to build it has been generated (about 1 year for amorphous silicon thin films against the 2 years of crystalline silicon). In comparison with crystalline silicon modules thin film modules show a lower dependence of efficiency on the operating temperature and a good response also when the diffused light component is more marked and the radiation levels are low, above all on cloudy days.

Table 1.1

	Single crystalline silicon	Polycrystalline silicon	Thin film (amorphous silicon)
η cell	14% - 17%	12% - 14%	4-6% single 7-10% tandem
Advantages	high η	lower cost	lower cost
	constant η	simpler production	reduced influence of the temperature
	reliable technology	optimum overall dimensions	higher energy output with diffused radiation
Disadvantages	higher energy	sensitivity to impurities in the manufacturing processes	bigger dimensions
	quantity necessary for production		cost of the structure and assembly time

Table 1.2

	GaAs (Gallum Arsenide)	CdTe (Cadmium Telluride)	CIS (Copper Iridium Selenide alloys)
η cell	32,5%	11%	12%
Advantages	high resistance at high temperatures (ok for concentrators)	low cost	very constant
Disadvantages	toxicity	toxicity	toxicity
	availability of the materials	availability of the materials	

[5] *According to some studies in this field, by 2020 the market share of thin films may reach 30% to 40%.*

1.5 Typologies of photovoltaic plants

1.5.1 Stand-alone plants

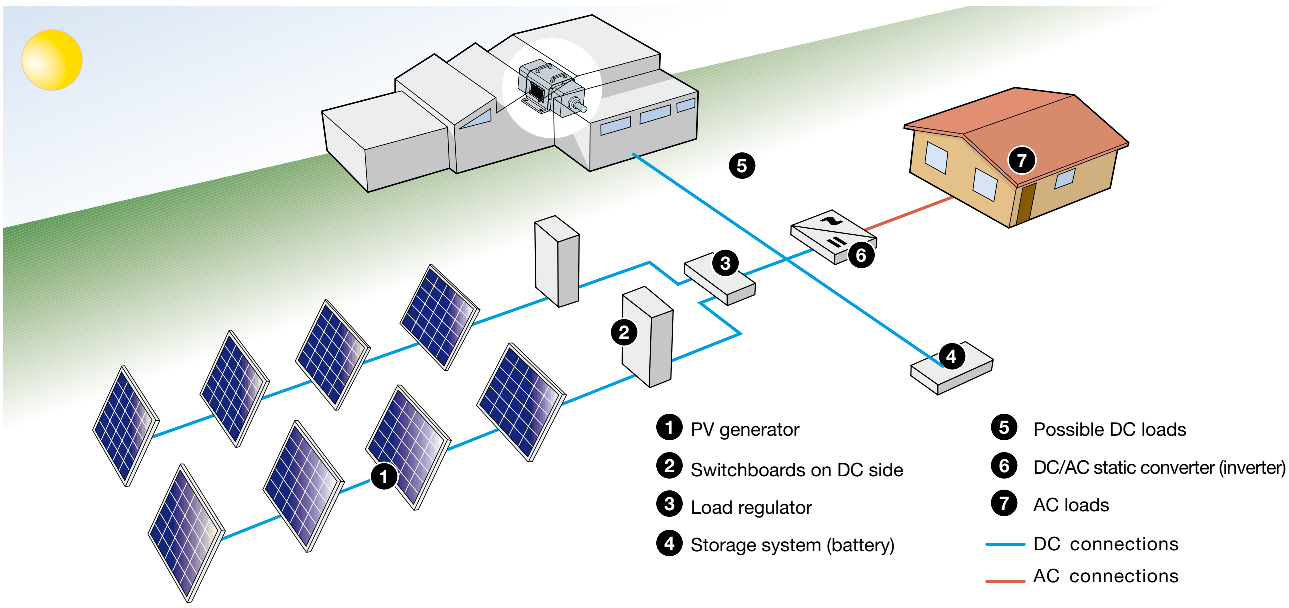
Stand-alone plants are plants which are not connected to the grid and consist of PV panels and of a storage system which guarantees electric energy supply also when lighting is poor or when it is dark. Since the current delivered by the PV generator is DC power, if the user plant needs AC current an inverter becomes necessary.
Such plants are advantageous from a technical and financial point of view whenever the electric network is not present or whenever it is not easy to reach, since they can replace motor generator sets. Besides, in a stand-alone configuration, the PV field is over-dimensioned so that, during the insolation hours, both the load supply as well as the recharge of the storing batteries can be guaranteed with a certain safety margin taking into account the days of poor insolation.

At present the most common applications are used to supply (Figure 1.20):
- pumping water equipment;
- radio repeaters, weather or seismic observation and data transmission stations;
- lightning systems;
- systems of signs for roads, harbors and airports;
- service supply in campers;
- advertising installations;
- refuges at high altitudes.

Figure 1.20 – Photovoltaic shelters and street lamps supplied by photovoltaic power

Figure 1.21 shows the principle diagram of a stand-alone PV plant.

Figure 1.21



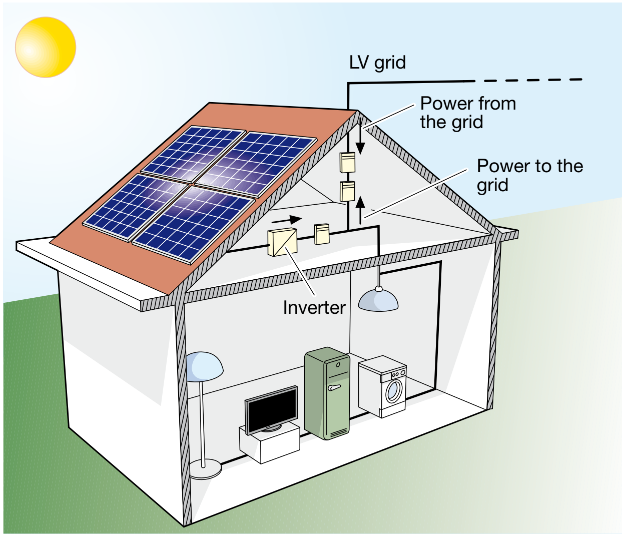
1.5.2 Grid-connected plants

Permanently grid-connected plants draw power from the grid during the hours when the PV generator cannot produce the energy necessary to satisfy the needs of the consumer. On the contrary, if the PV system produces excess electric power, the surplus is put into the grid, which therefore can operate as a big accumulator: as a consequence, grid-connected systems don't need accumulator banks (Figure 1.22).

These plants (Figure 1.23) offer the advantage of distributed - instead of centralized – generation: in fact

Figure 1.22

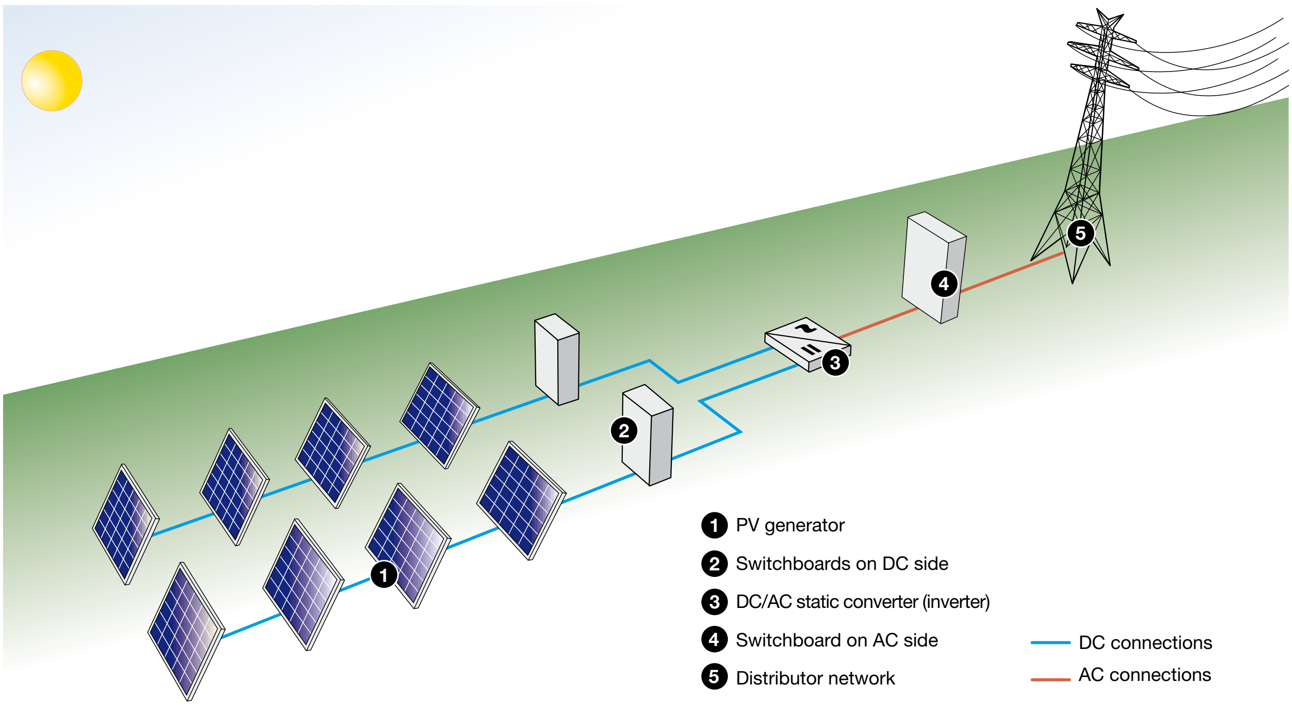
Figure 1.23



the energy produced near the consumption area has a value higher than that produced in traditional large power plants, because the transmission losses are limited and the expenses of the big transport and dispatch electric systems are reduced. In addition, the energy production in the insolation hours allows the requirements for the grid to be reduced during the day, that is when the demand is higher.

Figure 1.24 shows the principle diagram of a grid-connected photovoltaic plant.

Figure 1.24



1.6 Intermittence of generation and storage of the produced power

The PV utilization on a large scale is affected by a technical limit due to the uncertain intermittency of production. In fact, the national electrical distribution network can accept a limited quantity of intermittent input power, after which serious problems for the stability of the network can rise. The acceptance limit depends on the network configuration and on the degree of interconnection with the contiguous grids.

In particular, in the Italian situation, it is considered dangerous when the total intermittent power introduced into the network exceeds a value from 10% to 20% of the total power of the traditional power generation plants.

As a consequence, the presence of a constraint due to the intermittency of power generation restricts the real possibility of giving a significant PV contribution to the national energy balance and this remark can be extended to all intermittent renewable sources.

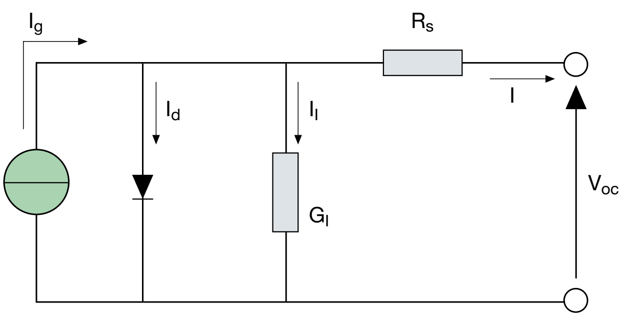
To get round this negative aspect it would be necessary to store for sufficiently long times the intermittent electric power thus produced to put it into the network in a more continuous and stable form. Electric power can be stored either in big superconducting coils or converting it into other form of energy: kinetic energy stored in flywheels or compressed gases, gravitational energy in water basins, chemical energy in synthesis fuels and electrochemical energy in electric accumulators (batteries). Through a technical selection of these options according to the requirement of maintaining energy efficiently for days and/or months, two storage systems emerge: that using batteries and the hydrogen one. At the state of the art of these two technologies, the electrochemical storage seems feasible, in the short-medium term, to store the energy for some hours to some days. Therefore, in relation to photovoltaics applied to small grid-connected plants, the insertion of a storage sub-system consisting in batteries of small dimensions may improve the situation of the inconveniences due to intermittency, thus allowing a partial overcoming of the acceptance limit of the network. As regards the seasonal storage of the huge quantity of electric power required to replace petroleum in all the usage sectors, hydrogen seems to be the most suitable technology for the long term since it takes advantage of the fact that solar electric productivity in summer is higher than the winter productivity of about a factor 3. The exceeding energy stored in summer could be used to optimize the annual capacity factor of renewable source power plants, increasing it from the present value of 1500-1600 hours without storage to a value nearer to the average one of the conventional power plants (about 6000 hours). In this case the power from renewable source could replace the thermoelectric one in its role, since the acceptance limit of the grid would be removed.

2 Energy production

2.1 Circuit equivalent to the cell

A photovoltaic cell can be considered as a current generator and can be represented by the equivalent circuit of Figure 2.1.
The current I at the outgoing terminals is equal to the current generated through the PV effect I_g by the ideal current generator, decreased by the diode current I_d and by the leakage current I_l.
The resistance series R_s represents the internal resistance to the flow of generated current and depends on the thick of the junction P-N, on the present impurities and on the contact resistances.
The leakage conductance G_l takes into account the current to earth under normal operation conditions.
In an ideal cell we would have R_s=0 and G_l=0. On the contrary, in a high-quality silicon cell we have R_s=0.05÷0.10Ω and G_l=3÷5mS. The conversion efficiency of the PV cell is greatly affected also by a small variation of R_s, whereas it is much less affected by a variation of G_l.

Figure 2.1



The no-load voltage V_{oc} occurs when the load does not absorb any current (I=0) and is given by the relation:

$$V_{oc} = \frac{I_l}{G_l} \quad [2.1]$$

The diode current is given by the classic formula for the direct current:

$$I_d = I_D \cdot \left[e^{\frac{Q \cdot V_{oc}}{A \cdot k \cdot T}} - 1 \right] \quad [2.2]$$

where:
- I_D is the saturation current of the diode;
- Q is the charge of the electron ($1.6 \cdot 10^{-19}$ C)
- A is the identity factor of the diode and depends on the recombination factors inside the diode itself (for crystalline silicon is about 2)
- k is the Boltzmann constant ($1.38 \cdot 10^{-23} \frac{J}{K}$)
- T is the absolute temperature in K degree

Therefore the current supplied to the load is given by:

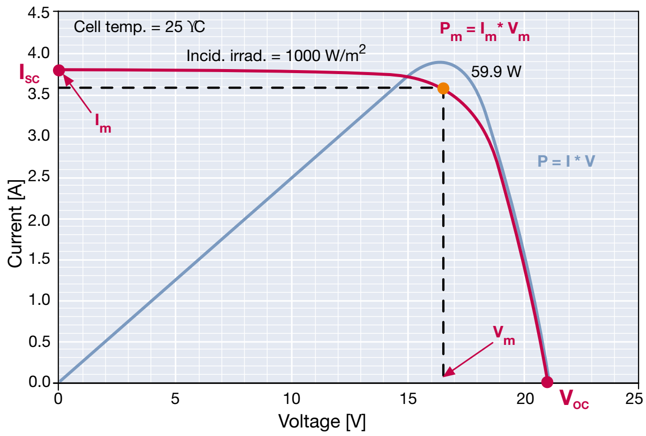
$$I = I_g - I_d - I_l = I_g - I_D \cdot \left[e^{\frac{Q \cdot V_{oc}}{A \cdot k \cdot T}} - 1 \right] - G_l \cdot V_{oc} \quad [2.3]$$

In the usual cells, the last term, i.e. the leakage current to earth I_l, is negligible with respect to the other two currents. As a consequence, the saturation current of the diode can be experimentally determined by applying the no-load voltage V_{oc} to a not-illuminated cell and measuring the current flowing inside the cell.

2.2 Voltage-current characteristic of the cell

The voltage-current characteristic curve of a PV cell is shown in Figure 2.2. Under short-circuit conditions the generated current is at the highest (I_{sc}), whereas with the circuit open the voltage (V_{oc}=open circuit voltage) is at the highest. Under the two above mentioned conditions the electric power produced in the cell is null, whereas under all the other conditions, when the voltage increases, the produced power rises too: at first it reaches the maximum power point (P_m) and then it falls suddenly near to the no-load voltage value.

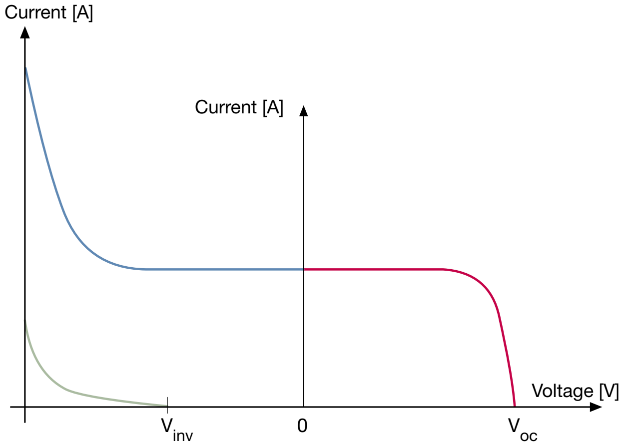
Figure 2.2



Therefore, the characteristic data of a solar cell can be summarized as follows:
- I_{sc} short-circuit current;
- V_{oc} no-load voltage;
- P_m maximum produced power under standard conditions (STC);
- I_m current produced at the maximum power point;
- V_m voltage at the maximum power point;
- FF filling factor: it is a parameter which determines the form of the characteristic curve V-I and it is the ratio between the maximum power and the product ($V_{oc} \cdot I_{sc}$) of the no-load voltage multiplied by the short-circuit current.

If a voltage is applied from the outside to the PV cell in reverse direction with respect to standard operation, the produced current remains constant and the power is absorbed by the cell. When a certain value of inverse voltage ("breakdown" voltage) is exceeded, the junction P-N is perforated, as it occurs in a diode, and the current reaches a high value thus damaging the cell. In absence of light, the generated current is null for reverse voltage up to the "breakdown" voltage, then there is a discharge current similarly to the lightening conditions (Figure 2.3 – left quadrant).

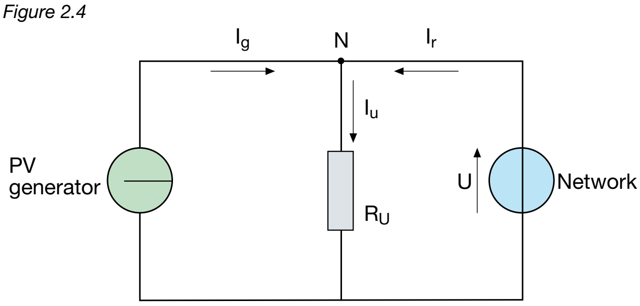
Figure 2.3



2.3 Grid connection scheme

A PV plant connected to the grid and supplying a consumer plant can be represented in a simplified way by the scheme of Figure 2.4.
The supply network (assumed to be at infinite short-circuit power) is schematized by means of an ideal voltage generator the value of which is independent of the load conditions of the consumer plant. On the contrary, the PV generator is represented by an ideal current generator (with constant current and equal insolation) whereas the consumer plant by a resistance R_u.

Figure 2.4



The currents I_g and I_r, which come from the PV generator and the network respectively, converge in the node N of Figure 2.4 and the current I_u absorbed by the consumer plant comes out from the node:

$$I_u = I_g + I_r \quad [2.4]$$

Since the current on the load is also the ratio between the network voltage U and the load resistance R_u:

$$I_u = \frac{U}{R_u} \quad [2.5]$$

the relation among the currents becomes:

$$I_r = \frac{U}{R_u} - I_g \quad [2.6]$$

If in the [2.6] we put $I_g = 0$, as it occurs during the night hours, the current absorbed from the grid results:

$$I_r = \frac{U}{R_u} \quad [2.7]$$

On the contrary, if all the current generated by the PV plant is absorbed by the consumer plant, the current supplied by the grid shall be null and consequently the formula [2.6] becomes:

$$I_g = \frac{U}{R_u} \quad [2.8]$$

When the insolation increases, if the generated current I_g becomes higher then that required by the load I_u, the current I_r becomes negative, that is no more drawn from the grid but put into it.
Multiplying the terms of the [2.4] by the network voltage U, the previous considerations can be made also for the powers, assuming as:

- $P_u = U \cdot I_u = \frac{U^2}{R_u}$ the power absorbed by the user plant;
- $P_g = U \cdot I_g$ the power generated by the PV plant;
- $P_r = U \cdot I_r$ the power delivered by the grid.

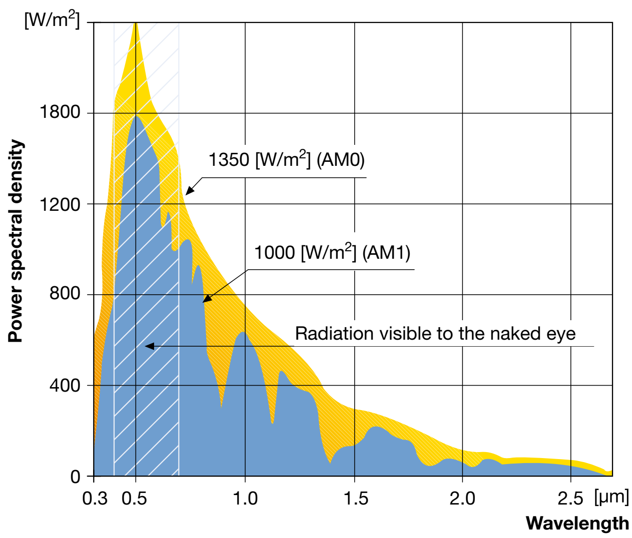
2.4 Nominal peak power

The nominal peak power (kWp) is the electric power that a PV plant is able to deliver under standard testing conditions (STC):

- 1 kW/m² insolation perpendicular to the panels;
- 25°C temperature in the cells;
- air mass (AM) equal to 1.5.

The air mass influences the PV energy production since it represents an index of the trend of the power spectral density of solar radiation. As a matter of fact the latter has a spectrum with a characteristic W/m²-wavelength which varies also as a function of the air density. In the diagram of Figure 2.5 the red surface represents the radiation perpendicular to the Earth surface absorbed by the atmosphere whereas the blue surface represents the solar radiation which really reaches the Earth surface; the difference between the trend of the two curves gives and indication of the spectrum variation due to the air mass[1].

Figure 2.5



The air mass index AM is calculated as follows:

$$AM = \frac{P}{P_o sen\,(h)} \quad [2.9]$$

where:

P is the atmospheric pressure measured at the point and instant considered [Pa];

P_o is the reference atmospheric pressure at the sea level [1.013 · 10^5 Pa];

h is the zenith angle, i.e. the elevation angle of the Sun above the local horizon at the instant considered.

[1] *The holes in the insolation correspond to the frequencies of the solar radiation absorbed by the water vapor present in the atmosphere.*

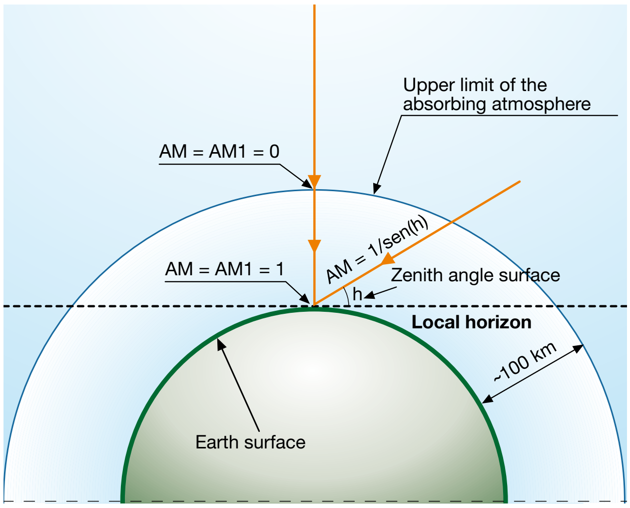
Remarkable values of AM are (Figure 2.6):

AM = 0 outside the atmosphere where P = 0;

AM = 1 at sea level in a day with clear sky and the sun at the zenith ($P = P_o$, sen(h) = 1);

AM = 2 at sea level in a beautiful day with the sun at 30° angle above the horizon ($P = P_o$, sen(h) = $\frac{1}{2}$).

Figure 2.6



2.5 Expected energy production per year

From an energetic point of view, the design principle usually adopted for a PV generator is maximizing the pick up of the available annual solar radiation. In some cases (e.g. stand-alone PV plants) the design criterion could be optimizing the energy production over definite periods of the year.

The electric power that a PV installation can produce in a year depends above all on:

- availability of the solar radiation;
- orientation and inclination of the modules;
- efficiency of the PV installation.

Since solar radiation is variable in time, to determine the electric energy which the plant can produce in a fixed time interval, the solar radiation relevant to that interval is taken into consideration, assuming that the performances of the modules are proportional to insolation. The values of the average solar radiation in Italy can be deduced from:

- *the Std. UNI 10349*: heating and cooling of the buildings. Climatic data;
- *the European Solar Atlas* based on the data registered by the CNR-IFA (Institute of Atmospheric Physics) in the period 1966-1975. It reports isoradiation maps of the Italian and European territory on horizontal or inclined surface;

- the ENEA data bank: since 1994 ENEA collects the data of the solar radiation in Italy through the imagines of the Meteosat satellite. The maps obtained up to now have been collected in two publications: one relevant to the year 1994 and another one relevant to the period 1995-1999.

The Tables 2.1 and 2.2 represent respectively, for different Italian sites, the values of the average annual solar radiation on the horizontal plane [kWh/m²] from the Std. UNI 10349 and mean daily values month by month [kWh/m²/day] from ENEA source.
The annual solar radiation for a given site may vary from a source to the other also by 10%, since it derives from the statistical processing of data gathered over different periods; moreover, these data are subject to the variation of the weather conditions from one year to the other. As a consequence the insolation values have a probabilistic meaning, that is they represent an expected value, not a definite one.

Starting from the mean annual radiation E_{ma}, to obtain the expected produced energy per year E_p for each kWp the following formula is applied:

$$E_p = E_{ma} \cdot \eta_{BOS} \text{ [kWh/kWp]} \quad [2.10]$$

where:
η_{BOS} (*Balance Of System*) is the overall efficiency of all the components of the PV plants on the load side of the panels (inverter, connections, losses due to the temperature effect, losses due to dissymetries in the performances, losses due to shading and low solar radiation, losses due to reflection…). Such efficiency, in a plant properly designed and installed, may range from 0.75 to 0.85.

Instead, taking into consideration the average daily insolation E_{mg}, to calculate the expected produced energy per year for each kWp:

$$E_p = E_{mg} \cdot 365 \cdot \eta_{BOS} \text{ [kWh/kWp]} \quad [2.11]$$

Example 2.1
We want to determine the annual mean power produced by a 3kWp PV plant, on a horizontal plane, in Bergamo. The efficiency of the plant components is equal to 0.75.

From the Table in the Std. UNI 10349, an annual mean radiation of 1276 kWh/m² is obtained. Assuming to be under the standard conditions of 1 kW/m², the expected annual mean production obtained is equal to:

$$E_p = 3 \cdot 1276 \cdot 0.75 = 3062 \text{ kWh}$$

Table 2.1

Annual solar radiation on the horizontal plane - UNI 10349

Site	Annual solar radiation (kWh/m²)	Site	Annual solar radiation (kWh/m²)	Site	Annual solar radiation (kWh/m²)	Site	Annual solar radiation (kWh/m²)	Site	Annual solar radiation (kWh/m²)
Agrigento	1923	Caltanisetta	1831	Lecce	1639	Pordenone	1291	Savona	1384
Alessandria	1275	Cuneo	1210	Livorno	1511	Prato	1350	Taranto	1681
Ancona	1471	Como	1252	Latina	1673	Parma	1470	Teramo	1487
Aosta	1274	Cremona	1347	Lucca	1415	Pistoia	1308	Trento	1423
Ascoli Piceno	1471	Cosenza	1852	Macerata	1499	Pesaro-Urbino	1411	Torino	1339
L'Aquila	1381	Catania	1829	Messina	1730	Pavia	1316	Trapani	1867
Arezzo	1329	Catanzaro	1663	Milan	1307	Potenza	1545	Terni	1409
Asti	1300	Enna	1850	Mantova	1316	Ravenna	1411	Trieste	1325
Avellino	1559	Ferrara	1368	Modena	1405	Reggio Calabria	1751	Treviso	1385
Bari	1734	Foggia	1630	Massa Carrara	1436	Reggio Emilia	1427	Udine	1272
Bergamo	1275	Florence	1475	Matera	1584	Ragusa	1833	Varese	1287
Belluno	1272	Forlì	1489	Naples	1645	Rieti	1366	Verbania	1326
Benevento	1510	Frosinone	1545	Novara	1327	Rome	1612	Vercelli	1327
Bologna	1420	Genoa	1425	Nuoro	1655	Rimini	1455	Venice	1473
Brindisi	1668	Gorizia	1326	Oristano	1654	Rovigo	1415	Vicenza	1315
Brescia	1371	Grosseto	1570	Palermo	1784	Salerno	1419	Verona	1267
Bolzano	1329	Imperia	1544	Piacenza	1400	Siena	1400	Viterbo	1468
Cagliari	1635	Isernia	1464	Padova	1266	Sondrio	1442		
Campobasso	1597	Crotone	1679	Pescara	1535	La Spezia	1452		
Caserta	1678	Lecco	1271	Perugia	1463	Siracusa	1870		
Chieti	1561	Lodi	1311	Pisa	1499	Sassari	1669		

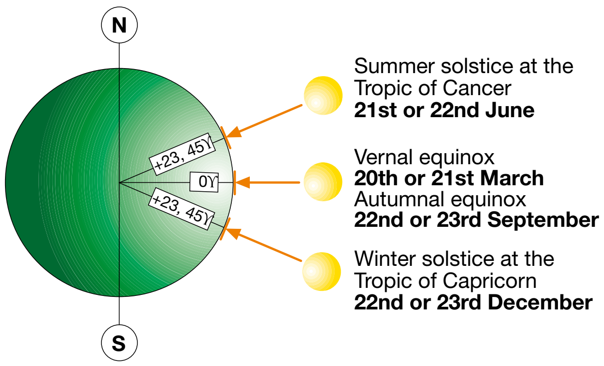
Table 2.2

Site	January	February	March	April	May	June	July	August	September	October	November	December
Milan	1.44	2.25	3.78	4.81	5.67	6.28	6.31	5.36	3.97	2.67	1.64	1.19
Venice	1.42	2.25	3.67	4.72	5.75	6.31	6.36	5.39	4.08	2.72	1.64	1.14
Bologna	1.50	2.28	3.81	4.81	5.86	6.42	6.47	5.47	4.19	2.81	1.72	1.25
Florence	1.58	2.33	3.75	4.72	5.86	6.39	6.44	5.50	4.17	2.86	1.83	1.39
Rome	1.92	2.61	3.94	4.92	6.08	6.56	6.58	5.72	4.39	3.17	2.11	1.58
Naples	1.92	2.67	3.92	5.03	6.08	6.64	6.58	5.81	4.50	3.28	2.17	1.69
Bari	1.86	2.58	3.97	5.08	6.08	6.69	6.64	5.81	4.53	3.25	2.08	1.69
Messina	2.11	2.94	4.19	5.19	6.22	6.69	6.67	5.89	4.64	3.53	2.36	1.94
Siracusa	2.36	3.22	4.33	5.39	6.36	6.78	6.75	6.00	4.81	3.69	2.58	2.17

2.6 Inclination and orientation of the panels

The maximum efficiency of a solar panel would be reached if the angle of incidence of solar rays were always 90°. In fact the incidence of solar radiation varies both according to latitude as well as to the solar declination during the year. In fact, since the Earth's rotation axis is tilted by about 23.45° with respect to the plane of the Earth orbit about the Sun, at definite latitude the height of the Sun on the horizon varies daily. The Sun is positioned at 90° angle of incidence with respect to the Earth surface (Zenith) at the equator in the two days of the equinox and along the tropics at the solstices (Figure 2.7).

Figure 2.7



Outside the Tropics latitude, the Sun cannot reach the Zenith above the Earth's surface, but it shall be at its highest point (depending on the latitude) with reference to the summer solstice day in the northern hemisphere and in the winter solstice day in the southern hemisphere. Therefore, if we wish to incline the panels so that they can be struck perpendicularly by the solar rays at noon of the longest day of the year it is necessary to know the maximum height (in degrees) which the Sun reaches above the horizon in that instant, obtained by the following formula:

$$\alpha = 90° - lat + \delta \qquad [2.12]$$

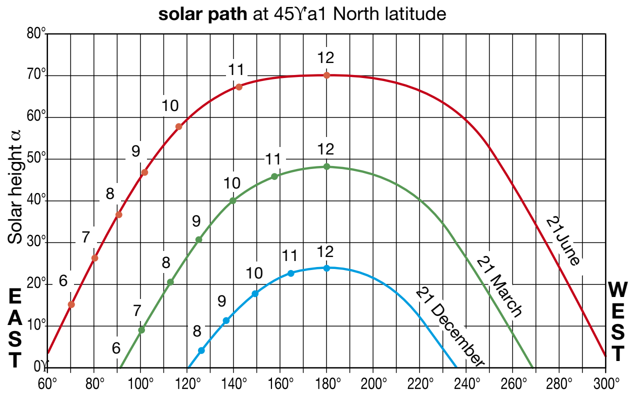
where:

lat is the value (in degrees) of latitude of the installation site of the panels;

δ is the angle of solar declination [23.45°]

Finding the complementary angle of α (90°-α), it is possible to obtain the tilt angle β, of the panels with respect to the horizontal plane (IEC/TS 61836) so that the panels are struck perpendicularly by the solar rays in the above mentioned moment[2].
However, it is not sufficient to know the angle α to determine the optimum orientation of the panels. It is necessary to take into consideration also the Sun path through the sky over the different periods of the year and therefore the tilt angle should be calculated taking into consideration all the days of the year[3] (Figure 2.8). This allows to obtain an annual total radiation captured by the panels (and therefore the annual energy production) higher than that obtained under the previous irradiance condition perpendicular to the panels during the solstice.

Figure 2.8



The fixed panels should be oriented as much as possible to south in the northern hemisphere[4] so as to get a better insolation of the panel surface at noon local hour and a better global daily insolation of the panels.
The orientation of the panels may be indicated with the *Azimuth*[5] *angle* (γ) of deviation with respect to the optimum direction to south (for the locations in the northern hemisphere) or to north (for the locations in the southern hemisphere).

[2] On gabled roofs the tilt angle is determined by the inclination of the roof itself.
[3] In Italy the optimum tilted angle is about 30°.
[4] Since the solar irradiance is maximum at noon, the collector surface must be oriented to south as much as possible. On the contrary, in the southern hemisphere, the optimum orientation is obviously to north.
[5] In astronomy the Azimuth angle is defined as the angular distance along the horizon, measured from north (0°) to east, of the point of intersection of the vertical circle passing through the object.

Positive values of the Azimuth angles show an orientation to west, whereas negative values an orientation to east (IEC 61194).
As regards ground-mounted panels, the combination of inclination and orientation determines the exposition of the panels themselves (Figure 2.9). On the contrary, when the panels are installed on the roofs of buildings, the exposition is determined by the inclination and the orientation of the roof pitches. Good results are obtained through collectors oriented to south-east or to south-west with a deviation with respect to the south up to 45° (Figure 2.10). Greater deviations can be compensated by means of a slight enlargement of the collector surface.

Figure 2.9

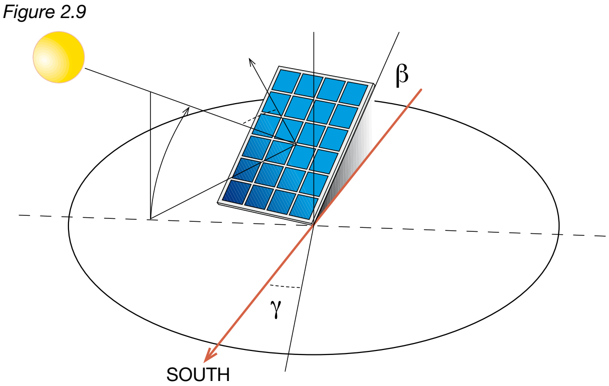
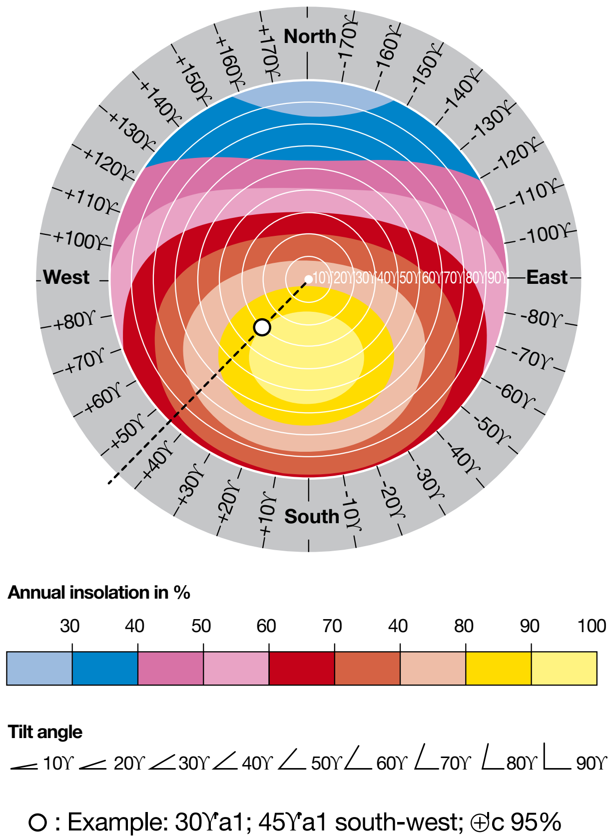


Figure 2.10



A non–horizontal panel receives, besides direct and diffuse radiation, also the radiation reflected by the surface surrounding it (albedo component). Usually an albedo coefficient of 0.2 is assumed.
For a first evaluation of the annual production capability of electric power of a PV installation it is usually sufficient to apply to the annual mean radiation on the horizontal plan (Tables 2.1-2.2) the correction coefficients of the Tables 2.3, 2.4 and 2.5[6].

[6] *Albedo assumed equal to 0.2.*

Table 2.3 – Northern Italy: 44°N latitude

	Orientation				
Inclination	0° (south)	± 15°	± 30°	± 45°	± 90° (east; west)
0°	1.00	1.00	1.00	1.00	1.00
10°	1.07	1.06	1.06	1.04	0.99
15°	1.09	1.09	1.07	1.06	0.98
20°	1.11	1.10	1.09	1.07	0.96
30°	1.13	1.12	1.10	1.07	0.93
40°	1.12	1.11	1.09	1.05	0.89
50°	1.09	1.08	1.05	1.02	0.83
60°	1.03	0.99	0.96	0.93	0.77
70°	0.95	0.95	0.93	0.89	0.71
90°	0.74	0.74	0.73	0.72	0.57

Table 2.4 - Central Italy: 41°N latitude

	Orientation				
Inclination	0° (south)	± 15°	± 30°	± 45°	± 90° (east; west)
0°	1.00	1.00	1.00	1.00	1.00
10°	1.07	1.07	1.06	1.04	0.99
15°	1.09	1.09	1.08	1.06	0.97
20°	1.11	1.11	1.09	1.07	0.96
30°	1.13	1.12	1.10	1.07	0.92
40°	1.12	1.12	1.09	1.05	0.87
50°	1.09	1.08	1.05	1.01	0.82
60°	1.03	1.02	0.99	0.96	0.76
70°	0.94	0.94	0.92	0.88	0.70
90°	0.72	0.72	0.71	0.70	0.56

Table 2.5 - Southern Italy: 38°N latitude

	Orientation				
Inclination	0° (south)	± 15°	± 30°	± 45°	± 90° (east; west)
0°	1.00	1.00	1.00	1.00	1.00
10°	1.06	1.06	1.05	1.04	0.99
15°	1.08	1.08	1.07	1.05	0.97
20°	1.10	1.09	1.08	1.06	0.96
30°	1.11	1.10	1.08	1.06	0.92
40°	1.10	1.09	1.07	1.03	0.87
50°	1.06	1.05	1.03	0.99	0.82
60°	0.99	0.99	0.96	0.93	0.75
70°	0.91	0.91	0.88	0.86	0.69
90°	0.68	0.68	0.68	0.67	0.55

Example 2.2

We wish to determine the annual mean energy produced by the PV installation of the previous example, now arranged with +15° orientation and 30° inclination.

From Table 2.3 an increasing coefficient equal to 1.12 is obtained. Multiplying this coefficient by the energy expected on horizontal plan obtained in the previous example, the expected production capability becomes:

$$E = 1.12 \cdot E_p = 1.12 \cdot 3062 \approx 3430 \text{ kWh}$$

2.7 Voltages and currents in a PV plant

PV panels generate a current from 4 to 10A at a voltage from 30 to 40V.
To get the projected peak power, the panels are electrically connected in series to form the strings, which are connected in parallel. The trend is developing strings constituted by as many panels as possible, given the complexity and cost of wiring, in particular of the paralleling switchboards between the strings.
The maximum number of panels which can be connected in series (and therefore the highest reachable voltage) to form a string is determined by the operation range of the inverter (see Chapter 3) and by the availability of the disconnection and protection devices suitable for the voltage reached.
In particular, the voltage of the inverter is bound, due to reasons of efficiency, to its power: generally, when using inverter with power lower than 10 kW, the voltage range most commonly used is from 250V to 750V, whereas if the power of the inverter exceeds 10 kW, the voltage range usually is from 500V to 900V.

2.8 Variation in the produced energy

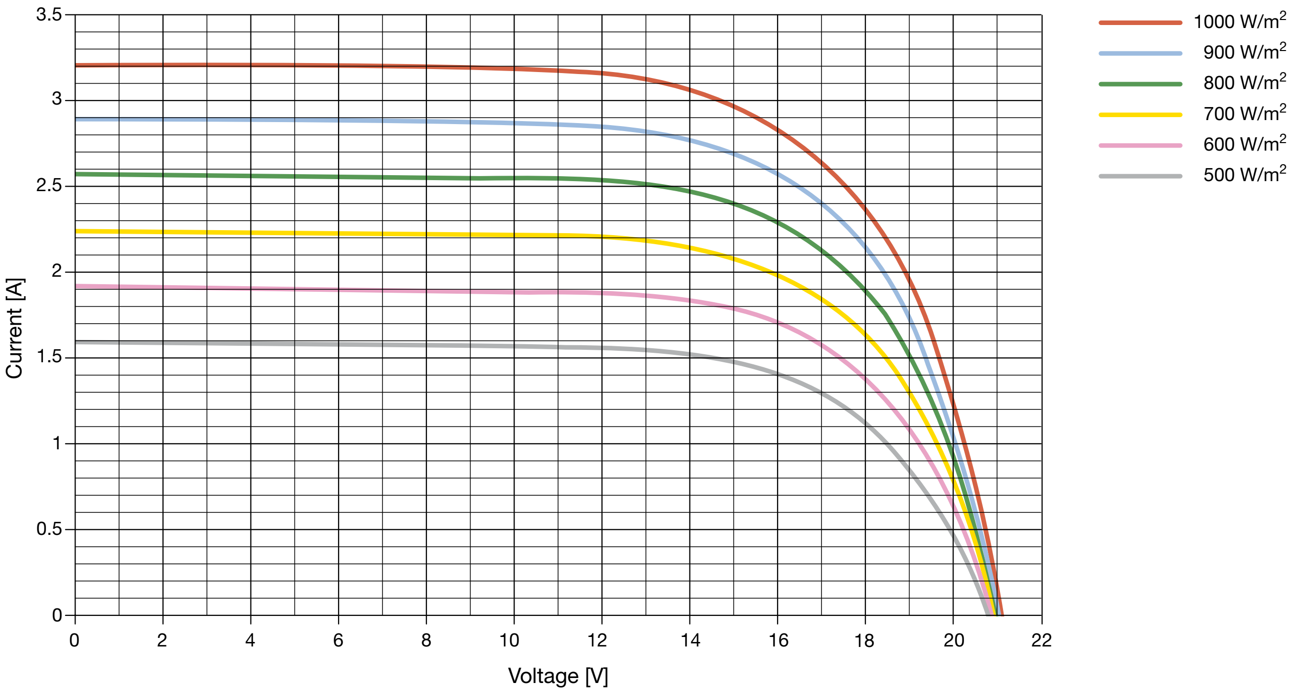
The main factors which influence the electric energy produced by a PV installation are:
- irradiance
- temperature of the modules
- shading.

2.8.1 Irradiance

As a function of the irradiance incident on the PV cells, the characteristic curve V-I of them changes as shown in Figure 2.11.
When the irradiance decreases, the generated PV current decreases proportionally, whereas the variation of the no-load voltage is very small.

As a matter of fact, the conversion efficiency is not influenced by the variation of the irradiance within the standard operation range of the cells, which means that the conversion efficiency is the same both in a clear as well as in a cloudy day.
Therefore the smaller power generated with cloudy sky is referable not to a drop of the efficiency but to a reduced generation of current because of lower solar irradiance.

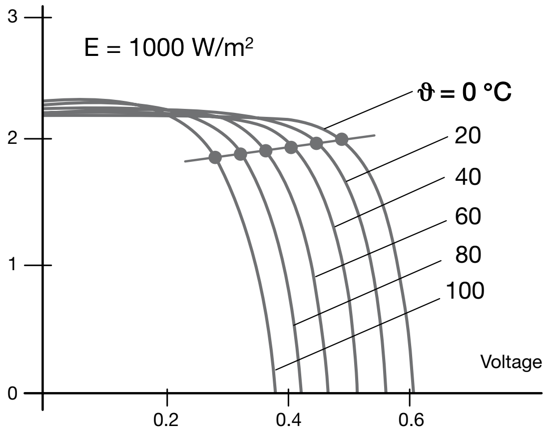
Figure 2.11



2.8.2 Temperature of the modules

Contrary to the previous case, when the temperature of the modules increases, the produced current remains practically unchanged, whereas the voltage decreases and with it there is a reduction in the performances of the panels in terms of produced electric power (Figure 2.12).

Figure 2.12



The variation in the no-load voltage V_{oc} of a PV module with respect to the standard conditions $V_{oc,stc}$, as a function of the operating temperature of the cells T_{cell}, is expressed by the following formula (Guidelines CEI 82-25, II ed.):

$$V_{oc}(T) = V_{oc,stc} - N_S \cdot \beta \cdot (25-T_{cel}) \quad [2.13]$$

where:

β is the variation coefficient of the voltage according to temperature and depends on the typology of PV module (usually -2.2 mV/°C/cell for crystalline silicon modules and about -1.5 ÷ -1.8 mV/°C/cell for thin film modules);

N_s is the number of cells in series in the module.

Therefore, to avoid an excessive reduction in the performances, it is opportune to keep under control the service temperature trying to give the panels good ventilation to limit the temperature variation on them. In this way it is possible to reduce the loss of energy owing to the temperature (in comparison with the temperature of 25°C under standard conditions) to a value around 7%[7].

[7] *The reduction in efficiency when the temperature increases can be estimated as 0.4 to 0.6 for each °C.*

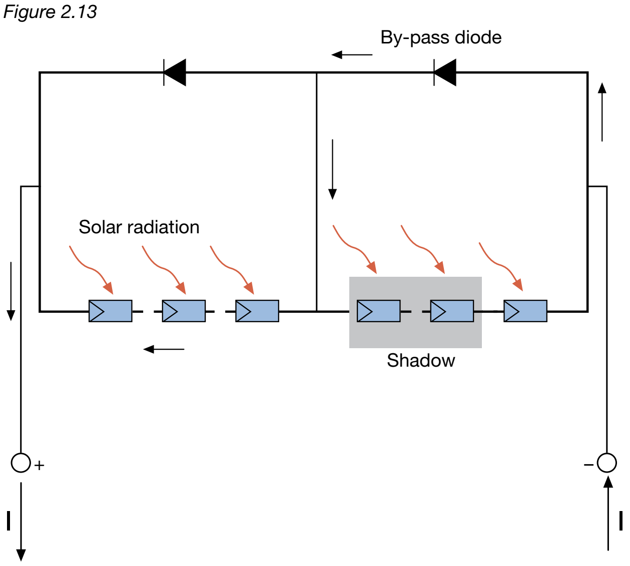
2.8.3 Shading

Taking into consideration the area occupied by the modules of a PV plant, part of them (one or more cells) may be shaded by trees, fallen leaves, chimneys, clouds or by PV panels installed nearby.

In case of shading, a PV cell consisting in a junction P-N stops producing energy and becomes a passive load. This cell behaves as a diode which blocks the current produced by the other cells connected in series thus jeopardizing the whole production of the module. Moreover the diode is subject to the voltage of the other cells which may cause the perforation of the junction due to localized overheating (hot spot) and damages to the module.

In order to avoid that one or more shaded cells thwart the production of a whole string, some diodes which by-pass the shaded or damaged part of module are inserted at the module level. Thus the functioning of the module is guaranteed even if with reduced efficiency. In theory it would be necessary to insert a by-pass diode in parallel to each single cell, but this would be too onerous for the ratio costs/benefits. Therefore 2÷4 by-pass diodes are usually installed for each module (Figure 2.13).

Figure 2.13



3 Installation methods and configuration

3.1 Architectural integration

In the last years the architectural integration of the panels with the building structure has been making great strides thanks to the manufacturing of the panels, which for dimensions and characteristics can completely substitute some components.

Three typologies or architectural integration of PV installations can be defined, also to the purpose of determining the relevant feed-in tariff (see Chapter 7):
1 non-integrated plants;
2 partially integrated plants;
3 integrated plants.

Non-integrated plants are plants with ground-mounted modules, that is with the modules positioned on the elements of street furniture, on the external surfaces of building envelopes, on buildings and structures for any function and purpose with modalities different from those provided for the typologies 2) and 3) (Figure 3.1).
Partially integrated plants are plants in which the modules are positioned in compliance with the typologies listed in Table 3.1, on elements of street furniture, on the external surfaces of building envelopes, on buildings and structures for any function and purpose without replacing the building materials of these structures (Figure 3.2).

Figure 3.1

Figure 3.2

Table 3.1

Specific typology 1	PV modules installed on flat roofs and terraces of buildings and edifices. When a perimeter balustrade is present, the maximum dimension referred to the medium axis of the PV modules shall not exceed the minimum height of the balustrade.
Specific typology 2	PV modules installed on roofs, coverings, facades, balustrades or parapets of buildings and edifices coplanar with the supporting surface without the replacement of the materials which constitute the supporting surfaces.
Specific typology 3	PV modules installed on elements of street furniture, soundproofing barriers, cantilever roofs, arbours and shelters coplanar with the supporting surface without the replacement of the materials which constitute the supporting surfaces.

The plants with architectural integration are those plants in which the modules are positioned according to the typologies listed in Table 3.2 and replace, either totally or in part, the function of building elements (withstand, soundproofing and thermal insulation, lighting, shading) (Figure 3.3).

Figure 3.3

Table 3.2

Specific typology 1	Replacement of the covering materials of roofs, roofing, building facades by PV modules having the same inclination and architectonic functionality as the covered surface.
Specific typology 2	Cantilever roofs, arbors and shelters in which the covering structure is constituted by the PV modules and their relevant support systems.
Specific typology 3	Parts of the roof covering of buildings in which the PV modules replace the transparent or semitransparent material suitable to allow natural lighting of one or more rooms.
Specific typology 4	Acoustic barriers in which part of the soundproof panels are constituted by PV modules.
Specific typology 5	Lighting elements in which the reflecting elements' surface exposed to solar radiation is constituted by PV modules.
Specific typology 6	Sunbreakers whose structural elements are constituted by the PV modules and their relevant supporting systems.
Specific typology 7	Balustrades and parapets in which the PV modules substitute the coating and covering elements.
Specific typology 8	Windows in which the PV modules substitute or integrate the glazed surfaces of the windows.
Specific typology 9	Shutters in which the PV modules constitute the structural elements of the shutters.
Specific typology 10	Any surface described in the above typologies on which the PV modules constitute coating or covering adherent to the surface itself.

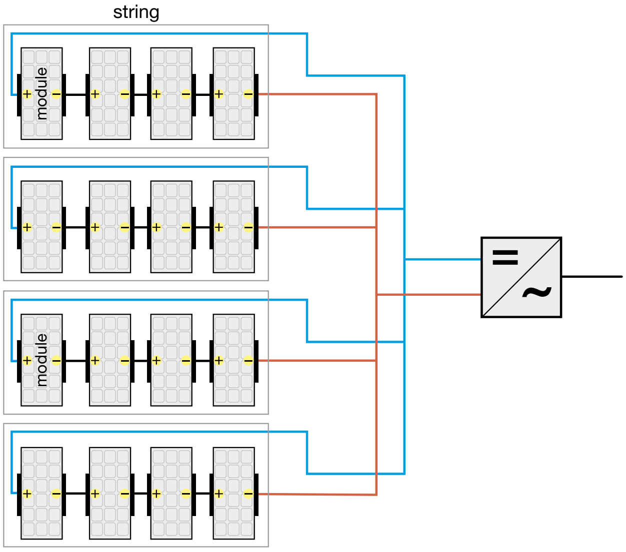
3.2 Solar field layout

The connection of the strings forming the solar field of the PV plant can occur chiefly providing:
- one single inverter for all the plants (single-inverter or with central inverter) (Figure 3.4);
- one inverter for each string (Figure 3.5);
- one inverter for more strings (multi-inverter plant) (Figure 3.6).

3.2.1 Single-inverter plant

This layout is used in small plants and with modules of the same type having the same exposition.
There are economic advantages deriving from the presence of one single inverter, in terms of reduction of the initial investment and of the maintenance costs. However, the failure of the single inverter causes the stoppage of the production of the whole plant. Besides, this solution is not very suitable to increase the size (and with it also the peak power) of the PV plant, since this increases the problems of protection against overcurrents and the problems deriving from a different shading, that is when the exposition of the panels is not the same in the whole plant.
The inverter regulates its functioning through the MPPT[1], taking into account the average parameters of the strings connected to the inverter; therefore, if all the strings are connected to a single inverter, the shading or the failure of one or part of them involves a higher reduction of the electrical performances of the plant in comparison with the other layouts.

Figure 3.4

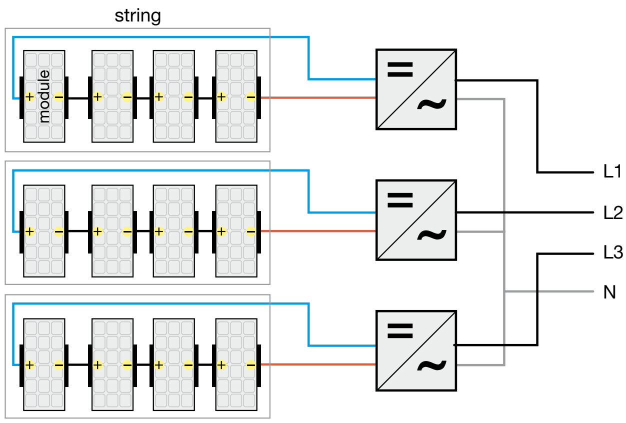


[1] *See Chapter 1.*

3.2.2 Plant with one inverter for each string

In a medium-size plant, each string may be directly connected to its own inverter and thus operate according to its own maximum power point.
With this layout, the blocking diode, which prevents the source direction from being reverse, is usually included in the inverter, the diagnosis on production is carried out directly by the inverter which moreover can provide for the protection against the overcurrents and overvoltages of atmospheric origin on the DC side.
Besides, having an inverter on each string limits the coupling problems between modules and inverters and the reduction of the performances caused by shading or different exposition. Moreover, in different strings, modules with different characteristics may be used, thus increasing the efficiency and reliability of the whole plant.

Figure 3.5

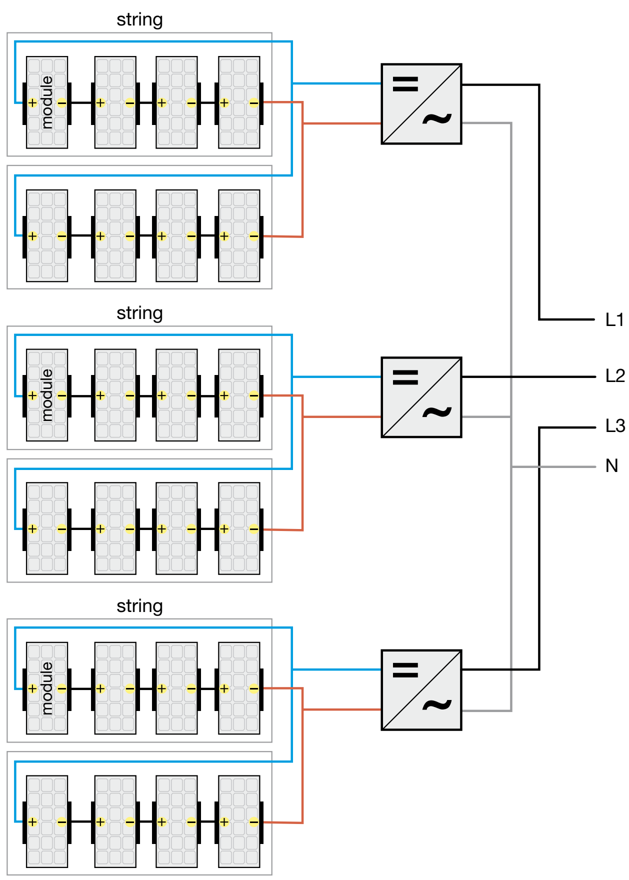


3.2.3 Multi-inverter plant

In large-size plants, the PV field is generally divided into more parts (subfields), each of them served by an inverter of one's own to which different strings in parallel are connected. In comparison with the layout previously described, in this case there is a smaller number of inverter with a consequent reduction of the investment and maintenance costs. However it remains the advantage of reduction of the problems of shading, different exposition of the strings and also of those due to the use of modules different from one another, provided that subfield strings with equal modules and with equal exposition are connected to the same inverter.
Besides, the failure of an inverter does not involve the loss of production of the whole plant (as in the case single-

inverter), but of the relevant subfield only. It is advisable that each string can be disconnected separately , so that the necessary operation and maintenance verifications can be carried out without putting out of service the whole PV generator.
When installing paralleling switchboard on the DC side, it is necessary to provide for the insertion on each string of a device for the protection against overcurrents and reverse currents so that the supply of shaded or faulted strings from the other ones in parallel is avoided. Protection against overcurrents can be obtained by means of either a thermomagnetic circuit-breaker or a fuse, whereas protection against reverse current is obtained through blocking diodes[3].
With this configuration the diagnosis of the plant is assigned to a supervision system which checks the production of the different strings.

Figure 3.6



3.3 Inverter selection and interfacing

The selection of the inverter and of its size is carried out according to the PV rated power it shall manage. The size of the inverter can be determined starting from a value from 0.8 to 0.9 for the ratio between the active power put into the network and the rated power of the PV generator. This ratio keeps into account the loss of power of the PV modules under the real operating conditions (working temperature, voltage drops on the electrical connections….) and the efficiency of the inverter. This ratio depends also on the methods of installation of the modules (latitude, inclination, ambient temperature…) which may cause a variation in the generated power. For this reason, the inverter is provided with an automatic limitation of the supplied power to get round situations in which the generated power is higher than that usually estimated.
Among the characteristics for the correct sizing of the inverter, the following ones should be considered:

- DC side:
  - rated power and maximum power;
  - rated voltage and maximum admitted voltage;
  - variation field of the MPPT voltage under standard operating conditions;
- AC side:
  - rated power and maximum power which can be continuatively delivered by the conversion group, as well as the field of ambient temperature at which such power can be supplied;
  - rated current supplied;
  - maximum delivered current allowing the calculation of the contribution of the PV plant to the short-circuit current;
  - maximum voltage and power factor distortion;
  - maximum conversion efficiency;
  - efficiency at partial load and at 100% of the rated power (through the “European efficiency[4]” or through the efficiency diagram[5] (Figure 3.7).

[2] *Note that the opening of the disconnecting device does not exclude that the voltage is still present on the DC side.*

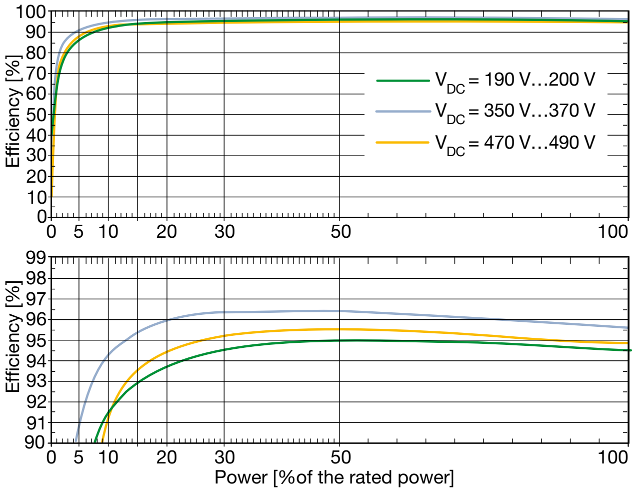
[3] *Diodes introduce a constant power loss due to the voltage drop on their junction. Such loss can be reduced through the use of components with semiconducting metal junction having a loss of 0.4V (Schottky diodes), instead of 0.7V as conventional diodes.*

[4] *The European efficiency is calculated by keeping into account the efficiencies at partial load of the inverter according to the formula:*

$$\eta_{euro} = 0.03 \cdot \eta_{5\%} + 0.06 \cdot \eta_{10\%} + 0.13 \cdot \eta_{20\%} + 0.10 \cdot \eta_{30\%} + 0.48 \cdot \eta_{50\%} + 0.20 \cdot \eta_{100\%}$$

[5] *From this diagram it is possible to see that the maximum efficiency ranges from 40% to 80% of the rated power of the inverter, which corresponds to the power interval in which the inverter works for the most part of the operating time.*

Figure 3.7



Moreover it is necessary to evaluate the rated values of the voltage and frequency at the output and of the voltage at the input of the inverter.
The voltage and frequency values at the output, for plants connected to the public distribution network are imposed by the network with defined tolerances[6].
As regards the voltage at the input, the extreme operating conditions of the PV generator shall be assessed in order to ensure a safe and productive operation of the inverter.
First of all it is necessary to verify that the no-load voltage U_{oc} at the output of the strings, at the minimum prospective temperature (-10°C), is lower than the maximum temperature which the inverter can withstand, that is:

$$U_{oc\ max} \leq U_{MAX} \qquad [3.1]$$

In some models of inverter there is a capacitor bank at the input; as a consequence the insertion into the PV field generates an inrush current equal to the sum of the short-circuit currents of all the connected strings and this current must not make the internal protections, if any, trip.
Each inverter is characterized by a normal operation range of voltages at the input. Since the voltage at the output of the PV panels is a function of the temperature, it is necessary to verify that under the predictable service conditions (from -10°C to +70°C), the inverter operates within the voltage range declared by the manufacturer. As a consequence, the two inequalities [3.2] and [3.3] must be simultaneously verified:

$$U_{min} \geq U_{MPPT\ min} \qquad [3.2]$$

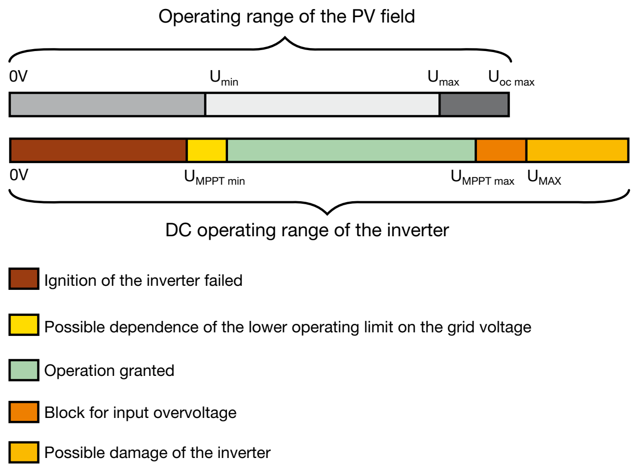
that is, the minimum voltage (at 70°C) at the corresponding maximum power at the output of the string under standard solar radiation conditions shall be higher than the minimum operating voltage of the MPPT of the inverter; the minimum voltage of the MPPT is the voltage which keeps the control logic active and allows a correct power delivery into the distributor's network. Besides, it shall be:

$$U_{max} \leq U_{MPPT\ max} \qquad [3.3]$$

that is, the minimum voltage (at -10°C), at the corresponding maximum power at the output of the string under standard solar radiation conditions, shall be lower than or equal to the maximum operating voltage of the MPPT of the inverter.

Figure 3.8 shows a coupling diagram between PV field and inverter taking into account the three above mentioned inequalities.
In addition to compliance with the three above mentioned conditions regarding voltage, it is necessary to verify that the maximum current of the PV generator when operating at the maximum power point (MPP) is lower than the maximum current admitted by the inverter at the input.

Figure 3.8



Legend:

- U_{min} voltage at the maximum power point (MPP) of the PV field, in correspondence with the maximum operating temperature expected for the PV modules at the installation site
- U_{max} voltage at the maximum power point (MPP) of the PV field, in correspondence with the minimum operating temperature expected for the PV modules at the installation site
- $U_{oc\ max}$ no-load voltage of the PV field, in correspondence with the minimum operating temperature expected for the PV modules at the installation site
- $U_{MPPT\ min}$ minimum input voltage admitted by the inverter
- $U_{MPPT\ max}$ maximum input voltage admitted by the inverter
- U_{MAX} maximum input voltage withstood by the inverter

[6] As from 2008 the European standardized voltage should be 230/400V with +6% and -10% tolerance, while the tolerance on frequency is ±0.3 Hz.

[7] As regards the selection of the inverter and of the other components of the PV plant on the AC side, a precautionary maximum string voltage value of 1.2 U_{oc} can be assumed.

The inverters available on the market have a rated power up to about 10 kW single-phase and about 100 kW three-phase.
In small-size plants up to 6 kW with single-phase connection to the LV network, a single inverter is usually installed, whereas in the plants over 6 kW with three-phase connection to the LV or MV grid, more inverters are usually installed.

In small/medium-size plants it is usually preferred the solution with more single-phase inverters distributed equally on the three phases and on the common neutral and a single transformer for the separation from the public network (Figure 3.9).

Instead, for medium- and large-size plants it is usually convenient to have a structure with few three-phase inverters to which several strings, in parallel on the DC side in the subfield switchboards, are connected (Figure 3.10).

Figure 3.9

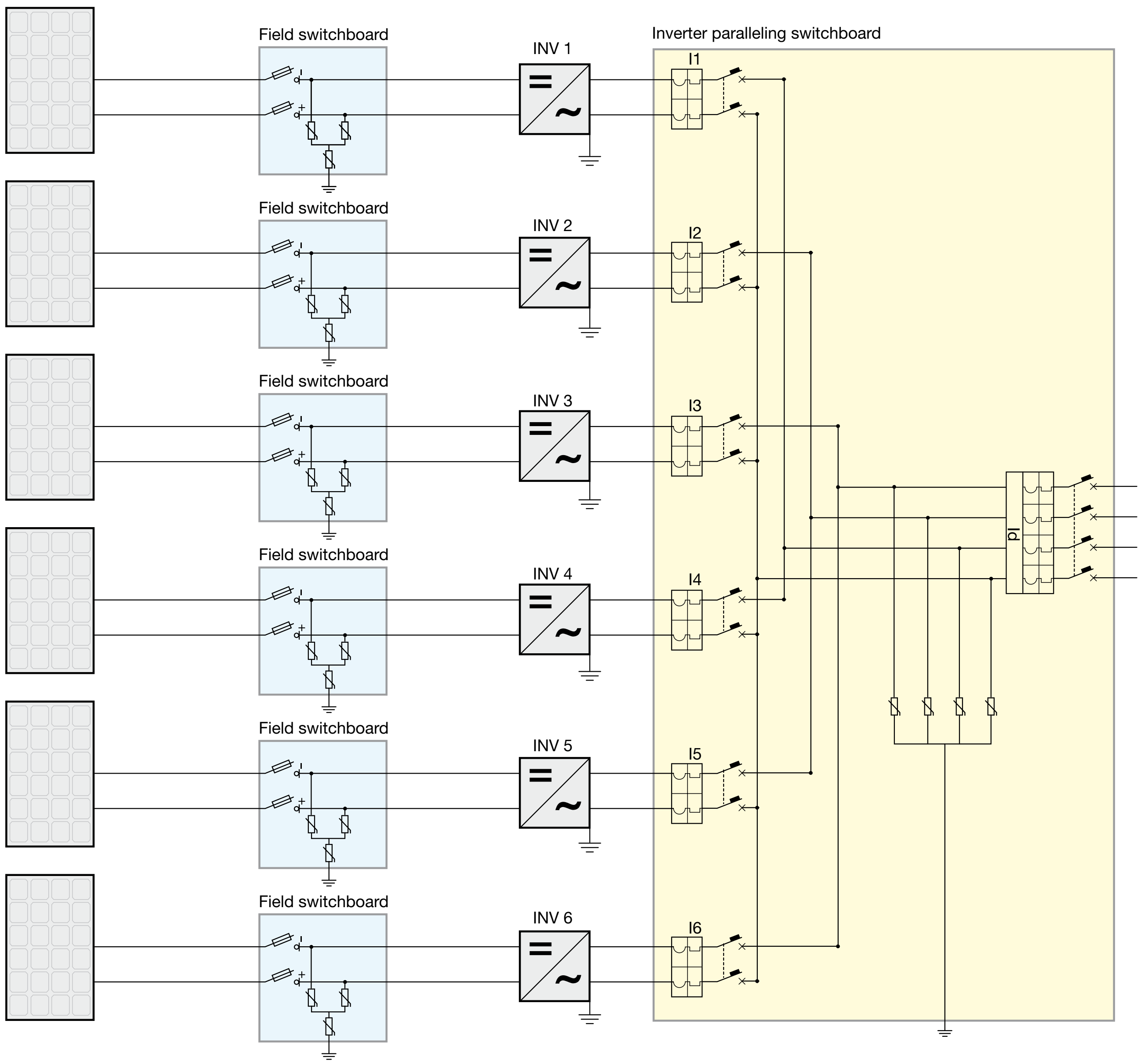
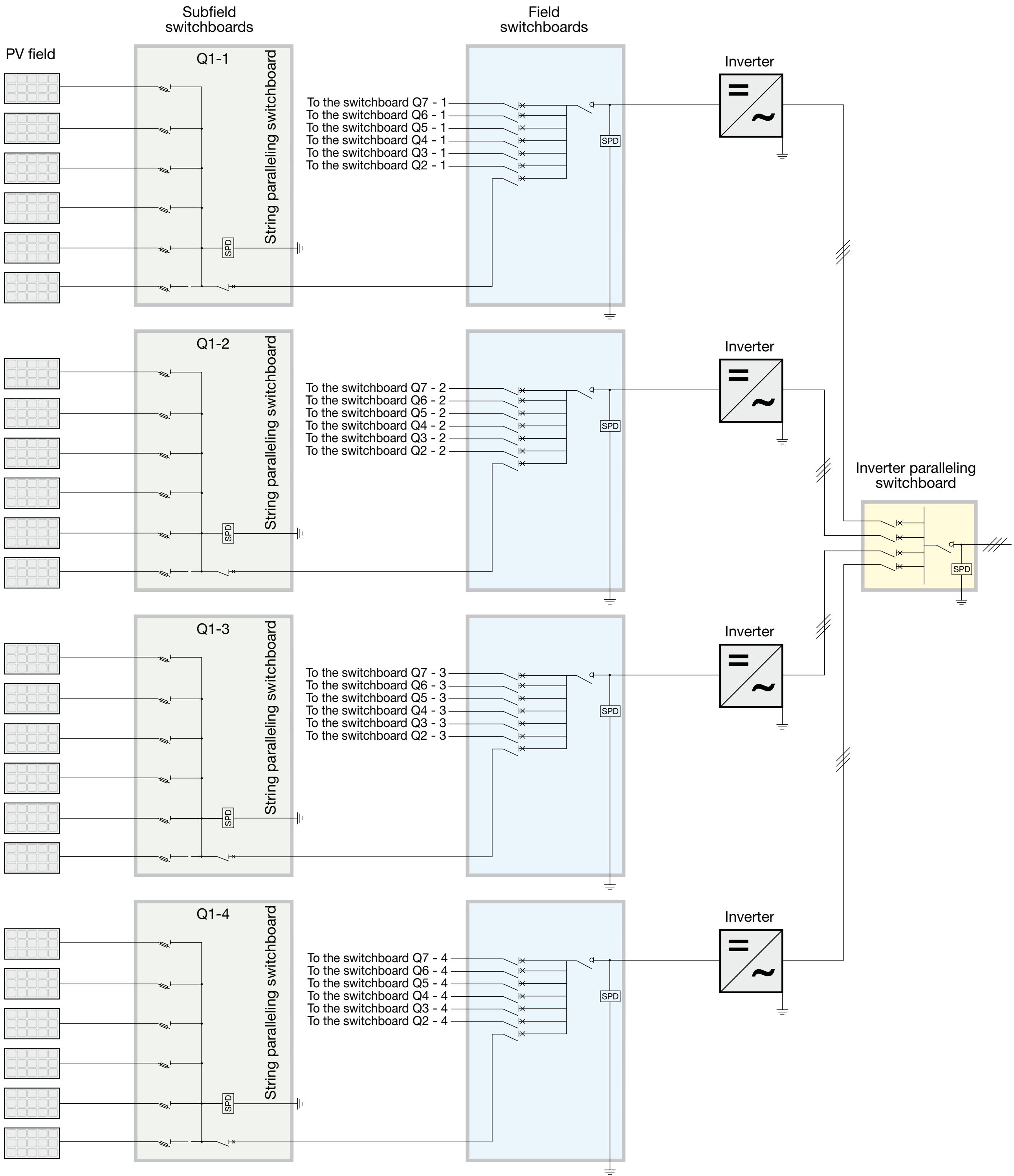


Figure 3.10



Disconnection of the inverter must be possible both on the DC side as well as on the AC side, so that maintenance is allowed by excluding both the supply sources, that is PV generator and grid.

Besides, as shown in Figure 3.10, it is advisable to install a disconnecting device on each string, so that verification and maintenance operations on each string are possible without putting out of service the other parts of the plant.

3.4 Choice of cables

The cables used in a PV plant must be able to stand, for the whole life cycle of the plant (20 to 25 years), severe environmental conditions in terms of high temperatures, atmospheric precipitations and ultraviolet radiations.
First of all, the cables shall have a rated voltage suitable for that of the plant. Under direct current conditions, the plant voltage shall not exceed of 50% the rated voltage of the cables (Figure 3.11) referred to their AC applications (in alternating current the voltage of the plant shall not exceed the rated voltage of the cables).

Table 3.3

alternating current (V)	direct current (V)
300/500	450/750
450/750	675/1125
600/1000	900/1500

3.4.1 Types of cables

The conductors on the DC side of the plant shall have double or reinforced isolation (class II) so as to minimize the risk of earth faults and short-circuits (IEC 60364-712).

The cables on the DC side are divided into:
- *solar cables* (or string cables) which connect the modules and the string of the first subfield switchboard or directly the inverter;
- *non-solar cables* which are used on the load side of the first switchboard.

The cables connecting the modules are fastened in the rear part of the modules themselves, where the temperature may reach 70° to 80°C. As a consequence, these cables shall be able to stand high temperatures and withstand ultraviolet rays, when installed at sight. Therefore particular cables are used, generally single-core cables with rubber sheath and isolation, rated voltage 0.6/1kV, with maximum operating temperature not lower than 90°C and with high resistance to UV rays.

Non-solar cables on the load side of the first switchboard are at an environmental temperature not higher than 30° to 40°C since they are far away from the modules. These cables cannot withstand UV rays and therefore, if laid out outside, they must be protected against solar radiation in conduit or trunking and however sheathed for outdoor use. On the contrary, if they are laid out inside the buildings, the rules usually applied to the electrical plants are valid.

For cables erected on the AC side downstream the inverter what said for non-solar cables erected on the DC side is valid.

[8] *The whole of cables and conduit or trunking system in which they are placed.*

3.4.2 Cross sectional area and current carrying capacity

The cross sectional area of a cable shall be such as that:
- its current carrying capacity I_z is not lower than the design current I_b;
- the voltage drop at its end is within the fixed limits.

Under normal service conditions, each module supplies a current near to the short-circuit one, so that the service current for the string circuit is assumed to be equal to:

$$I_b = 1.25 \cdot I_{SC} \qquad [3.4]$$

where I_{sc} is the short-circuit current under standard test conditions and the 25% rise takes into account radiation values higher than 1kW/m².

When the PV plant is large-sized and divided into subfields, the cables connecting the subfield switchboards to the inverter shall carry a design current equal to:

$$I_b = y \cdot 1.25 \cdot I_{SC} \qquad [3.5]$$

where y is the number of strings of the subfield relevant to the same switchboard.

The current carrying capacity I_o of the cables is usually stated by the manufacturers at 30°C in free air. To take into account also the methods of installation and the temperature conditions, the current carrying capacity I_o shall be reduced by a correction factor (when not declared by the manufacturer) equal to[9]:

- $k_1 = 0.58 \cdot 0.9 \;\; = 0.52$ for solar cables
- $k_2 = 0.58 \cdot 0.91 = 0.53$ for non-solar cables.

The correction factor 0.58 takes into consideration installation on the rear of the panels where the ambient temperature reaches 70°C[10], the factor 0.9 the installation of solar cables in conduit or trunking system, while the factor 0.91 takes into consideration the installation of non-solar cables into conduit exposed to sun.

In PV plants the accepted voltage drop is 1 to 2% (instead of the usual 4% of the user plants) so that the loss of produced energy caused by the Joule effect on the cables[11] is limited as much as possible.

[9] *Besides, the resulting carrying capacity shall be multiplied by a second reduction coefficient, as it usually occurs, which takes into consideration the installation in bunch into the same conduit or trunking system.*

[10] *At 70°C ambient temperature and assuming a maximum service temperature for the insulating material equal to 90°C it results:*

$$\sqrt{\frac{\theta_{max} - 0}{\theta_{max} - 0_0}} = \sqrt{\frac{90 - 70}{90 - 30}} = \sqrt{\frac{1}{3}} = 0.58$$

[11] *On the DC side the voltage drop in the cables is purely resistive and in percentage it corresponds to the power loss:*

$$\Delta U\% = \frac{\Delta U}{U_n} = \frac{\Delta U \cdot I_n}{U_n \cdot I_n} = \frac{\Delta P}{P_n} = \Delta P\%$$

4 Connection to the grid and measure of the energy

4.1 General

A PV plant can be connected in parallel to the public distribution network if the following conditions are complied with (CEI 0-16):
- the parallel connection shall not cause perturbations to the continuity and quality of the service of the public network to preserve the level of the service for the other users connected;
- the production plant must not be connected or the connection in parallel must immediately and automatically interrupt in case of absence of the supply from the distribution network or if the voltage and frequency values of the network are not in the range of the allowed values;
- the production plant must not be connected or the connection in parallel must immediately and automatically interrupt if the unbalance value of the power generated by three-phase plants consisting of single-phase generators is not lower than the maximum value allowed for single-phase connections.

This in order to avoid that (CEI 0-16):
- in case of lack of voltage in the grid, the connected active user may supply the grid itself;
- in case of fault on the MV line, the grid itself may be supplied by the PV plant connected to it;
- in case of automatic or manual reclosing of the circuit-breakers of the distribution network, the PV generator may be out of phase with the network voltage, with likely damage to the generator.

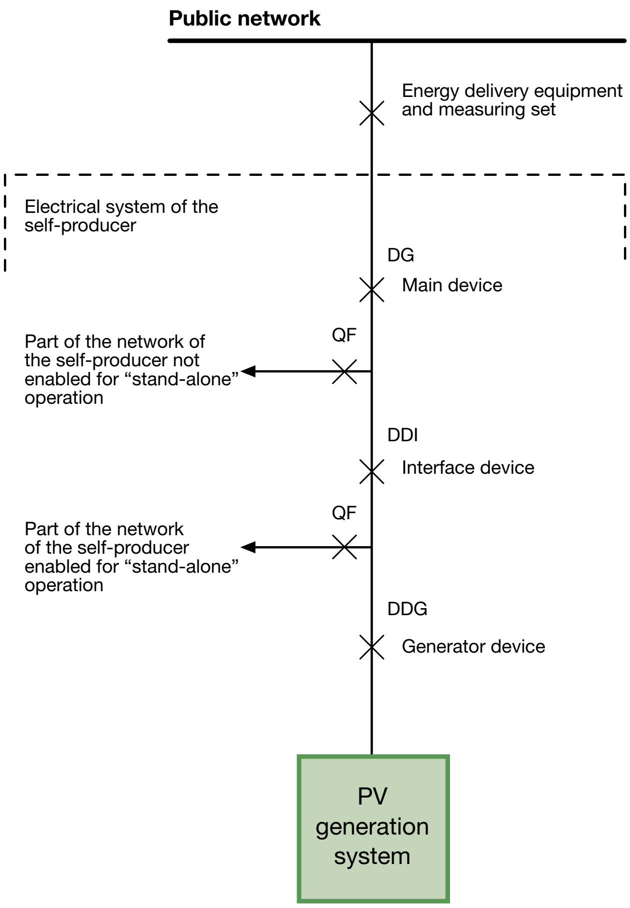
The PV plant can be connected to the LV, MV or HV grid in relation to the value of the generated peak power (TICA):
- connection to the LV grid for plants up to 100 kW[1];
- connection to the MV grid for plants up to 6 MW.

In particular, the connection of the PV plant to the LV network
- can be single-phase for powers up to 6 kW;
- must be three-phase for powers higher than 6 kW and, if the inverters are single-phase, the maximum difference between the phases must not exceed 6 kW.

The principle diagram of the layout of the generation system in parallel with the public network is shown in Figure 4.1 (Guide CEI 82-25, II ed.).

[1] These limits can be exceeded to the discretion of the distribution authority. Besides, as regards the plants already connected to the grid, these limits are increased up to the power level already available for the withdrawal.

Figure 4.1



With reference to the particular diagram of the PV plant, the Standard (CEI 0-16) allows that more functions are carried out by the same device provided that between the generation and the network two circuit-breakers or a circuit-breaker and a contactor in series are present.

When choosing the breaking capacity of the QF devices, it is necessary to take into consideration that also the generation plant, in addition to the grid and to the large motors running, can contribute to the short-circuit current at the installation point.

4.2 In parallel with the LV network

From an analysis of Figure 4.1, it can be noticed that three switching devices are interposed between the production plant of the user and the public network (Guide CEI 82-25, II ed.):

- *main device*, it separates the user plant from the public network; it trips due to a fault in the PV plant or, in case of plants with net metering, due to a fault of the PV system or of the user's plant; it consists of a circuit-breaker suitable for disconnection with overcurrent releases and for tripping all the phases and the neutral;
- *interface device*, it separates the generation plant from the user's grid not enabled for stand-alone operation and consequently from the public network; it trips due to disturbances on the network of the distributor and it consists of a contactor or of an automatic circuit-breaker with an undervoltage release tripping all the involved phases and the neutral, category AC-7a if single-phase or AC-1 if three-phase (CEI EN 60947-4-1);
- *generator device*, it separates the single PV generator from the rest of the user's plant; it trips due to a fault inside the generator and can be constituted by a contactor or an automatic circuit-breaker tripping all the involved phases and the neutral.

The interface protection system, which acts on the interface device, is constituted by the functions listed in the Table 4.1.

Table 4.1

Protection	Version	Setting value	Tripping time
Maximum voltage (59)	Single-/ three-pole(1)	≤ 1.2 Un	≤ 0.1 s
Minimum voltage (27)	Single-/ three-pole(1)	≥ 0.8 Un	≤ 0.2 s
Maximum frequency (81>)	Single-pole	50.3 o 51 Hz(2)	Without intentional delay
Minimum frequency (81<)	Single-pole	49 o 49.7 Hz(2)	Without intentional delay
Frequency derivative (Δ81)(3)	Single-pole	0.5 Hz/s	Without intentional delay

(1) Single-pole for single-phase systems and three-pole for three-phase systems.

(2) The default settings are 49.7 Hz and 50.3 Hz. If, under normal service conditions, the frequency variation of the distributor's grid are such as to cause unwanted trips of the protection against maximum/minimum frequency, the settings of 49 and 51 Hz shall be adopted.

(3) In particular cases only.

For power up to 6kW in single-phase and 20kW in three-phase systems the interface device can also be internal to the conversion system. For installations up to 20kW the interface function can be carried out by more different devices up to 3 (Guide for the connection to the electrical networks by Enel Distribution).

In PV plants, with power not higher than 20 kW and with maximum three inverters, to which loads for stand-alone operation are not connected, the generator device can also accomplish the function of interface device (Figure 4.1a), whereas in the PV plants for generation only, that is those to which no consumer plants are associated, the interface device may coincide with the main device (Figure 4.1b).

Figure 4.1a

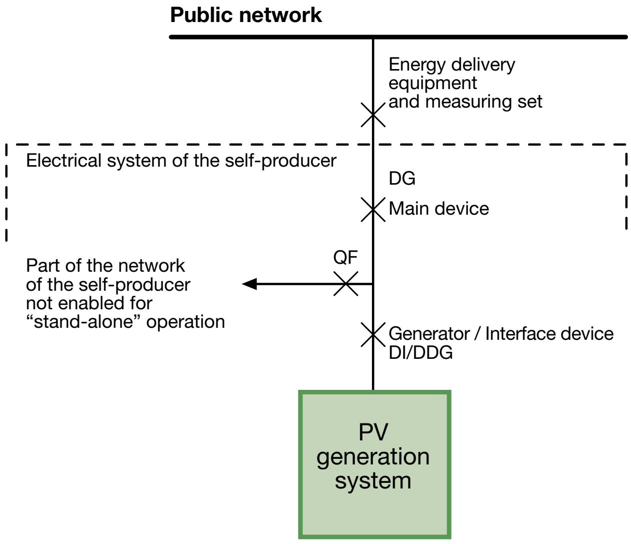
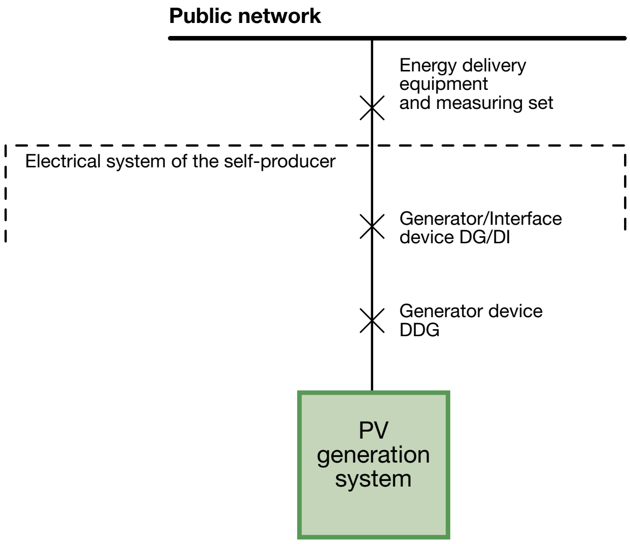


Figure 4.1b



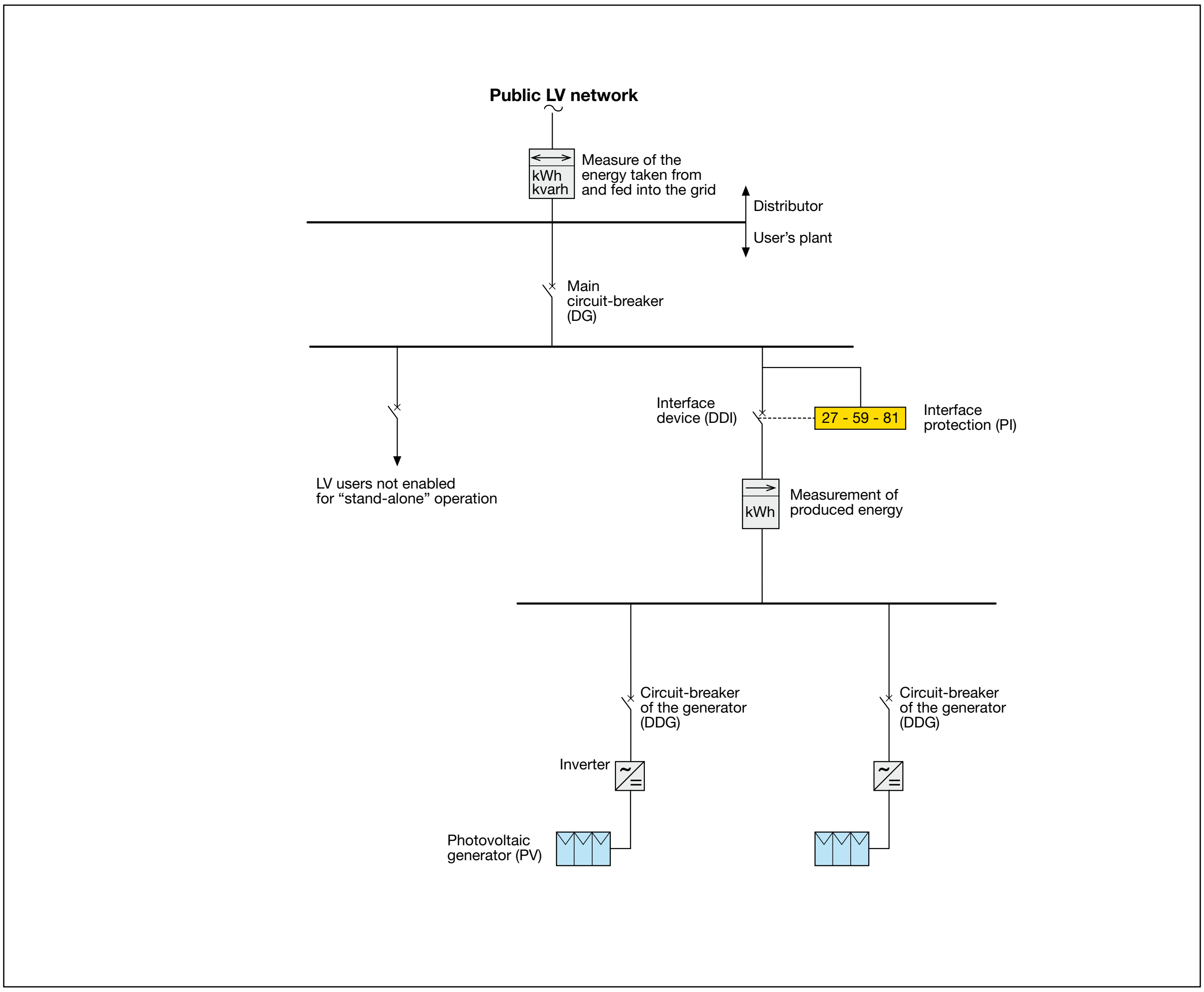
A metal separation between the PV plant and the public network shall be guaranteed in order not to feed direct currents into the grid. For plants with total generated power not higher than 20kW such separation can be replaced by a protection (generally inside the electronic control and setting system of the inverter) which makes the interface (or generator) device open in case of values of total direct component exceeding 0.5% of the r.m.s. value of the fundamental component of the total maximum current coming out from the converters. For plants with total generation power exceeding 20kW and with inverters without metal separation between the direct and alternating current parts, the insertion of a LV/lv at industrial frequency is necessary (Guide CEI 82-25, II ed.).
Figure 4.2 shows a single-line diagram typical of a PV plant connected to the LV grid in the presence of a user's plant.

PV installations can deliver active energy with a power factor (Guide CEI 82-25, II ed.)[3]:
- not lower than 0.8 delayed (absorption of reactive power), when the supplied active power ranges from 20% to 100% of the installed total power;
- unitary;
- in advance, when they deliver a total reactive power not exceeding the minimum value between 1kvar and (0.05+P/20)kvar (where P is the installed total power expressed in kW).

[2] *A high frequency transformer is not suitable since it has output direct current components exceeding the allowed limits; moreover only a separation transformer is admitted for more inverters.*

[3] *Referred to the fundamental component.*

Figure 4.2



4.3 In parallel with the MV network

The *main device* consists of (CEI 0 -16):

- a three-pole circuit-breaker in withdrawable version with opening trip unit;
- or a three-pole circuit-breaker with opening trip unit and three-pole switch- disconnector to be installed on the supply side of the circuit-breaker.

As regards the opening command of the main device due to the intervention of the main protection, an undervoltage coil must be used because if, for any reason, the supply voltage of the main protection lacks, the opening of the main device occurs also in case of absence of the command coming from the main protection.

The general protection includes (CEI 0-16):

- an overcurrent release with three trip thresholds, one with inverse time-delay I> (overload threshold 51), two with constant time I>> (threshold with intentional delay 51) and I>>> (instantaneous threshold 50);
- a zero-sequence overcurrent release 51N with two constant time trip thresholds Io> and Io>>, one for the single-phase earth faults and one for the double single-phase earth faults, or a directional zero-sequence overcurrent release with two thresholds 67N.1 and 67N.2 , one for the selection of internal faults in case of networks with compensated neutral and one in case of insulated neutral, in addition to the zero-sequence overcurrent release with one threshold for the double single-phase earth faults.

The *interface device* can be positioned both on the MV as well as on the LV side. If this device is installed on the MV part of the plant, it can consists of (CEI 0-16 Interpretation Sheet):

- a three-pole circuit-breaker in withdrawable version with undervoltage opening release or
- a three-pole circuit-breaker with undervoltage opening release and a switch-disconnector installed either on the supply or on the load side of the circuit-breaker[5].

For plants with more PV generators, as a rule, the interface device shall be one and such as to exclude at the same time all the generators, but more interface devices are allowed provided that the trip command of each protection acts on all the devices, so that an anomalous condition detected by a single protection disconnects all the generators from the network[6].

If single-phase inverters with power up to 10kW are used, the interface protection system can be integrated into the converter itself for total generated powers not higher than 30kW (CEI 0-16 Interpretation Sheet).

Moreover, since the inverters used in PV plants work as current generators and not as voltage generators it is not necessary to integrate into the interface protection also the zero-sequence overvoltage protections (59N) and the additional protection against failed opening of the interface device (Guide CEI 82-25, II ed.).

The interface protection system consists of the functions listed in the Table 4.2 (CEI 0-16 Interpretation Sheet).

Table 4.2

Protection	Setting value	Fault extinction time	Intentional delay
Maximum voltage (59)	≤ 1.2 Un	≤ 170 ms	100 ms
Minimum voltage (27)	≥ 0.7 Un	≤ 370 ms	300 ms
Maximum frequency (81>)	50.3 Hz	≤ 170 ms	100 ms
Minimum frequency (81<)	49.7 Hz	≤ 170 ms	100 ms

As regards the *generator device,* what pointed out for the parallel connection with the LV part is valid.

The Figures 4.3 and 4.4 show two typical diagrams for the connection of the MV network of a PV plant. In particular the diagram of Figure 4.3 shows a plant equipped with more single-phase inverters and in which the interface device is positioned on the LV. This configuration is typical of plants with power up to one hundred kW.

Instead larger plants use three-phase inverters with one or more LV/MV transformers and the interface device is generally positioned on the MV (Figure 4.4).

[4] *Protection 67N is required when the contribution to the single-phase ground fault capacitive current of the MV grid of the user exceeds the 80% of the setting current fixed by the distributor for the protection 51N. In practice, when the MV cables of the user exceed the length of:*
- *400m for grids with Un=20 kV*
- *533m for grids with Un=15kV.*

[5] *The possible presence of two switch-disconnectors (one on the supply side and one on the load side) shall be considered by the user according to the need of safety during maintenance operations.*

[6] *When a PV plant (with total power not higher than 1 MW) is added to plants connected to the grid since more than a year, it is possible to install no more than three interface devices and each of them can subtend maximum 400 kW (CEI 0-16 Interpretation Sheet).*

Figure 4.3

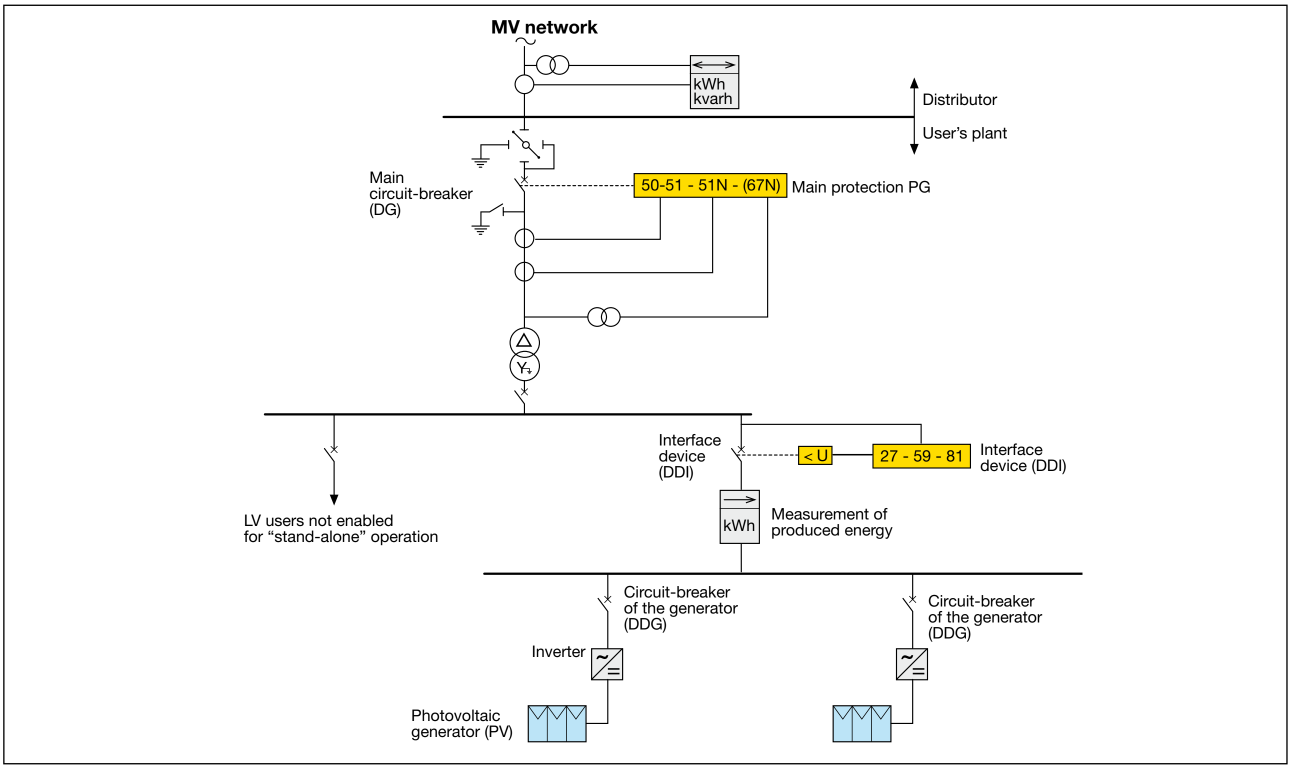
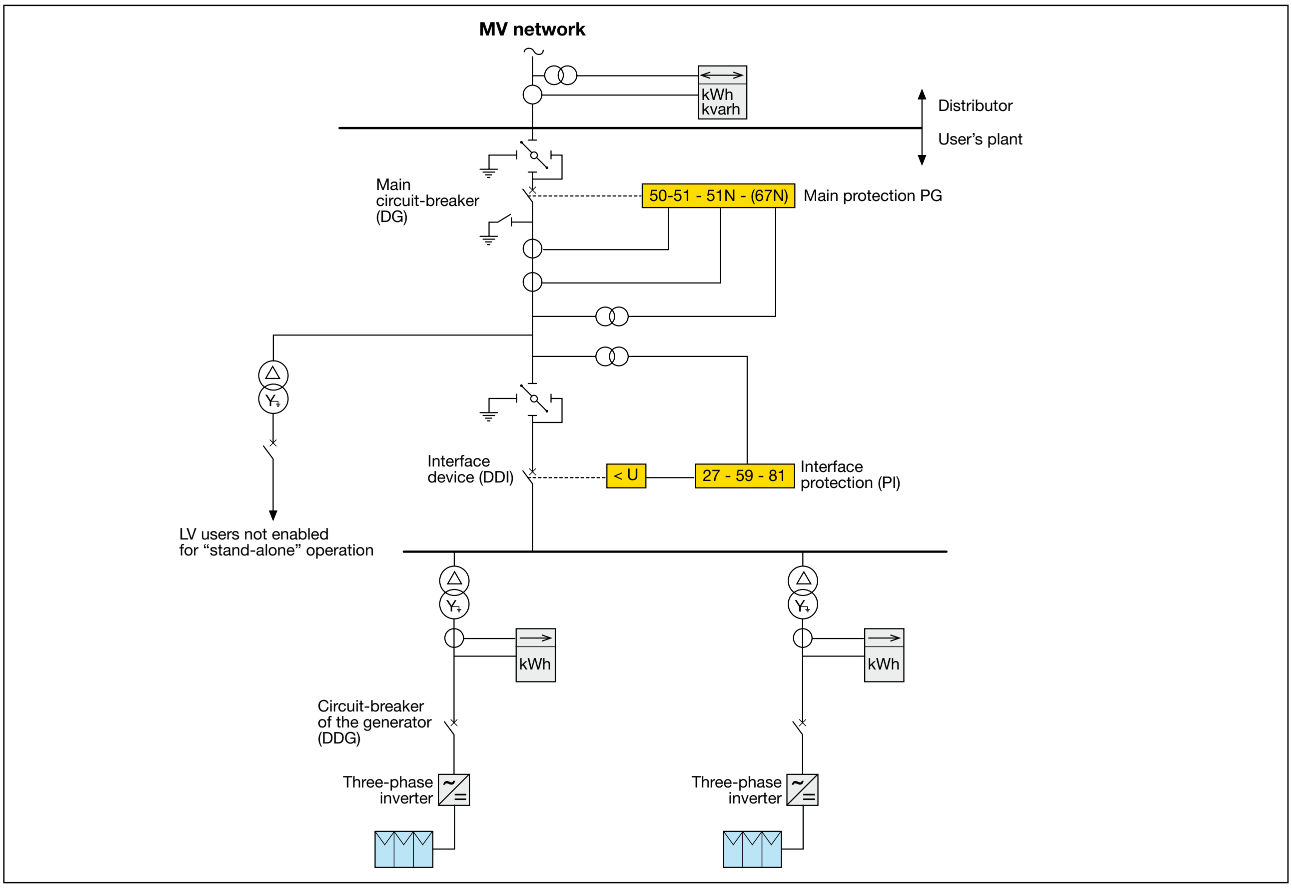


Figure 4.4

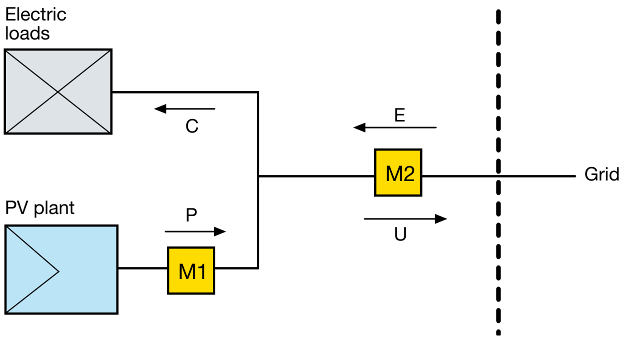


4.4 Measurement of the energy produced and exchanged with the grid

In a PV plant connected to the public network the interposition of measuring systems is necessary to detect:
- the electrical energy taken from the grid;
- the electrical energy fed into the grid;
- the energy produced by the PV plant.

The insertion modality of the measuring systems is shown in Figure 4.5.

Figure 4.5



The energy balance of the system, referred to a specific time period, is given by:

$$U - E = P - C \qquad [4.1]$$

where:

U is the energy produced by the PV plant and energy fed into the grid;
E is the energy drawn from the network;
P is the energy produced by the PV plant (energy supported by feed-in tariff);
C is the energy consumed by the user's plant.

During the night or when the PV plant does not produce energy due to some other reasons, (U=P=0) the formula [4.1] becomes:

$$E = C \qquad [4.2]$$

that is all the consumed energy is taken from the network.

On the contrary, when the PV plant is generating energy, the two following situations may occur:
- P > C: in this case the balance is positive and energy is fed into the network;
- P < C: in this case the balance is negative and energy is drawn from the network.

The energy exchanged with the network is generally measured by a bidirectional electronic meter M2 and the measuring system shall be hour-based.

The distribution utility is generally responsible for the installation and maintenance of the measuring set for the exchanged energy.
The Ministerial Decree DM 19/2/07 defines the electric energy produced by a PV plant as "the electric energy measured at the output of the inverter set converting direct current to alternating current, including the possible transformer, before this energy is made available for the electric loads of the responsible subject and/or fed into the public network".

The measure of the produced energy is carried out by a meter M1, which shall be able to detect the energy produced on hour-basis and shall be equipped with a device for telecom inquiry and acquisition of the measures from the network grid administrator.
The measuring set for the produced energy shall be installed as near as possible to the inverter and shall be equipped with suitable anti-fraud devices.

For plants with rated power not higher than 20 kW, the responsible for the measuring of the produced energy is the grid administrator, whereas for powers higher than 20 kW responsible is the "active" user (i.e. the user which also produces energy), who has the faculty of making use of the grid administrator to carry out such activity, while maintaining the responsibility of such service.

5 Earthing and protection against indirect contact

5.1 Earthing

The concept of earthing applied to a photovoltaic (PV) system may involve both the exposed conductive parts (e.g. metal frame of the panels) as well as the generation power system (live parts of the PV system e.g. the cells).
A PV system can be earthed only if it is galvanically separated (e.g. by means of a transformer) from the electrical network by means of a transformer. A PV insulated system could seem apparently safer for the people touching a live part; as a matter of fact, the insulation resistance to earth of the live parts is not infinite and then a person may be passed through by a current returning through such resistance. This current rises when the voltage to earth of the plant and the plant size increase since the insulation resistance to earth decreases. Besides, the physiological decay of the insulators, due to the passage of time and the presence of humidity, reduces the insulation resistance itself. Consequently, in very big plants, the current passing through a person in touch with the live part may cause electrocution and therefore the advantage over the earthed systems is present only in case of small plants.

5.2 Plants with transformer

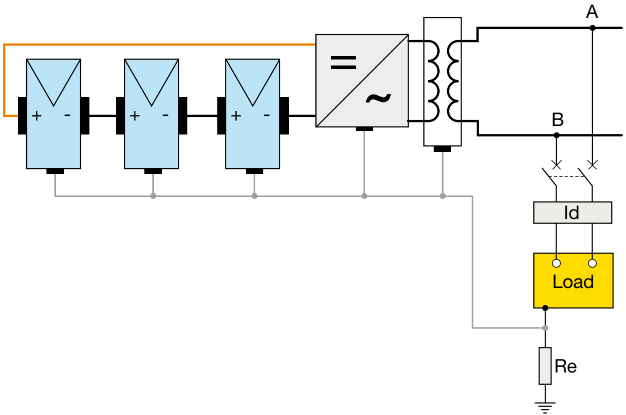
In the plants with transformer, in addition to the analysis of the PV system either insulated or earthed, for the protection against indirect contacts it is necessary to make a difference between the exposed conductive parts upstream and downstream the transformer[1].

5.2.1 Exposed conductive parts on the load side of the transformer

5.2.1.1 Plant with IT system

In this type of plant the live parts result insulated from earth, whereas the exposed conductive parts are earthed[2] (Figure 5.1).

Figure 5.1



In this case the earthing resistance R_e of the exposed conductive parts shall meet the condition (CEI 64-8):

$$R_e \quad \frac{120}{I_d} \qquad [5.1]$$

where I_d is the current of first fault to earth, which is not known in advance, but which is generally very low in small-sized plants. As a consequence, the earthing resistance R_e of the consumer plant, which is defined for a fault in the network, usually satisfies only the relation [5.1].
In case of a double earth fault, since the PV generator is a current generator, the voltage of the interconnected exposed conductive parts shall be lower than:

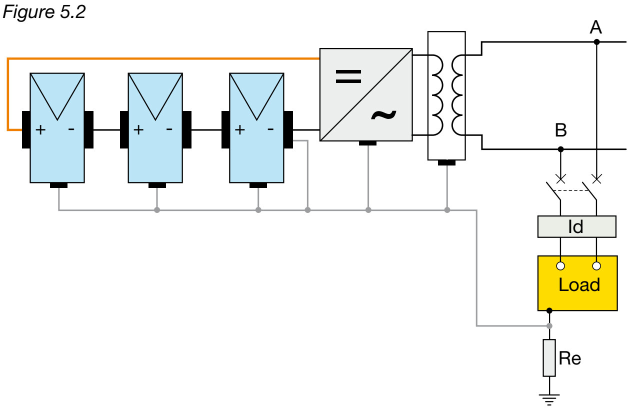
$$I_{sc} \cdot R_{eqp} \leq 120V \qquad [5.2]$$

where I_{sc} is the short-circuit current of the cells involved, whereas R_{eqp} is the resistance of the conductor interconnecting the exposed conductive parts affected by fault. For instance, if $R_{eqp} = 1\Omega$ (value approximated by excess), the relation [5.2] is fulfilled for I_{sc} not exceeding 120A, which is usual in small-sized plants; therefore the effective touch voltage in case of a second earth fault does not result hazardous. On the contrary, in large-sized plants it is necessary to reduce to acceptable limits the chance that a second earth fault occurs by eliminating the first earth fault detected by the insulation controller (either inside the inverter or external).

5.2.1.2 Plant with TN system

In this type of plant the live parts and the exposed conductive parts are connected to the same earthing system (earthing system of the consumer's plant). Thus a TN system on the DC side is obtained (Figure 5.2).

Figure 5.2



[1] *In this case upstream and downstream are referred to the direction of the electric power produced by the PV plant.*

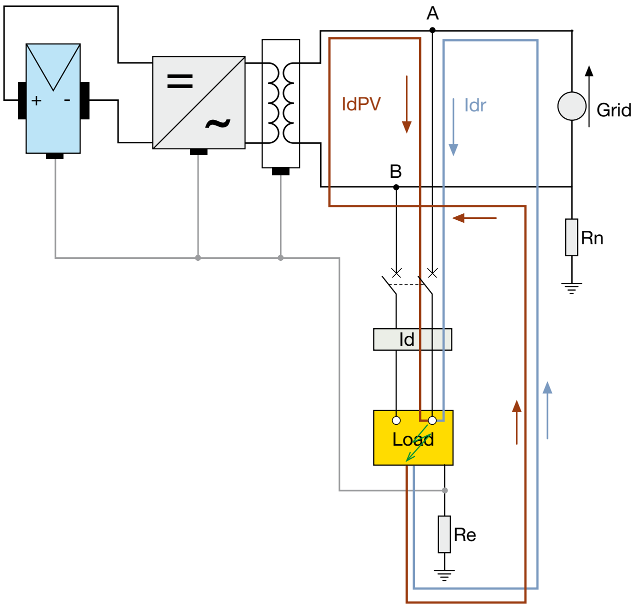
[2] *For safety reasons the earthing system of the PV plant results to be in common with the consumer's one. However, to make the insulation controller of the inverter operate properly and monitor the PV generator it is necessary that the frames and/or the supporting structures of the panels (even if of class II) are earthed.*

In the presence of an earth fault, a short-circuit occurs as in the usual TN systems, but such current cannot be detected by the maximum current devices since the characteristic of the PV plants is the generation of fault currents with values not much higher than the rated current. Therefore, as regards the dangerousness of this fault, the considerations made in the previous paragraph[3] on the second fault for an IT system are valid.

5.2.2 Exposed conductive parts on the supply side of the transformer

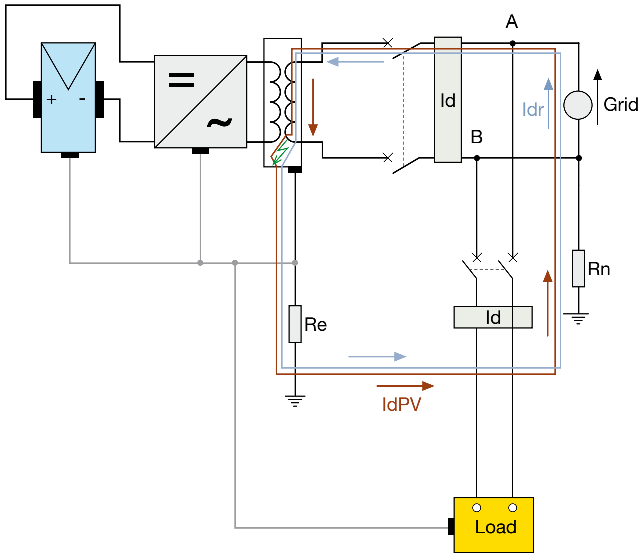
Take into consideration the network-consumer system of TT type. The exposed conductive parts belonging to the consumer's plant protected by a residual current circuit-breakers positioned at the beginning of the consumer's plant (Figure 5.3) result protected both towards the network as well as towards the PV generator.

Figure 5.3



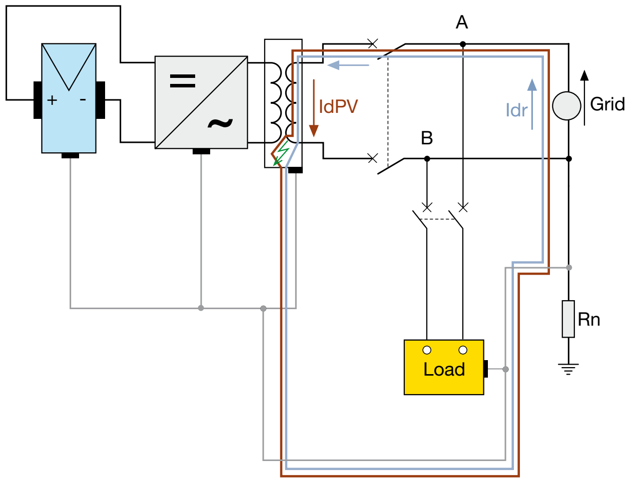
There must not be an exposed conductive part between the parallel point A-B and the network because, in such case, the normative requirement that all the exposed conductive parts of a consumer's plant in a TT system must be protected by a residual current circuit-breaker fails.
As regards the exposed conductive parts upstream the parallel point A-B, such as for instance the exposed conductive part of the transformer or of the inverter when the transformer is incorporated, a residual current device[4] shall be interposed as Figure 5.4 shows; this residual current device detects the leakage currents coming both from the network as well as from the PV generator. When the residual current device trips due to an earth fault current, the inverter goes in stand by due to lack of network voltage.

Figure 5.4



On the contrary, if the network-consumer system is type TN, for both the supply possibilities, either from the network or from the PV generator, residual current circuit-breakers are not needed provided that the fault current on the AC side causes the tripping of the overcurrent devices by the times prescribed in the Std. (Figure 5.5).

Figure 5.5



[3] *The Std. IEC 60364-7 recommends that the whole installation on the DC side (switchboards, cables, and terminal boards) is erected by use of class II devices or equivalent insulation. However, to make the insulation controller of the inverter operate properly and monitor the PV generator it is necessary that the frames and/or the supporting structures of the panels (even if of class II) are earthed.*

[4] *The rated residual current shall be coordinated with the earth resistance R_e, in compliance with the usual relation of the TT systems:*

$$R_e \le \frac{50}{I_{dn}}$$

5.3 Plants without transformer

In case of absence of the separation transformer between the PV installation and the network, the PV installation itself shall be insulated from earth in its active parts becoming an extension of the supply network, generally with a point connected to earth (TT or TN system).
As regards the exposed conductive parts of the consumer's plant and upstream the parallel point A-B, from a conceptual point of view, what described in clause 5.2.2 is still valid.

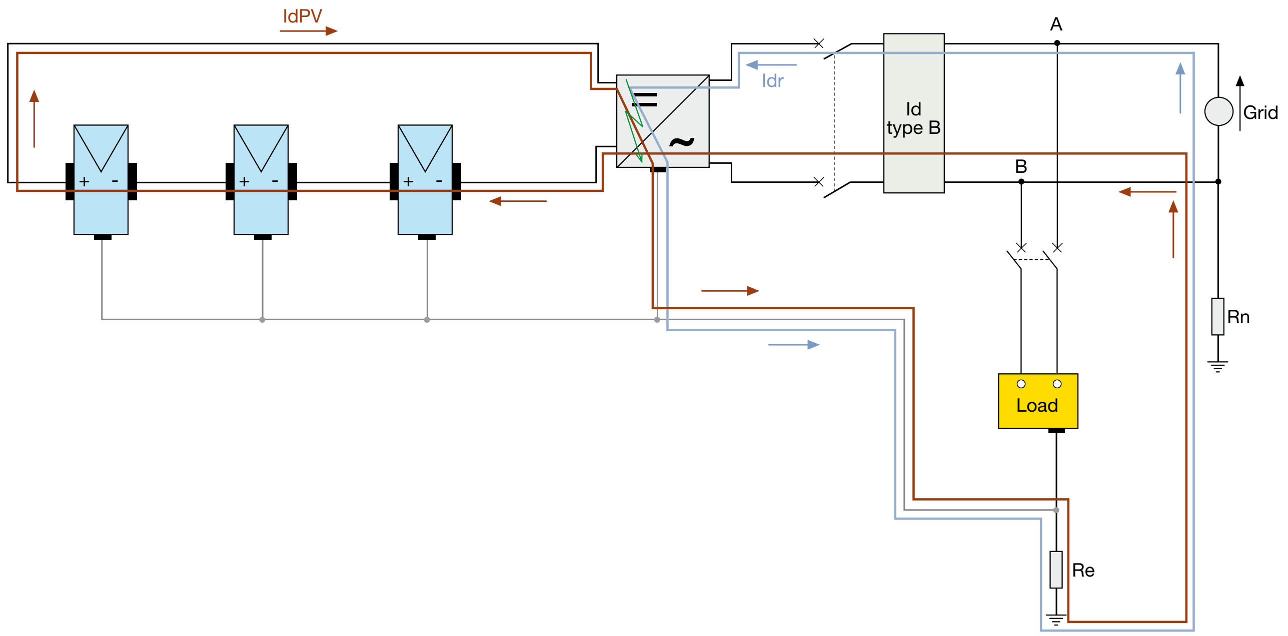
On the DC side an earth fault on the exposed conductive parts determines the tripping of the residual current circuit-breaker positioned downstream the inverter (Figure 5.6). After the tripping of the residual current device, the inverter goes in stand by due to the lack of network voltage, but the fault is supplied by the PV generator. Since the PV system is type IT, the considerations made in clause 5.2.2.1 are valid.

For earth faults on the DC side and on the exposed conductive parts upstream the parallel point A-B, the residual current circuit-breaker on the load side of the inverter is passed through by a residual current which is not alternating. Therefore such device must be of type B[5], unless the inverter is by construction such as not to inject DC earth fault currents (IEC 60364-7)[6].

[5] The residual current device of type B detects the following typologies of earth fault currents:
- *alternating (also at frequency exceeding the network one, e.g. up to 1000 Hz);*
- *pulsating unidirectional;*
- *direct.*

[6] The Std. CEI EN 62040-1 prescribes that the protection of the UPS (including an inverter) against earth faults is realized by using residual current devices type B (for three-phase UPS) and type A (for single-phase UPS), whenever an earth fault current with DC components may be possible according to the UPS design.

Figure 5.6



6 Protection against overcurrents and overvoltages

When defining the layout of a photovoltaic plant it is necessary to provide, where needed, for the protection of the different sections of the plant against overcurrents and overvoltages of atmospheric origin.
Here are given, firstly, the conditions for the protection against overcurrents in the PV plant on the supply (DC side) and on the load side of the inverter (AC side), then the methods for the protection of the plant against any damage caused by possible direct or indirect fulmination[1].

6.1 Protection against overcurrents on DC side

6.1.1 Cable protections

From the point of view of the protection against overloads, it is not necessary to protect the cables (CEI 64-8/7) if they are chosen with a current carrying capacity not lower than the maximum current which might affect them ($1.25\ I_{sc}$)[2].

As regards the short-circuit, the cables on the DC side are affected by such overcurrent in case of:

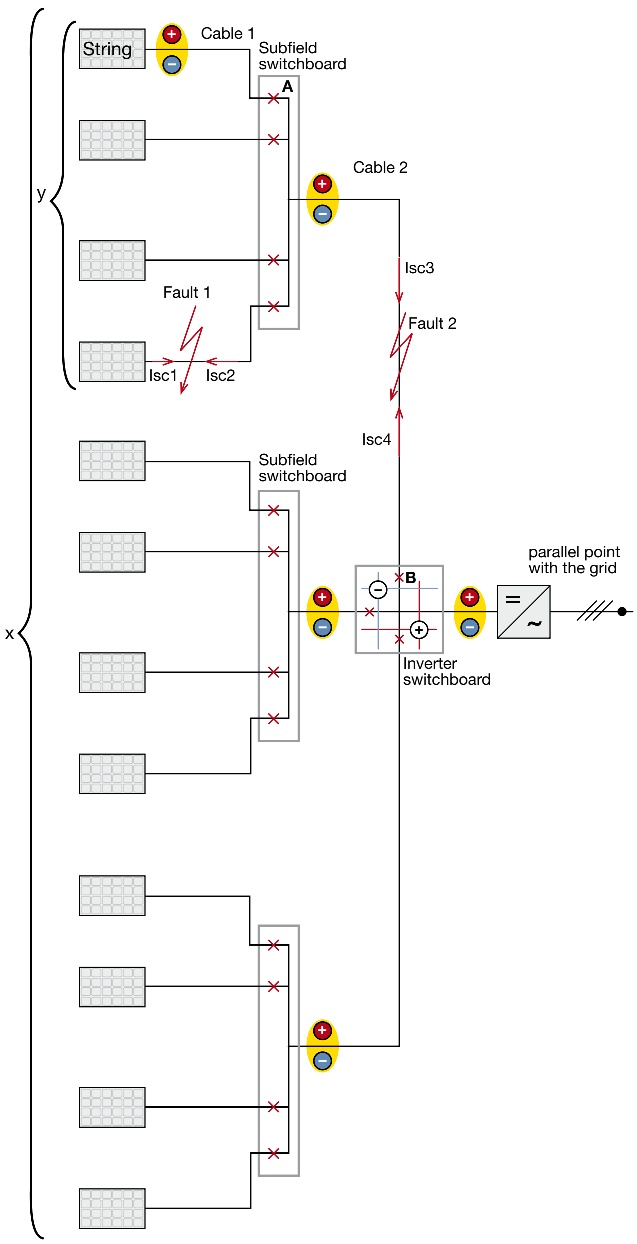
- fault between the polarity of the PV system;
- fault to earth in the earthed systems;
- double fault to earth in the earth-insulated systems.

A short-circuit on a cable for the connection string to subfield switchboard (fault 1 of Figure 6.1) is supplied simultaneously upstream of the load side by the string under consideration ($I_{sc1} = 1.25 \cdot I_{sc}$) and downstream by the other x-1 strings connected to the same inverter ($I_{sc2} = (x-1) \cdot 1.25 \cdot I_{sc}$).
If the PV plant is small-sized with two strings only (x=2), it results that $I_{sc2} = 1.25 \cdot I_{sc} = I_{sc1}$ and therefore it is not necessary to protect the string cables against short-circuit.
On the contrary, when three or more strings (x≥3) are connected to the inverter, the current I_{sc2} is higher than the service current and therefore the cables must be protected against the short-circuit when their current carrying capacity is lower than I_{sc2}, that is $I_z < (x-1) \cdot 1.25 \cdot I_{sc}$.
A short-circuit between a subfield switchboard and the inverter switchboard (fault 2 of the Figure 6.1) is supplied upstream by the y strings in parallel of the subfield (I_{sc3}) and downstream by the remaining (x-y) strings relevant to the same inverter switchboard.

The short-circuit current $I_{sc3} = y \cdot 1.25 \cdot I_{sc}$ coincides with the service current of the circuit between the subfield switchboard and inverter, whereas the current $I_{sc4} = (x-y) \cdot 1.25 \cdot I_{sc}$ is higher than the service current if $x-y > y \Rightarrow x > 2y$.
In this case it is necessary to protect the cable against short-circuit if its current carrying capacity is lower than I_{sc4}, that is $I_z<(x-y) \cdot 1.25 \cdot I_{sc}$.

Figure 6.1

"A" represents the protective device in the subfield switchboard for the protection of the "cable 1" connecting the string to the switchboard itself.
"B" represents the protection device installed in the inverter switchboard to protect the "cable 2" for the connection between the inverter and the subfield switchboard.
"y" number of strings connected to the same subfield switchboard.
"x" total number of strings connected to the same inverter.



[1] As regards the power factor correction of a user plant in the presence of a PV plant see Annex E of the QT8 "Power factor correction and harmonic filtering in electrical plants".

[2] I_{sc} is the short-circuit current in the module under standard test conditions and the twenty-five per cent rise takes the insolation values exceeding 1kW/m² (see Chapter 3) into account.

6.1.2 Protection of the strings against reverse current

Due to shading or fault a string becomes passive, absorbing and dissipating the electric power generated by the other strings connected in parallel to the same inverter through a current which flows through the string under consideration in a reverse direction with respect to that of standard operation, with possible damages to the modules.
These are able to withstand a reverse current ranging from 2.5 and 3 I_{sc} (IEC TS 62257-7-1). Since with x strings in parallel connected to the same inverter the highest reverse current is equal to $I_{inv} = (x-1) \cdot 1.25 \cdot I_{sc}$, it is not necessary to protect the strings if $I_{inv} \leq 2.5 \cdot I_{sc}$ that is $(x-1) \cdot 1.25 \leq 2.5 \Rightarrow x \leq 3$[3].

6.1.3 Behaviour of the inverter

The contribution to the short-circuit on the DC side of the inverter may come from the grid and from the discharge of the capacitors inside the inverter.
The grid current is due to the recirculating diodes of the bridge inverter which in this case act as a bridge rectifier. Such current is limited by the impedances of the transformer and of the inductors belonging to the output circuit and by the protection fuses of the inverter on the AC side chosen so that they can limit the thermal effects of possible internal faults on the semiconductors. As a consequence the I^2t passing through will be normally reduced. Indicatively a final current value (internal capacitors completely discharged) of 10In can be an upper limit value. This current is present in case of inverter with galvanic insulation at 50Hz, while it is null in case of inverter without transformer. In fact these inverters usually have an input DC/DC converter so that the operation on a wide voltage range of the PV generator is guaranteed; this converter, due to its constructive typology, includes at least one blocking diode which prevents the contribution of the grid current to the short-circuit.
The discharge current of the capacitors is limited by the cables between inverter and fault and exhausts itself with exponential trend: the lowest the impedance of the cable stretch, the highest the initial current, but the lowest the time constant of the discharge. The energy which flows is limited to that one initially stored in the capacitors. Moreover, if a blocking diode or other similar device is in series with one of the two poles, this contribution to the short-circuit is null.
In each case, the short-circuit on the DC side causes a drop of the direct voltage, the inverter certainly shuts down and probably is disconnected from the grid. Normally the shut down times of the inverter are of the order of some milliseconds, while the disconnection times may be of the order of some dozens of milliseconds. In the interval between the shut down and the disconnection, the grid might cause the above mentioned effect, while the internal capacitors, if involved, participate up to their complete discharge.
However, the influences of both the grid and the internal capacitors on the short-circuit have only a transient nature and they are usually not such as to affect the sizing of the protection, switching and disconnection devices positioned on the DC side.

6.1.4 Choice of the protective devices

As regards the protection against the short-circuits on the DC side, the devices shall be obviously suitable for DC use and have a rated service voltage Ue equal or higher than the maximum voltage of the PV generator which is equal to 1.2 U_{oc}[4] (IEC TS 62257-7-1).

Moreover the protection devices shall be positioned at the end of the circuit to be protected, proceeding from the strings towards the inverter, that is in the various subfield switchboards and inverter switchboards since the short-circuit currents come from the other strings, that is from the load side and not from the supply side (IEC TS 62257-7-1).

In order to avoid unwanted tripping under standard operation conditions, the protective devices positioned in the subfield switchboards (device A in the Figure 6.1) shall have a rated current I_n[5]:

$$I_n \geq 1.25 \cdot I_{sc} \quad [6.1]$$

These devices shall protect:
- every single string against the reverse current;
- the connection cable[6] string to subswitchboard (cable 1 of Figure 6.1) if the latter has a current carrying capacity lower than the maximum short-circuit current of the other x-1 strings connected to the same inverter switchboard[7], i.e. if:

$$I_z < I_{sc2} = (x - 1) \cdot 1.25 \cdot I_{sc} \quad [6.2]$$

[3] *The blocking diodes can be used, but they do not replace the protections against overcurrent (IEC TS 62257-7-1), since it is taken into consideration the possibility that the blocking diode does not work properly and is short-circuited. Moreover the diodes introduce a loss of power due to the voltage drop on the junction, a loss which can be reduced by using Schottky diodes with 0.4V drop instead of 0.7V of conventional diodes. However the rated reverse voltage of the diodes shall be ≥ 2 U_{oc} and the rated current ≥ 1.25 I_{sc} (CEI Guide 82-25).*

[4] *U_{oc} is the no load voltage coming out of the strings (see Chapter 3).*

[5] *For thermomagnetic circuit-breakers the [6.1] becomes $I_1 \geq 1.25 \cdot I_{sc}$, while for magnetic only circuit-breakers $I_u \geq 1.25 \cdot I_{sc}$ so that their overheating can be avoided.*

[6] *Protection against short-circuit only because $I_z \geq 1.25 \cdot I_{sc}$.*

[7] *The short-circuit $I_{sc1} = 1.25 \cdot I_{sc}$ (fig. 6.1) (Figure 6.1) is unimportant because the string cable has a current carrying capacity not lower than $1.25 \cdot I_{sc}$.*

To the purpose of protection for the string, the rated current of the protective device (either thermomagnetic circuit-breaker or fuse) must not exceed that one declared by the manufacturer for the panel protection (clause 6.1.2); if no indications are given by the manufacturer, the following is assumed (IEC TS 62257-7-1):

$$1.25 \cdot I_{sc} \leq I_n \leq 2 \cdot I_{sc} \quad [6.3]$$

To the purpose of protection for the connection cable, the protective device must be chosen so that the following relation is satisfied for each value of short-circuit (IEC 60364)[8] up to a maximum of $(x-1) \cdot 1.25 \cdot I_{sc}$:

$$I^2t \leq K^2 S^2 \quad [6.4]$$

The breaking capacity of the device must not be lower than the short-circuit current of the other n-1 strings, that is:

$$I_{cu} \geq (x-1) \cdot 1.25 \cdot I_{sc} \quad [6.5]$$

The devices in the inverter switchboard must protect against the short-circuit the connection cables subfield switchboard-inverter switchboard when these cables have a current carrying capacity lower than $I_{sc4} = (x-y) \cdot 1.25 \cdot I_{sc}$[9] (Figure 6.1). In this case these devices shall satisfy the relations [6.1] and [6.4], while their current carrying capacity shall not be lower than the short-circuit current of the other n-m strings, that is:

$$I_{cu} \geq (x-y) \cdot 1.25 \cdot I_{sc} \quad [6.6]$$

In short, the cable for the connection inverter switchboard to inverter must not be protected if its current carrying capacity is chosen at least equal to (CEI 64-8/7):

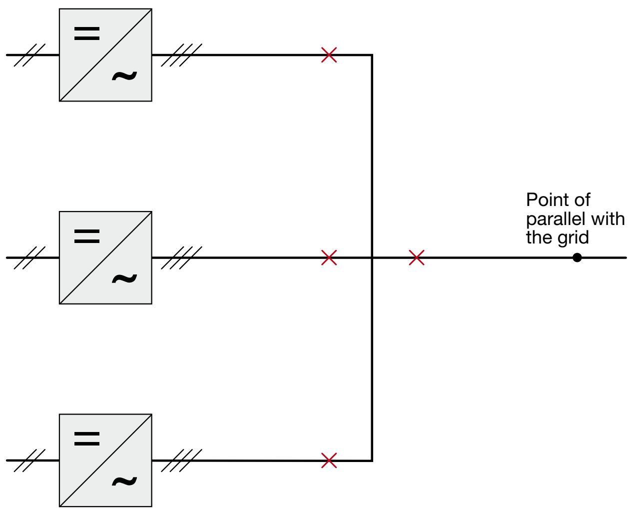
$$I_z \geq x \cdot 1.25 \cdot I_{sc} \quad [6.7]$$

6.2 Protection against overcurrents on AC side

Since the cable connecting the inverter to the point of connection with the grid is usually dimensioned to obtain a current carrying capacity higher than the maximum current which the inverter can deliver, a protection against overload is not needed. However the cable must be protected against a short circuit supplied by the grid[10] through a protective device positioned near the point of parallel with the grid.

To protect such cable the main circuit-breaker of the consumer plant can be used if the specific let-through energy is withstood by the cable. However, the trip of the main circuit-breaker put all the consumer plant out of service. In the multi-inverter plants (Figure 6.2), the presence of one protection for each line allows, in case of fault on an inverter, the functioning of the other ones, provided that the circuit-breakers on each line are selective with the main circuit-breaker.

Figure 6.2



6.3 Choice of the switching and disconnecting devices

The installation of a disconnecting device on each string is advisable in order to allow verification or maintenance interventions on the string without putting out of service other parts of the PV plant (CEI Guide 82-25 II ed.)[11].

[8] *For the magnetic only circuit-breaker it is necessary, if possible, to set I_3 at a value equal to the value I_z of the cable in order to determine the tripping of the device when the short circuit current exceeds the current carrying capacity of the protected cable. Besides, it is possible to use a magnetic only circuit-breaker if the number of strings connected to the same inverter is maximum 3; otherwise for the protection of the string it is necessary to use a thermomagnetic circuit-breaker chosen according to [6.3].*

[9] *The short-circuit current $I_{sc3} = y \cdot 1.25 \cdot I_{sc}$ (Figure 6.1) is unimportant since the string cable has a current carrying capacity not lower than $y \cdot 1.25 \cdot I_{sc}$.*

[10] *The inverter generally limits the output current to a value which is the double of its rated current and goes in stand-by in few tenths of seconds due to the trip of the internal protection. As a consequence, the contribution of the inverter to the short-circuit current is negligible in comparison with the contribution of the grid.*

[11] *When an automatic circuit-breaker is used the switching and disconnecting function is already included.*

The disconnection of the inverter must be possible both on the DC side as well as on the AC side so that maintenance is allowed by excluding both the supply sources (grid and PV generator) (CEI 64-8/7).
On the DC side of the inverter a disconnecting device shall be installed which can be switched under load, such as a switch-disconnector. On the AC side a general disconnecting device shall be provided. The protective device installed at the point of connection with the grid can be used; if this device is not close to the inverter, it is advisable to position a disconnecting device immediately on the load side of the inverter.

6.4 Protection against overvoltages

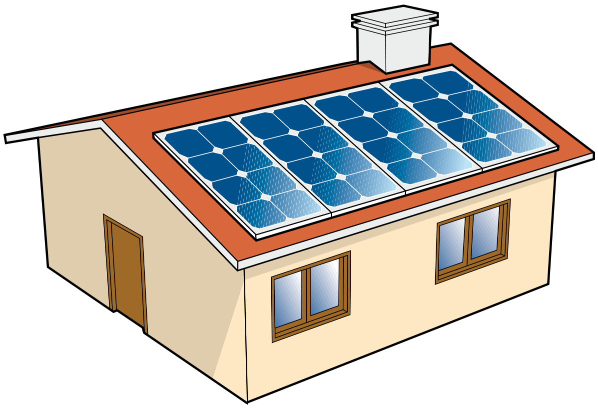
The PV installations, since they usually are outside the buildings, may be subject to overvoltages of atmospheric origin, both direct (lightning striking the structure) as well as indirect (lightning falling near to the structure of the building or affecting the energy or signaling lines entering the structure) through resistive or inductive coupling.
The resistive coupling occurs when lightning strikes the electrical line entering the building. The lightning current, through the characteristic impedance of the line, originates an overvoltage which may exceed the impulse withstand voltage of the equipment, with consequent damaging and fire hazard.
The inductive coupling occurs because the lightning current is impulsive and therefore it generates in the surrounding space an electromagnetic field highly variable. As a consequence, the variation in the magnetic field generates some overvoltages induced on the electric circuits nearby.
In addition to the overvoltages of atmospheric origin, the PV plant may be exposed to internal switching overvoltages.

6.4.1 Direct lightning

6.4.1.1 Building without LPS[12]

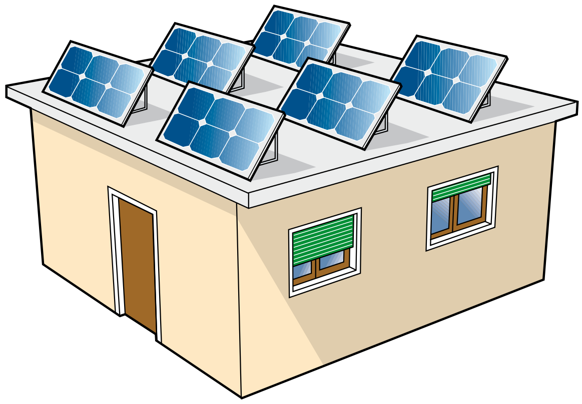
Generally, the erection of a PV plant does not change the outline of a building and therefore the frequency of the fulminations; therefore no specific measures against the risk of fulmination are necessary (CEI Guide 82-25, II ed.) (Figure 6.3).

Figure 6.3



On the contrary, in case the PV installation changes significantly the outline of the building, it is necessary to reconsider the frequency of fulminations on it and consequently to take into consideration the necessity of realizing an LPS (CEI Guide 82-25 II ed.) (Figure 6.4).

Figure 6.4



6.4.1.2 Building with LPS

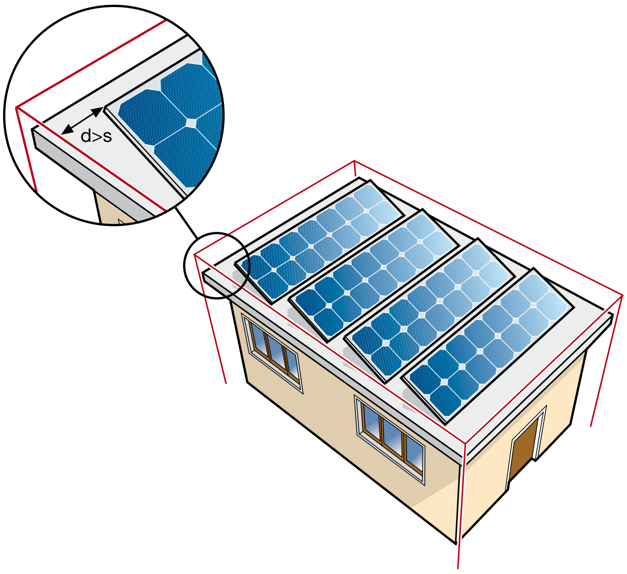
In case of presence of a protection system against atmospheric discharges[13], if the PV plant does not alter the outline of the building and if the minimum distance *d* between the PV plant and the LPS plant is higher than the safety distance *s* (EN 62305-3) other additional measures

[12] Lightning Protection System: it is constituted by the protective systems both external (detectors, lightning conductors and ground electrodes) as well as internal (protective measures in order to reduce the electromagnetic effects of the lightning current entering the structure to be protected).

[13] It is advisable that the protection grounding plant is connected to that for the protection against lightning.

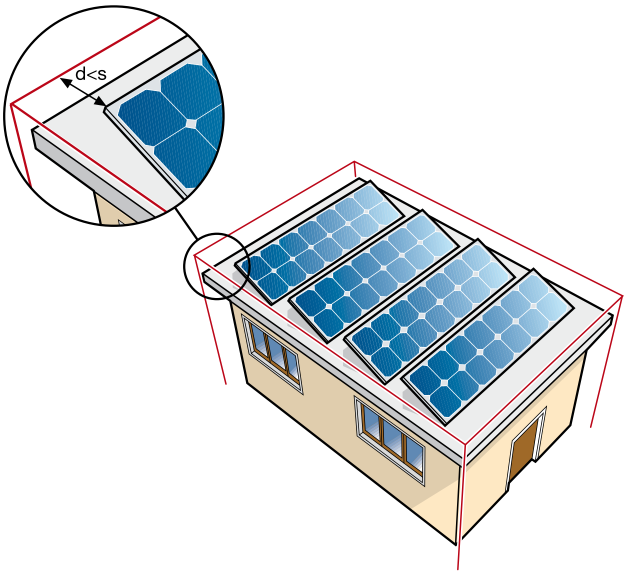
for the protection of the new plant (CEI Guide 82-25 II ed.) are not required (Figure 6.5).

Figure 6.5



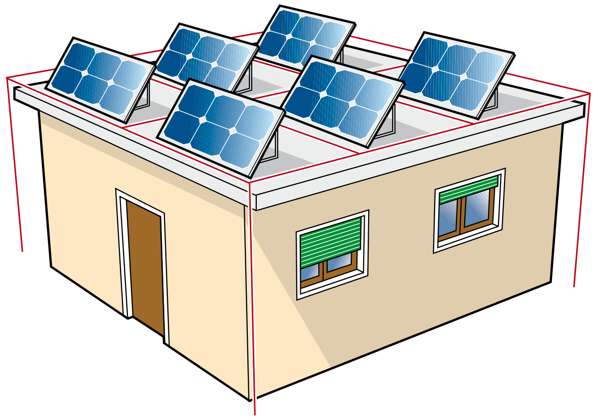
On the contrary, if the PV plant does not alter the outline of the building, but the minimum distance *d* is lower than the distance *s* it is appropriate to extend the LPS plant and connect it to the metal structures of the PV installation (CEI Guide 82-25, II ed.) (Figure 6.6).

Figure 6.6



Finally, if the PV plant alters the outline of the building a new risk evaluation and/or a modification of the LPS are necessary (CEI Guide 82-25, II ed.) (Figure 6.7).

Figure 6.7



6.4.1.3 PV plant on the ground

If a PV plant is erected on the ground there is no fire risk due to direct fulmination and the only hazard for human beings is represented by the step and touch voltages. When the surface resistivity exceeds 5 kΩm (e.g. rocky asphalted ground, at least 5 cm thickness or laid with gravel for minimum 15 cm), it is not necessary to take any particular measure since the touch and step voltage values are negligible (CEI 81-10). Instead, if the ground resistivity were equal to or lower than 5 kΩm, it would be necessary to verify theoretically whether some protective measures against the step and touch voltages are necessary; however, in this case, the probability of lightning strikes is very small and therefore the problem occurs only with very large plants.

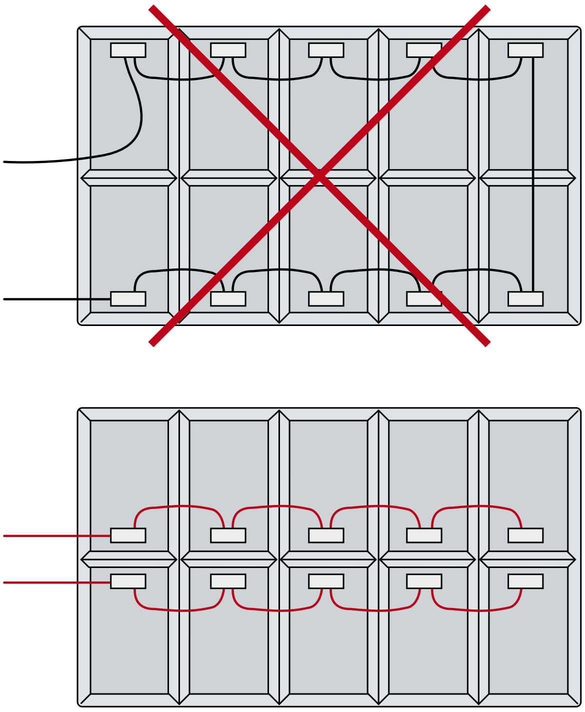
6.4.2 Indirect lightning

Also in case lightning does not strike directly the structure of the PV plant, it is necessary to take some measures to minimize the overvoltages caused by any likely indirect strike of lightning:

- shielding of the circuits in order to reduce the magnetic field inside the enclosure with a consequent reduction of the induced overvoltages[14];
- reduction of the area of the turn of the induced circuit obtained by connecting suitably the modules one to the other (Figure 6.8), by twisting the conductors together and bringing the live conductor as much as possible near to the PE.

[14] The shielding effect of a metal enclosure originates thanks to the currents induced in the enclosure itself; they create a magnetic field which by Lenz's law opposes the cause generating them, that is the magnetic field of the lightning current; the higher the currents induced in the shield (i.e. the higher its conductance), the better the shielding effect.

Figure 6.8



The overvoltages, even if limited, which may be generated must be discharged to ground by means of SPD (Surge Protective Device) to protect the equipment. In fact, SPDs are devices with impedance variable according to the voltage applied: at the rated voltage of the plant they have a very high impedance, whereas in the presence of an overvoltage they reduce their impedance, deriving the current associated to the overvoltage and keeping the latter within a determined range of values. According to their operation modalities SPDs can be divided into:

- switching SPDs, such as spinterometers or controlled diodes, when the voltage exceeds a defined value, reduce instantaneously their impedance and consequently the voltage at their ends;
- limitation SPDs, such as varistors or Zener diodes, have an impedance which decreases gradually at the increase of the voltage at their ends;
- combined SPDs which comprise the two above mentioned devices connected in series or in parallel.

6.4.2.1 Protection on DC side

For the protection on the DC side it is advisable to use varistors SPDs or combined SPDs.
Inverters usually have an internal protection against overvoltages, but if SPDs are added to the inverter terminals, its protection is improved and at the same time it is possible to avoid that the tripping of the internal protections put out of service the inverter, thus causing suspension of energy production and making necessary the intervention of skilled personnel.
These SPDs should have the following characteristics:

- Type 2
- Maximum rated service voltage $U_e > 1.25\ U_{oc}$
- Protection level $U_p \leq U_{inv}$[15]
- Nominal discharge current $I_n \geq 5$ kA
- Thermal protection with the capability of estinguishing the short-circuit current at the end of life and coordination with suitable back-up protection.

Since the modules of the strings generally have an impulse withstand voltage higher than that of the inverter, the SPDs installed to protect the inverter generally allow the protection of the modules too, provided that the distance between modules and inverter is shorter than 10 m[16].

[15] U_{inv} is the impulse withstand voltage of the inverter DC side.

[16] The SPD shall be installed on the supply side (direction of the energy of the PV generator) of the disconnecting device of the inverter so that it protects the modules also when the disconnecting device is open.

6.4.2.2 Protection on AC side

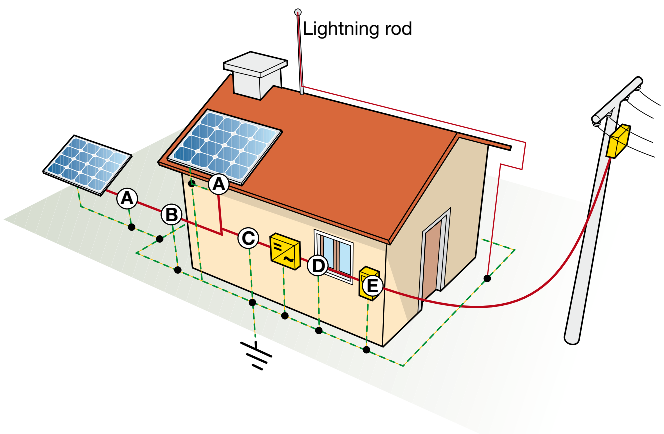
A PV plant connected to the grid is subject also to the overvoltages coming from the line itself. If a separation transformer is present, with earthed metal shield, the inverter is protected against the overvoltages of the transformer itself. If the transformer is not present or in case of a transformer without shield, it is necessary to install a suitable SPD immediately downstream the inverter.
This SPDs should have the following characteristics:

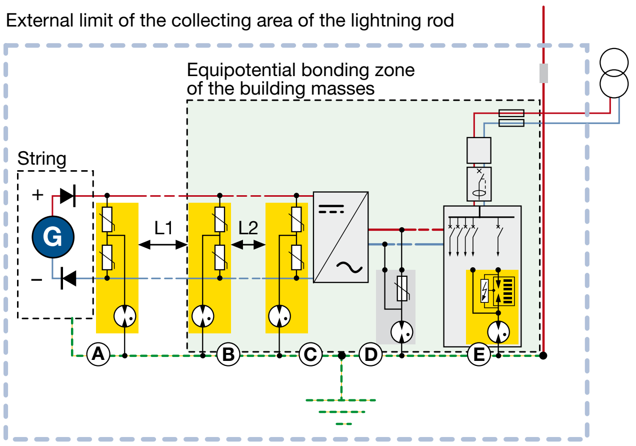
- Type 2
- Maximum rated service voltage $U_e > 1.1\ U_o$[17]
- Protection level $U_p \leq U_{inv}$[18]
- Nominal discharge current $I_n \geq 5$ kA
- Thermal protection with the capability of estinguishing the short-circuit current at the end of life and coordination with suitable back-up protection.

If the risk analysis for the building prescribes the installation of an outside LPS, it is necessary to position an SPD for the protection against direct lightning at the power delivery point. Such SPD should have the following characteristics:

- Type 1
- Maximum rated service voltage $U_e > 1.1\ U_o$
- Protection level $U_p \leq U_{inv}$
- Impulse current $I_{imp} \geq 25$ kA for each pole
- Extinction of the follow-up current Ifi exceeding the short-circuit current at the installation point and coordination with a suitable back-up protection.

The figures below show the layout of a PV plant divided in zones from A to E and indicate the protection function carried out by the SPD when installed in each zone.





SPD position	Function	Recommendation	Remarks
(A)	Protection of each solar panel (cell+connections)	Recommended if the distance L1 exceeds 10 m or if there is a risk of inductive coupling	The connection to the panel must be as short and straight as possible. If required by the environment, the SPD shall be installed in an enclosure with suitable IP degree
(B)	Protection of the main DC line (at the entrance of the building)	Always recommended	The connection to the equipotential bonding bar must be as short and straight as possible
(C)	Protection of the inverter input, on DC side	Recommended if the distance L2 exceeds 10 m	The connection to the equipotential bonding bar and to the mass of the inverter on ther DC side must be as short and straight as possible
(D) ∿	Protection of the inverter output, on AC side	Always recommended	The connection to the equipotential bonding bar and to the mass of the inverter on the AC side must be as short and straight as possible
(E) ∿	Main protection at the delivery point of energy	Always recommended	The connection to the equipotential bonding bar must be as short and straight as possible

[17] U_o is the voltage to earth for TT and TN systems; in case of an IT system it is $U_e > 1.73\ U_o$.

[18] U_{inv} is the impulse withstand voltage of the inverter on the AC side.

7 Feed-in Tariff

7.1 Feed-in Tariff system and incentive tariffs

Further to the Ministerial Decree DM dated 19/02/2007, who erects a PV installation connected to the network and without energy storage systems can obtain "incentive tariffs", defined according to the peak power of the installation and to the type of architectural integration (Table 7.1).
The Feed-in Tariff consists in the remuneration for the produced energy and not in the incentive of the capital necessary to the erection of the PV plant (Initial Capital Cost).
The tariffs, which are paid out unchanged for a period of over 20 years[1], are applied to the whole energy produced by the plant, independently of the use that the user is going to make of such production: sale or self-consumption. With subsequent decrees (starting from 2009) the Ministries of Economic Development and of the Environment and the Safeguard of the Territory and of the Sea shall update the incentive tariffs for installations erected after 2010.

Table 7.1

	Not integrated (€ kWh)	**Partially integrated** (€ kWh)	**Integrated** (€ kWh)
1-3 kWp	2009: 0.392 2010: 0.384	2009: 0.431 2010: 0.422	2009: 0.48 2010: 0.47
3-20 kWp	2009: 0.372 2010: 0.364	2009: 0.412 2010: 0.404	2009: 0.451 2010: 0.442
>20 kWp	2009: 0.353 2010: 0.346	2009: 0.392 2010: 0.384	2009: 0.431 2010: 0.422

The maximum power for which incentives can be provided is 1200 MW with a "moratorium period" of 14 months (24 months for public bodies) as from the date of achievement of the power limit for which incentives can be obtained. For the PV installations which will be put into service after such "moratorium period" however, incentive tariffs can be provided, but these tariffs are not accumulative with green certificates and with white certificates (Energy Efficiency Credits) and shall not be granted for installations erected for law obligations (311/2006) and put into service after 31st December 2010.

The "basic" incentive tariff can be increased by 5% in particular non-cumulative cases:
- for installations with peak power higher than 3kW non integrated, whose owner self-consumes at least 70% of the produced energy;
- for installations whose owner is either a public/accredited school or a public structure;
- for installations integrated in buildings, houses, building structures for agricultural uses in replacement of Ethernet covering or including asbestos;
- for installations whose public subjects are local bodies with resident population not exceeding 5000 inhabitants.

The PV installations, for which local bodies are responsible, can be included in the typology of integrated installations, not depending on the real architectural configurations of the plant.

In addition to the incentive, the subject responsible for the plant can count on a further economical advantage deriving from:
- power delivery to the grid;
- own self-consumption (partial or total cover);
- Net Metering with the grid (for installations with power up to 200kW).

With the financial act of 2008, as from January 1st, 2009 for the granting of the building permission for new buildings, the erection of plants for the production of electrical energy from renewable sources must be provided, so that a power production not lower than 1kW for each house unit shall be guaranteed, technical feasibility permitting. As regards industrial buildings, with size not lower than 100 m^2, the minimum power production is 5 kW.
Besides, the net metering system is extended to all the plants supplied by renewable sources with annual average power not exceeding 200 kW.

[1] *The financial cover for incentive tariffs is guaranteed by the compulsory drawing in support of the renewable sources present since 1991 in all the electricity bills of all the energy distribution authorities.*

7.2 Valorization of the power produced by the installation

As already mentioned, a further revenue source for the installation owner, in addition to the Feed-in Tariff, is constituted by the valorization of the power produced by the plant which can be self-consumed (also under Net Metering) or sold on the electricity market.
The self-consumption of the energy produced represents an implied revenue source because it involves the suppression of the charges for the energy which otherwise would be drawn from the grid for a quota equal to the self-produced one. Instead, the sale of the power produced and not self-consumed constitutes an explicit revenue source.
It is possible to choose the type of contract - sale or Net Metering - for the plants with a peak power up to 20kW if put into service before 31/12/07, or up to 200kW if put into service after that date[2]. Over such power, a sale contract must be drawn up.

7.2.1 Net Metering

Net Metering, which is regulated by the Deliberation of the AEEG ARG/elt 74/08 Annex A (Net Metering Integrated Text), allows that the energy produced is injected to the grid but not immediately self-consumed and it is managed by a single subject at national level, the GSE (Electrical Utilities Administrator).

In such case, the energy is not sold and the grid is used as power "storage" facility into which the produced power in excess but not self-consumed shall be poured and from which the power required by the consumer plant in the night hours or whenever the produced energy is insufficient for the connected loads shall be drawn.

Net Metering is an advantageous system for the consumer when, on an annual basis, the quota of energy supplied to the public grid is close to the burden associated to the energy drawn from the grid itself. This because the annual settlement occurs no more on an energetic basis balancing the kilowatt hour inflows and outflows from the grid, but on a financial basis, taking into account the value of the electricity put into the grid, the energy drawn and the expenses sustained by the user to access the grid according to the exchanged energy[4].

The Legislative Decree 387-2003 forbade the sale of the electrical energy produced by installations supplied by renewable sources based on Net Metering. Therefore, when the value of the energy supplied to the grid on annual basis exceeded that of the energy drawn, this balance represented a credit for the consumer, who could use it in the following years to compensate possible deficits.
According to the Resolution ARG/elt 186/09 by AEEG (Article 27, paragraph 45, of the Law No. 99/09) instead, in the above mentioned case the consumer of Net Metering can choose either the management "on credit" of the possible energy surplus for the solar years following the year to which the surplus is referred to, or to be paid by the GSE for the surplus of produced energy.

7.2.2 Sale of the energy produced

The energy produced by the PV installation may be sold according to two different modalities:
- indirect sale, that is according to an agreement for the collection of the energy by the GSE;
- direct sale, that is by selling the energy on the Stock Exchange or to a wholesale dealer.

In case of indirect sale (in compliance with the resolution AEEG 280/07) the GSE buys the energy independently of the network to which the plant is connected and refund to the consumer/producer, for each hour, the market price relevant to the area where the installation is situated.
For installations with peak power up to 1 MW minimum guaranteed prices have been defined and they are periodically updated by the AEEG. If at the end of each year the valorization at the minimum price is lower than the one which could be obtained at market prices, the GSE shall recognize the relevant settlement to the producer.
Indirect sale is generally preferred both due to the easy management as well as for the higher profitability of the minimum price in comparison with the market price.
Under direct sale the user can choose to sell the produced power directly either on the Stock Exchange (by previous registration to the electrical energy market) or according to an agreement with an electricity wholesale dealer at a settled price. Direct sale is generally made for energy productions of large-size installations of megawatt order; therefore it is not advisable for medium/small-sized PV installations because of both its complexity and onerousness.

[2] In case the consumer of Net Metering is the Ministry of Defense, that is a third subject mandate holder of the Ministry itself, the limit of 200 kW is not applicable (Resolution ARG/elt 186/09).

[3] The rate of the energy supplied to the grid differs from that of the energy drawn, also at the same value of kilowatt hour, if the day hourly band of energy inflows and outflows is different. Typically the PV power supplied to the grid has a higher value because it is produced in the daylight hours, corresponding to a greater load for the grid.

[4] The charges for the access to the grid refer to the transport and dispatch of the electric power.

8 Economic analysis of the investment

8.1 Theoretical notes

A solution for the design of an installation must be supported by two feasibility analyses: a technical one and an economic one. When carrying out the technical analysis it is often necessary to choose between possible alternatives, which are all good from a technical point of view and which guarantee an optimum sizing of the installation. What often leads to opt for a solution compared with another is the result of the evaluation of the economic advantage of an investment.
The comprehensive economic analysis is carried out through a cost-benefit analysis, consisting in a comparison between the initial investment and the NPV which is expected to inflow during the life of the plant.
If the term relative to the investment prevails in the arithmetic comparison, the investment under consideration shall not be advantageous from a strictly financial point of view. If we want to represent this concept in a simplified way, the earning G for a given pluriannual investment allowing a return R in the face of a series of costs C, is given by this simple relation:

$$G = R - C \qquad [8.1]$$

This relation would be valid only if the economic solution had an instant duration. In reality, there is always a temporal deviation between the initial investment and the subsequent cash flows available according to particular time schemes. As a consequence, the comparison shall be carried out by using correlation coefficients which equalize the value of the money available over different times.

8.1.1 Net Present Value (NPV)

Suppose that an investment I_o originates in the future years some positive or negative cash flows which are produced in the various years j of duration of the investment itself. These cash flows are: FC1 in the first year, FC2 in the second year, FCj in the j-th year. To make this comparison, the cash flows must be "updated", each one referred to the year in which it shall be available, multiplying it by the relevant discount factor:

$$\frac{1}{(1 + C_C)^j} \qquad [8.2]$$

where:
C_c is the cost of the capital given by the relation $C_c = i\text{-}f$, difference between the estimated interest rate "i" and the rate of inflation "f".

Therefore, by Net Present Value it is meant the difference between the sum of the n discounted cash flows (n=years of duration of the investment) and the initial investment I_o:

$$NPV = \sum_{j=1}^{n} \frac{FC_j}{(1 + C_C)^j} - I_0 \qquad [8.3]$$

When the NPV results to be positive, it means that - at the end of life of the investment - the discounted cash flows produced will have given greater returns than the cost of the initial investment and therefore the erection of a plant is convenient from a financial point of view; vice versa when the NPV is negative.

8.1.2 Economic indicators

8.1.2.1 Internal Rate of Return (IRR)

It is the value of the cost of the capital C_c for which the NPV is equal to null and it represents the profitability of the investment whose suitability is being evaluated. If the IIR exceeds the value of C_c taken for the calculation of the NPV, the considered investment shall be profitable.
On the contrary, if the IIR resulted to be lower than the return R, the investment would have to be avoided. Besides, when choosing among possible alternatives of investment with equal risk, that one with the higher IIR must be chosen.

8.1.2.2 Discounted Payback

If "n" is the number of years foreseen for the investment, the number of years "N" after which the NPV is null represents the discounted payback. If N<n the investment shall be favorable, the opposite when N>n.

8.1.2.3 Simple Payback

The payback time is defined as the ratio between the initial investment and the expected cash flow, considered fixed in amount and periodically scheduled:

$$TR = \frac{I_0}{FC} \qquad [8.4]$$

This economic indicator is very used, but it can give too optimistic indications, since it doesn't take into account the duration of the investment and of the cost of the capital.

8.2 Economic considerations on PV installations

The revenues obtained by connecting the plant to the grid during the useful life of the plant itself (usually 25 years) are constituted by the following elements:

- incentive tariff on the produced energy (supplied for 20 years);
- non-paid cost for the energy not drawn from the grid but self-consumed and possibly sold (sale contract).

The installation of a PV plant requires a high initial investment, but the running costs are limited: the fuel is available free of charge and the maintenance costs are limited since, in the majority of cases, there are no moving parts in the system.
These costs are estimated to be about from 1 to 2% of the cost of the plant per year and include the charges for the replacement of the inverter in the 10th-12th year and an insurance policy against theft and adverse atmospheric conditions which might damage the installation.

In spite of the technological developments in the most recent years, the costs for the erection of a plant are still quite high, especially when compared to electric generation from fossil sources and in some cases also in comparison with other renewable sources. A small size plant (1-3kWp) costs around 6000 to 7000 €/kWp; a medium size plant (from some dozens to hundreds of kWp) costs about 4500 to 6000 €/kWp; a PV power station (exceeding 100 kWp power) costs from 4000 to 5000 €/kWp[1].

For the erection of a PV plant the cut value-added tax (VAT) rate of 10% can be applied, thanks to the DPR 633/72 regarding heat-energy and electric energy generation plants and distribution networks from solar and PV source. If the plant is erected with third-party financing, it is necessary to take into consideration also the costs deriving from the interests paid, whereas if the plant is self-financed, it is necessary to make a comparison with the interest deriving from alternative investments with equal risk.
Currently, in Italy, the payback time of a PV plant is about 11 years.

8.3 Examples of investment analysis

8.3.1 Self-financed 3kWp photovoltaic plant

We take into consideration the installation sized in the Annex C, clause 2, a plant for a detached house with the following characteristics:

- annual average consumption of energy 4000 kWh
- service modality Net Metering
- expected annual average production 3430 kWh
- decrease in production 0.5 %/year
- unit cost of the installation 6500 €/kWp
- VAT 10%
- total cost of the installation 21450 €
- incentive tariff (see Chapter 7) 0.431€/kWh
- saving on the bill 0.18€/kWh produced
- running costs 60 €/year
- maintenance costs 1% installation cost/year
- economical cover 100% own capital
- useful life of the installation 25 years

[1] *The specific cost of a PV plant is not significantly affected by the scale effect, since about 70% of the total cost is bound to the PV field (panels and structures).*

To calculate the cash flow discounted in the j-th year, the following data have been assumed:

- interest rate i 5.5%
- rate of inflation f 2%
- cost of the capital C_C 3.5%

As it can be noticed in Figure 8.1, the non discounted cash flow is negative in the first year due to the initial investment and afterwards it is always positive because the revenues deriving from the incentives for the energy produced in the first twenty years and from the non-paid cost for the self-consumed energy exceed the annual running and maintenance costs.
The payback period is twelve years.

The cash flow in the j-th year is calculated as the difference between the revenues, which derive from the incentive for the annual energy production and the saving for the self-consumed energy thus not drawn from the grid, and the annual running and maintenance costs (Table 8.1).
Once determined the relevant cash flow for each year, the NPV (Figure 8.2) calculated in the space of 25 years by applying [8.3] results to be positive and equal to about 3900 €, which means that the investment is profitable and it is as (according to [8.1]) with an investment cost of 21450 € there would be a return of 25350 € giving an earning equal to the NPV.
The internal rate of return (IIR) is equal to 5.4% and since it is higher than the cost of the capital, the investment is convenient.

Table 8.1

Year	Produced power [kWh]	Revenues (produced power+ self-consumption) [€]		Running costs [€]	Maintenance costs [€]	Non discounted cash flow [€]	Earnings [€]	Discounted cash flow [€]	Net Present Value (NPV) [€]
1	3430	1478	617	60	214,5	-19629	-19629	-19690	-19690
2	3413	1471	614	60	214,5	1811	-17818	1690	-18000
3	3396	1464	611	60	214,5	1800	-16018	1624	-16376
4	3379	1456	608	60	214,5	1790	-14228	1560	-14816
5	3362	1449	605	60	214,5	1780	-12448	1498	-13318
6	3345	1442	602	60	214,5	1769	-10679	1439	-11879
7	3328	1435	599	60	214,5	1759	-8920	1383	-10496
8	3312	1427	596	60	214,5	1749	-7171	1328	-9168
9	3295	1420	593	60	214,5	1739	-5432	1276	-7892
10	3279	1413	590	60	214,5	1729	-3703	1226	-6666
11	3262	1406	587	60	214,5	1719	-1984	1177	-5489
12	3246	1399	584	60	214,5	1709	-275	1131	-4358
13	3230	1392	581	60	214,5	1699	1423	1086	-3272
14	3214	1385	578	60	214,5	1689	3112	1043	-2228
15	3198	1378	576	60	214,5	1679	4792	1002	-1226
16	3182	1371	573	60	214,5	1669	6461	963	-263
17	3166	1364	570	60	214,5	1660	8121	925	661
18	3150	1358	567	60	214,5	1650	9771	888	1550
19	3134	1351	564	60	214,5	1640	11411	853	2403
20	3118	1344	561	60	214,5	1631	13042	820	3223
21	3103	0	559	60	214,5	284	13326	138	3360
22	3087	0	556	60	214,5	281	13607	132	3492
23	3072	0	553	60	214,5	278	13886	126	3619
24	3057	0	550	60	214,5	276	14161	121	3739
25	3041	0	547	60	214,5	273	14434	115	3855

Figure 8.1

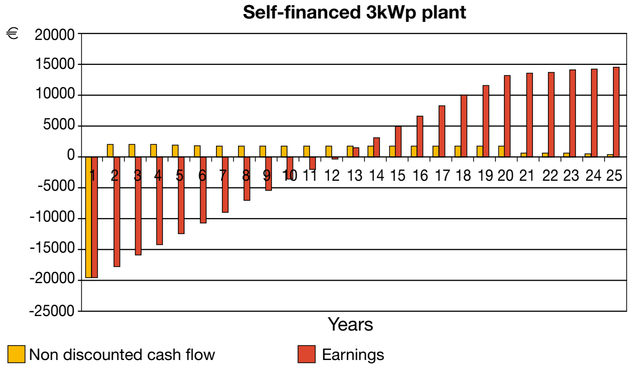
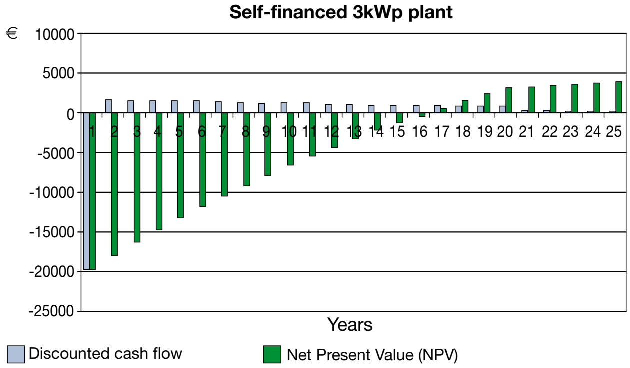


Figure 8.2



8.3.2 Financed 3kWp photovoltaic plant

In a financed PV plant, the initial investment is totally or partially financed by a bank, which schedules the payback of the loan granted on the basis of the assignment of the credit deriving from the incentive tariff on the produced power. The loan is designed with a determined fixed or variable interest rate, with rates and period variable depending on the real annual power production of the PV plant.

In this case, the above mentioned plant is now financed at 75% of the initial investment cost (about 14600€) with a fixed interest rate of 5%; therefore the user's capital initially invested decreases to about 6800 € including 10% VAT. As it can be noticed in Figure 8.3, in comparison with the previous case, the payback time is now 15 years, whereas the debt is extinguished (Figure 8.4) at the end of the 14th year; up to that year the user takes advantage only of the benefit deriving from the non-paid cost for the energy self-produced and consumed. From the 15th to the 20th year the earnings increase (Figure 8.3) because the user receives also the public incentive tariff which is no more assigned to the bank.

However, the NPV (Figure 8.4) is positive and equal to about 2300 €, but lower than the previous one, whereas the internal rate of return is slightly greater and equal to 5.8%.

Table 8.2

Year	Produced power [kWh]	Revenues (produced power + self-consumption) [€]		Running costs [€]	Maintenance costs [€]	Non discounted cash flow [€]	Earnings [€]	Discounted cash flow [€]	Net Present Value (NPV) [€]	Residual debt [€]
1	3430	1478	617	60	214,5	-6482	-6482	-6494	-6494	13878
2	3413	1471	614	60	214,5	340	-6142	317	-6176	13101
3	3396	1464	611	60	214,5	337	-5806	304	-5873	12292
4	3379	1456	608	60	214,5	334	-5472	291	-5582	11451
5	3362	1449	605	60	214,5	331	-5141	278	-5304	10574
6	3345	1442	602	60	214,5	328	-4814	267	-5037	9661
7	3328	1435	599	60	214,5	325	-4489	255	-4782	8710
8	3312	1427	596	60	214,5	322	-4167	244	-4538	7718
9	3295	1420	593	60	214,5	319	-3849	234	-4304	6684
10	3279	1413	590	60	214,5	316	-3533	224	-4080	5605
11	3262	1406	587	60	214,5	313	-3220	214	-3866	4479
12	3246	1399	584	60	214,5	310	-2911	205	-3661	3304
13	3230	1392	581	60	214,5	307	-2604	196	-3465	2077
14	3214	1385	578	60	214,5	304	-2300	188	-3277	796
15	3198	1378	576	60	214,5	884	-1416	527	-2750	0
16	3182	1371	573	60	214,5	1669	253	963	-1787	0
17	3166	1364	570	60	214,5	1660	1913	925	-862	0
18	3150	1358	567	60	214,5	1650	3563	888	26	0
19	3134	1351	564	60	214,5	1640	5203	853	880	0
20	3118	1344	561	60	214,5	1631	6834	820	1699	0
21	3103	0	559	60	214,5	284	7118	138	1837	0
22	3087	0	556	60	214,5	281	7399	132	1969	0
23	3072	0	553	60	214,5	278	7678	126	2095	0
24	3057	0	550	60	214,5	276	7954	121	2216	0
25	3041	0	547	60	214,5	273	8227	115	2332	0

Figure 8.3

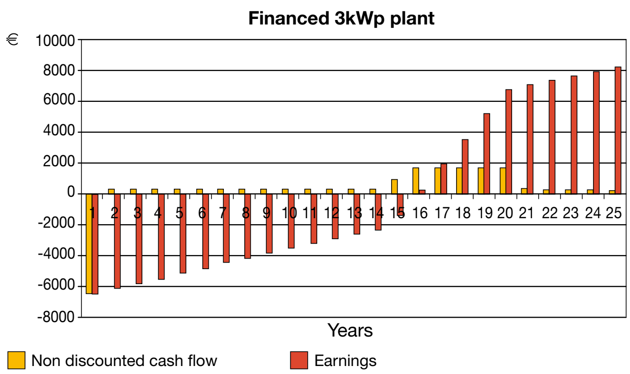
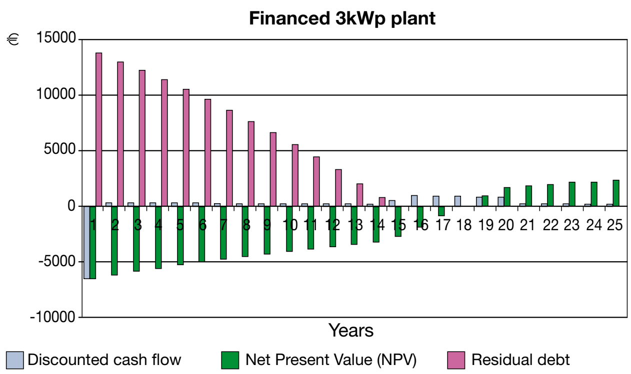


Figure 8.4



8.3.3 Self-financed 60kWp photovoltaic plant

Now we take into consideration the installation sized in the Annex C, clause 3, a plant for an artisan manufacturing industry with the following characteristics:

- annual average consumption of energy 70 MWh
- service modality Net Metering
- expected annual average production 67 MWh
- decrease in production 0.5 %/year
- unit cost of the installation 6000 €/kWp
- VAT 10%
- total cost of the installation 396000 €
- incentive tariff (see Chapter 7) 0.392 €/kWh
- saving on the bill 0.12 €/kWh produced
- running costs 70 €/year
- maintenance costs 1% installation cost/year
- economical cover 100% own capital
- useful life of the installation 25 years

To calculate the cash flow discounted in the j-th year, the following data have been assumed:

- interest rate i 5%
- rate of inflation f 2%
- cost of the capital C_C 3%

The payback period is 13 years (Figure 8.5) and the investment is profitable since the NPV (Figure 8.6) is positive and equal to about 41300 €.
The internal rate of return (IIR) is equal to 4% and since it is higher than the cost of capital the investment is advantageous.

Tabella 8.3

Year	Produced power [kWh]	Revenues (produced power +self-consumption) [€]		Running costs [€]	Maintenance costs [€]	Non discounted cash flow [€]	Earnings [€]	Discounted cash flow [€]	Net Present Value (NPV) [€]
1	67000	26264	8040	70	3960	-365726	-365726	-366608	-366608
2	66665	26133	8000	70	3960	30102	-335624	28374	-338233
3	66332	26002	7960	70	3960	29932	-305692	27392	-310841
4	66000	25872	7920	70	3960	29762	-275930	26443	-284398
5	65670	25743	7880	70	3960	29593	-246337	25527	-258871
6	65342	25614	7841	70	3960	29425	-216912	24643	-234228
7	65015	25486	7802	70	3960	29258	-187654	23789	-210439
8	64690	25358	7763	70	3960	29091	-158563	22965	-187474
9	64366	25232	7724	70	3960	28926	-129637	22169	-165305
10	64045	25105	7685	70	3960	28761	-100876	21401	-143904
11	63724	24980	7647	70	3960	28597	-72280	20659	-123245
12	63406	24855	7609	70	3960	28434	-43846	19943	-103302
13	63089	24731	7571	70	3960	28271	-15574	19251	-84051
14	62773	24607	7533	70	3960	28110	12536	18584	-65467
15	62459	24484	7495	70	3960	27949	40485	17940	-47527
16	62147	24362	7458	70	3960	27789	68274	17317	-30210
17	61836	24240	7420	70	3960	27630	95904	16717	-13493
18	61527	24119	7383	70	3960	27472	123376	16137	2644
19	61220	23998	7346	70	3960	27314	150691	15577	18221
20	60913	23878	7310	70	3960	27158	177848	15037	33257
21	60609	0	7273	70	3960	3243	181091	1743	35000
22	60306	0	7237	70	3960	3207	184298	1674	36674
23	60004	0	7201	70	3960	3171	187469	1606	38280
24	59704	0	7165	70	3960	3135	190603	1542	39822
25	59406	0	7129	70	3960	3099	193702	1480	41302

Figure 8.5

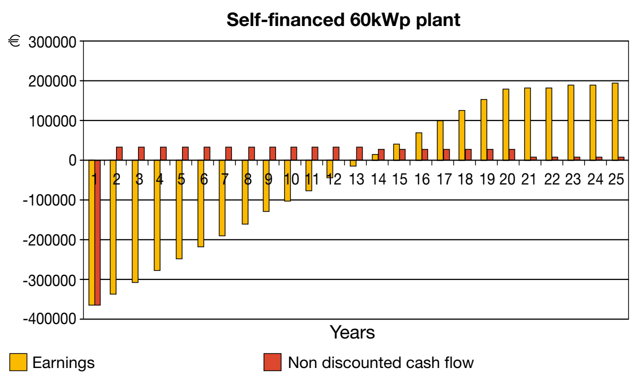
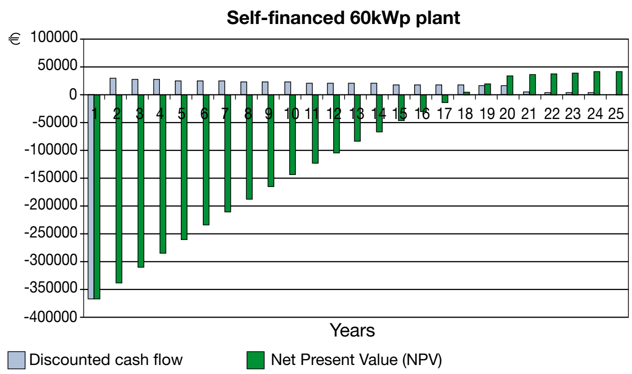


Figure 8.6



8.3.4 Financed 60kWp photovoltaic plant

In this case the above mentioned plant is now financed at 60% of the initial investment cost (21.6000 €) with a fixed interest of 5%; therefore the own capital initially invested by the user reduces to about 180000 €, 10% VAT included.

As it can be noticed from Figure 8.7, in comparison with the previous case, the payback period is now 16 years, whereas the paying off of the debt (Figure 8.8) occurs at the end of the 11th year.

The NPV (Figure 8.8) is positive and about 16.600 €, but lower than the previous one, and the IIR is equal to 3.6%.

Table 8.4

Year	Produced power [kWh]	Revenues (produced power +self-consumption) [€]		Running costs [€]	Maintenance costs [€]	Non discounted cash flow [€]	Earnings [€]	Discounted cash flow [€]	Net Present Value (NPV) [€]	Residual debt [€]
1	67000	26264	8040	70	3960	-175990	-175990	-176107	-176107	200536
2	66665	26133	8000	70	3960	3970	-172020	3742	-172365	184430
3	66332	26002	7960	70	3960	3930	-168090	3596	-168769	167650
4	66000	25872	7920	70	3960	3890	-164200	3456	-165312	150160
5	65670	25743	7880	70	3960	3850	-160350	3321	-161991	131925
6	65342	25614	7841	70	3960	3811	-156539	3192	-158799	112908
7	65015	25486	7802	70	3960	3772	-152767	3067	-155732	93067
8	64690	25358	7763	70	3960	3733	-149034	2947	-152786	72362
9	64366	25232	7724	70	3960	3694	-145340	2831	-149955	50749
10	64045	25105	7685	70	3960	3655	-141685	2720	-147235	28181
11	63724	24980	7647	70	3960	3617	-138068	2613	-144622	4610
12	63406	24855	7609	70	3960	23710	-114358	16630	-127992	0
13	63089	24731	7571	70	3960	28271	-86086	19251	-108740	0
14	62773	24607	7533	70	3960	28110	-57976	18584	-90156	0
15	62459	24484	7495	70	3960	27949	-30027	17940	-72217	0
16	62147	24362	7458	70	3960	27789	-2238	17317	-54899	0
17	61836	24240	7420	70	3960	27630	25392	16717	-38183	0
18	61527	24119	7383	70	3960	27472	52864	16137	-22046	0
19	61220	23998	7346	70	3960	27314	80179	15577	-6469	0
20	60913	23878	7310	70	3960	27158	107336	15037	8568	0
21	60609	0	7273	70	3960	3243	110580	1743	10311	0
22	60306	0	7237	70	3960	3207	113786	1674	11985	0
23	60004	0	7201	70	3960	3171	116957	1606	13591	0
24	59704	0	7165	70	3960	3135	120091	1542	15133	0
25	59406	0	7129	70	3960	3099	123190	1480	**16613**	0

Figure 8.7

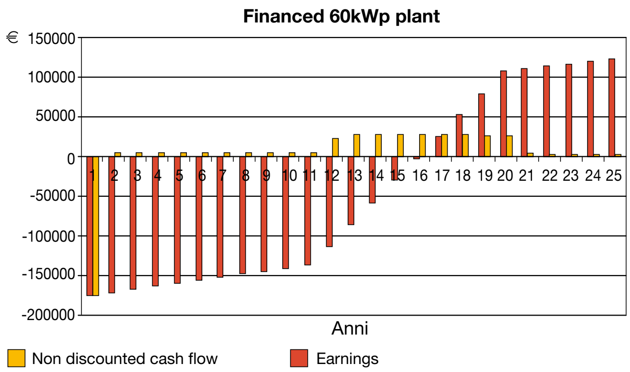
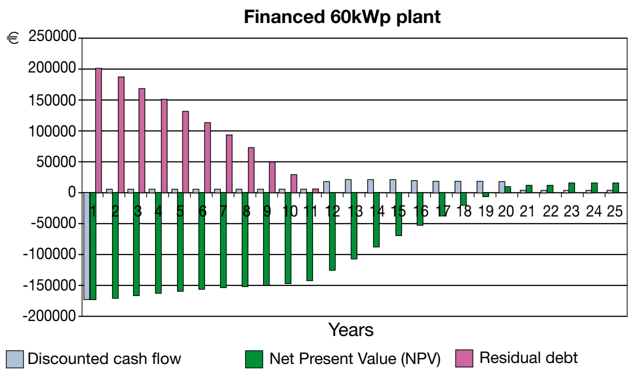


Figure 8.8



9 ABB solutions for photovoltaic applications

9.1 Molded-case and air circuit-breakers

ABB offers the following types of molded-case and air circuit-breakers and switch-disconnectors for the protection against overcurrents and the disconnection of PV installations both in DC as well as AC sections.

9.1.1 Tmax T molded-case circuit-breakers for alternating current applications

Tmax molded-case circuit-breakers complying with the Std. IEC 60947-2 have an application range from 1A to 1600A, 690V rated operating voltage and breaking capacities from 16kA to 200kA (@ 380/415V).
For the protection of the AC section of the PV installations the following circuit-breakers are available:

- Tmax T1B, 1p, equipped with thermomagnetic trip units type TMF with fixed thermal and magnetic thresholds (I_3 = 10 x I_n);
- Tmax T1, T2, T3 and T4 circuit-breakers (up to 50A) equipped with thermomagnetic trip units type TMD with adjustable thermal threshold (I_1 = 0.7..1 x I_n) and fixed magnetic threshold (I_3 = 10 x I_n);
- Tmax T4, T5 and T6 circuit-breakers equipped with thermomagnetic trip units type TMA with adjustable thermal (I_1 = 0.7..1 x I_n) and magnetic threshold (I_3 = 5..10 x I_n);
- Tmax T2 with electronic trip unit type PR221DS;
- Tmax T4, T5, T6 circuit-breakers equipped with electronic trip units type PR221DS, PR222DS and PR223DS;
- Tmax T7 circuit-breaker equipped with electronic trip units type PR231/P, PR232/P, PR331/P and PR332/P, available in the two versions with manual operating mechanism or motorizable with stored energy operating mechanism.

		T1 1P	T1			T2						T3		T4					T5					T6				T7			
Rated uninterrupted current **Iu**	[A]	160	160			160						250		250/320					400/630					630/800/1000				800/1000 1250/1600			
Poles	[Nr.]	1	3/4			3/4						3/4		3/4					3/4					3/4				3/4			
Rated service voltage **Ue**	[V] (AC) 50-60 Hz	240	690			690						690		690					690					690				690			
Rated impulse withstand voltage Uimp	[kV]	8	8			8						8		8					8					8				8			
Rated insulation voltage **Ui**	[V]	500	800			800						800		1000					1000					1000				1000			
Test voltage at industrial frequency for 1 min.	[V]	3000	3000			3000						3000		3500					3500					3500				3500			
Rated ultimate short-circuit breaking capacity **Icu**		B	B	C	N	B	C	N	S	H	L	N	S	N	S	H	L	V	N	S	H	L	V	N	S	H	L	S	H	L	V[3]
(AC) 220-230V 50-60Hz	[kA]	25*	25	40	50	25	40	65	85	100	120	50	85	70	85	100	200	200	70	85	100	200	200	70	85	100	200	85	100	200	200
(AC) 380-400-415V 50-60Hz	[kA]	-	16	25	36	16	25	36	50	70	85	36	50	36	50	70	120	200	36	50	70	120	200	36	50	70	100	50	70	120	150
(AC) 440V 50-60Hz	[kA]	-	10	15	22	10	15	30	45	55	75	25	40	30	40	65	100	180	30	40	65	100	180	30	45	50	80	50	65	100	130
(AC) 500V 50-60Hz	[kA]	-	8	10	15	8	10	25	30	36	50	20	30	25	30	50	85	150	25	30	50	85	150	25	35	50	65	50	50	85	100
(AC) 690V 50-60Hz	[kA]	-	3	4	6	3	4	6	7	8	10	5	8	20	25	40	70	80	20	25	40	70	80	20	22	25	30	30	42	50	60
Utilization category (IEC 60947-2)		A	A			A						A		A					B (400A)[1] - A (630A)					B (630A-800A)[2] A (1000A)				B[4]			
Isolation behaviour		■	■			■						■		■					■					■				■			
Trip units:																															
thermomagnetic T fixed, M fixed	TMF	■	-			-						-		-					-					-				-			
T adjustable, M fixed	TMD	-	■			■						■		■ (up to 50A)					-					-				-			
T adjustable, M adjustable (5..10 x In)	TMA	-	-			-						-		■ (up to 250A)					■ (up to 500A)					■ (up to 800A)				-			
magnetic only	MA	-	-			■ (MF up to 12.5A)						■		■					-					-				-			
electronic		-																													
PR221DS		-	-			■						-		■					■					■				-			
PR222DS		-	-			-						-		■					■					■				-			
PR223DS		-	-			-						-		■					■					■				-			
PR231/P		-	-			-						-		-					-					-				■			
PR232/P		-	-			-						-		-					-					-				■			
PR331/P		-	-			-						-		-					-					-				■			
PR332/P		-	-			-						-		-					-					-				■			
Interchangeability		-	-			-						-		■					■					■				■			
Versions		F	F			F-P						F-P		F-P-W					F-P-W					F-W				F-W			

* The breaking capacity for settings In=16A and In=20A is 16kA
(1) Icw = 5kA
(2) Icw = 7.6kA (630A) - 10kA (800A)
(3) Only for T7 800/1000/1250A
(4) Icw = 20kA (S,H,L version) - 15kA (V version)

9.1.2 New range of molded-case circuit-breakers SACE Tmax XT

In addition, ABB offers the new range of molded-case circuit-breakers SACE Tmax XT up to 250A.
For the protection of the AC section of the PV installations the following circuit-breakers are available:

- XT1 160 and XT3 250 circuit-breakers equipped with thermomagnetic trip units type TMD with adjustable thermal threshold (I_1 = 0.7..1 x I_n) and fixed magnetic threshold (I_3 = 10 x I_n);
- XT2 160 and XT4 250 circuit-breakers equipped with thermomagnetic trip units type TMA (for In ≥ 40A) with adjustable thermal threshold (I_1 = 0.7..1 x I_n) and magnetic threshold I_3 adjustable in the range 8..10 x I_n for 40A, 6..10 x I_n for 50A and 5..10 x I_n for In ≥ 63A, or with Ekip electronic trip units also with neutral increased at 160%.

		XT1					XT2					XT3		XT4				
Size	[A]	160					160					250		160/250				
Poles	[Nr.]	3/4					3/4					3/4		3/4				
Rated service voltage, **Ue**	[V] (AC) 50-60 Hz	690					690					690		690				
Rated impulse withstand voltage, **Uimp**	[kV]	8					8					8		8				
Rated insulation voltage, **Ui**	[V]	800					1000					800		1000				
Rated ultimate short-circuit breaking capacity, **Icu**		B	C	N	S	H	N	S	H	L	V	N	S	N	S	H	L	V
(AC) 240V 50-60Hz	[kA]	25	40	65	85	100	65	85	100	150	200	50	85	65	85	100	150	200
(AC) 380V 50-60Hz	[kA]	18	25	36	50	70	36	50	70	120	200	36	50	36	50	70	120	150
(AC) 415V 50-60Hz	[kA]	18	25	36	50	70	36	50	70	120	150	36	50	36	50	70	120	150
(AC) 440V 50-60Hz	[kA]	15	25	36	50	65	36	50	65	100	150	25	40	36	50	65	100	150
(AC) 500V 50-60Hz	[kA]	8	18	30	36	50	30	36	50	60	70	20	30	30	36	50	60	70
(AC) 525V 50-60Hz	[kA]	6	8	22	35	35	20	25	30	36	50	13	20	20	25	45	50	50
(AC) 690V 50-60Hz	[kA]	3	4	6	8	10	10	12	15	18	20	5	8	10	12	15	20	25 (90)[(1)]
Utilization Category (IEC 60947-2)		A					A					A		A				
Isolation behaviour		■					■					■		■				
Trip units: thermomagnetic																		
T regolabile, M fixed	TMD	■					■ (up to 32A)					■		■ (up to 32A)				
T adjustable, M adjustable	TMA	-					■					-		■				
magnetic only	MF/MA	-					■					■		■				
electronic Ekip		-					■					-		■				
Interchangeable		-					■					-		■				
Versions		F-P					F-P-W					F-P		F-P-W				

(1) 90kA@690V only for XT4 160.
Available shortly, please ask ABB SACE.

9.1.3 Molded-case circuit-breakers for applications up to 1150 V AC

The range of T4, T5 and T6 circuit-breakers for applications in alternating current up to 1150V also comes into the panorama of the Tmax proposals.
These circuit-breakers are available in the three-pole and four-pole version with TMD or TMA thermomagnetic trip units or with PR221DS, PR222DS and PR223DS electronic trip units.
These circuit-breakers are available in the fixed, plug-in and withdrawable version (for which the use of the 1000 V fixed parts supplied only by upper terminals is mandatory) and they are compatible with all the accessories except for the residual current release.

T4-T5 circuit-breakers for use up to 1150 V AC and T6 circuit-breakers for use up to 1000 V AC

			T4		T5		T6
Rated uninterrupted current, **Iu**		[A]	250		400/630		630/800
Poles			3/4		3/4		3/4
Rated service voltage, **Ue**		[V]	1000	1150	1000	1150	1000
Rated impulse withstand voltage, **Uimp**		[kV]	8		8		8
Rated insulation voltage, **Ui**		[V]	1000	1150	1000	1150	1000
Test voltage at industrial frequency for 1 min.		[V]	3500		3500		3500
Rated ultimate short-circuit breaking capacity, **Icu**			L	V(1)	L	V(1)	L(1)
(AC) 1000V 50-60Hz		[kA]	12	20	12	20	12
(AC) 1150V 50-60Hz		[kA]	-	12	-	12	-
Utilization category (IEC 60947-2)			A		B (400A)(2) - A (630A)		B(3)
Isolation behaviour			■		■		■
Trip units:	thermomagnetic						
	T adjustable, M fixed	TMD		■			
	T adjustable, M adjustable (5..10 x In)	TMA		■		■	■
	electronic						
	PR221DS		■	■	■	■	■
	PR222DS		■	■	■	■	■
Versions			F-P-W	F	F-P-W(4)	F	F(5)

(1) Power supply only from the top
(2) Icw = 5kA
(3) Icw = 7.6 kA (630A) - 10kA (800A)
(4) Tmax T5630 is only available in the fixed version
(5) For T6 in the withdrawable version, please ask ABB SACE

Rated currents available for molded-case circuit-breakers with the different typologies of electronic trip units

	In [A]	10	25	63	100	160	250	320	400	630	800	1000	1250	1600
PR221DS	**T2**	■	■	■	■	■								
	T4				■	■	■	■						
	T5							■	■	■				
	T6									■	■	■		
PR222DS/P	**T4**				■	■	■	■						
PR222DS/PD	**T5**							■	■	■				
PR223DS	**T6**									■	■	■		
PR231/P **PR232/P** **PR331/P** **PR332/P**	**T7**								■	■	■	■	■	■

Rated currents available for molded-case circuit-breakers with the different typologies of thermomagnetic trip units

	T1 1P 160	T1 160	T2 160			T3 250		T4 250-320			T5 400-630	T6 630-800
In [A]	**TMF**	**TMD**	**TMD**	**MF**	**MA**	**TMD**	**MA**	**TMD**	**TMA**	**MA**	**TMA**	**TMA**
1				■								
1,6			■	■								
2			■	■								
2,5			■	■								
3,2			■	■								
4			■	■								
5			■	■								
6,3			■									
6,5				■								
8			■	■								
8,5				■								
10			■							■		
11				■								
12,5			■	■								
16	■	■	■									
20	■	■	■		■			■				
25	■	■	■							■		
32	■	■	■		■			■				
40	■	■	■									
50	■	■	■					■				
52					■					■		
63	■	■	■			■						
80	■	■	■		■	■			■	■		
100	■	■	■		■	■	■		■	■		
125	■	■	■			■	■		■	■		
160	■	■	■			■	■		■	■		
200						■	■		■	■		
250						■			■			
320											■	
400											■	
500											■	
630												■
800												■

MF = magnetic only trip unit with fixed magnetic thresholds
MA = magnetic only trip unit with adjustable magnetic thresholds
TMF = thermomagnetic trip unit with fixed thermal and magnetic thresholds
TMD = thermomagnetic trip unit with adjustable thermal and fixed magnetic thresholds
TMA = thermomagnetic trip unit with adjustable thermal and magnetic thresholds

Rated currents available for molded-case circuit-breakers SACE Tmax XT with Ekip electronic trip unit

	In [A]	10	25	40	63	100	160	250
Ekip	XT2	■	■		■	■	■	
	XT4			■	■	■	■	■

Rated currents available for molded-case circuit-breakers SACE Tmax XT with the typologies of magnetic trip units

	XT1 160	XT2 160			XT3 250		XT4 160-250	
In [A]	TMD	TMD/TMA	MF	MA	TMD	MA	TMD/TMA	MA
1			■					
1,6		■						
2		■	■					
2,5		■						
3,2		■						
4		■	■					
5		■						
6,3		■						
8		■						
8,5			■					
10		■						■
12,5		■	■					■
16	■	■					■	
20	■	■		■			■	■
25	■	■					■	■
32	■	■		■			■	■
40	■	■					■	
50	■	■					■	
52				■				■
63	■	■			■		■	
80	■	■		■	■		■	■
100	■	■		■	■	■	■	■
125	■	■			■	■	■	■
160	■	■			■	■	■	■
200					■	■	■	■
225								
250					■		■	

MF = magnetic only trip unit with fixed magnetic thresholds
MA = magnetic only trip unit with adjustable magnetic thresholds
TMD = thermomagnetic trip unit with adjustable thermal and fixed magnetic thresholds
TMA = thermomagnetic trip unit with adjustable thermal and magnetic thresholds

9.1.4 Molded-case switch-disconnectors type Tmax T and SACE Tmax XT

The Tmax and SACE Tmax XT derive from the corresponding circuit-breakers from which they differ only for the absence of the protection trip units. The main function carried out by these apparatus consists in the isolation of the circuit they are inserted in. Once the contacts are open they are at a distance which prevents an arc from striking, in compliance with the prescriptions of the Standards as regards the isolation behavior.

The position of the operating lever corresponds definitely with that of the contacts (positive operation). Each switch-disconnector must be protected on the supply side by a coordinated device which safeguards it against short-circuits.

The Tmax and SACE Tmax XT circuit-breaker which can carry out this protection function is always a device of a size corresponding to or smaller than that of the switch-disconnector under consideration.

		T1D	T3D	T4D	T5D	T6D	T7D
Conventional thermal current, **Ith**	[A]	160	250	250/320	400/630	630/800/1000[1]	1000/1250/1600
Rated service current in category AC22, **Ie**	[A]	160	250	250/320	400/630	630/800/1000	1000/1250/1600
Rated service current in category AC23, **Ie**	[A]	125	200	250	400	630/800/800	1000/1250/1250
Poles	[Nr.]	3/4	3/4	3/4	3/4	3/4	3/4
Rated service voltage, **Ue**	[V] (AC) 50-60 Hz	690	690	690	690	690	690
Rated impulse withstand voltage, **Uimp**	[kV]	8	8	8	8	8	8
Rated insulation voltage, **Ui**	[V]	800	800	800	800	1000	1000
Test voltage at industrial frequency for 1 minute	[V]	3000	3000	3500	3500	3500	3500
Rated short-time withstand current for 1s, **Icw**	[kA]	2	3,6	3,6	6	15	20
Reference Standard		IEC 60947-3	IEC 60947-3	IEC 60947-3	IEC 60947-3	IEC 60947-3	IEC 60947-3
Versions		F	F-P	F-P-W	F-P-W	F-W	F-W

[1] Withdrawable version not available for T6 1000 A.

		XT1D	XT3D	XT4D
Conventional thermal current, **Ith**	[A]	160	250	250
Rated service current in category AC22, **Ie**	[A]	160	250	250
Rated service current in category AC23, **Ie**	[A]	125	200	200
Poles	[Nr.]	3/4	3/4	3/4
Rated service voltage, **Ue**	[V] (AC) 50-60 Hz	690	690	690
Rated impulse withstand voltage, **Uimp**	[kV]	8	8	8
Rated insulation voltage, **Ui**	[V]	800	800	800
Test voltage at industrial frequency for 1 minute	[V]	3000	3000	3000
Rated short-time withstand current for 1s, **Icw**	[kA]	2	3,6	3,6
Reference Standard		IEC 60947-3	IEC 60947-3	IEC 60947-3
Versions		F-P	F-P	F-P-W

9.1.5 Air circuit-breakers for alternating current applications

Air circuit-breakers of Emax E1...E6 series, complying with the Std. IEC 60947-2, have an application range from 400A to 6300A, breaking capacities from 42kA to 150kA @ 400V and are equipped with electronic relays type PR121/P, PR122/P and PR123/P.

Emax X1circuit-breakers have an application range from 400A to 1600A, breaking capacities from 42kA to 65kA @ 400V and are equipped with electronic relays type PR331/P, PR332/P and PR333/P.

		E1		E2				E3					E4			E6		X1		
Rated service voltage, **Ue**	[V]	690		690				690					690			690		690		
Rated impulse withstand voltage, **Uimp**	[kV]	12		12				12					12			12		12		
Rated insulation voltage, **Ui**	[V]	1000		1000				1000					1000			1000		1000		
Poles	[Nr.]	3/4		3/4				3/4					3/4			3/4		3/4		
Rated uninterrupted current **Iu**		B	N	B	N	S	L	N	S	H	V	L	S	H	V	H	V	B	N	L
	[A]	800	800	1600	1000	800	1250	2500	1000	800	800	2000	4000	3200	3200	4000	3200	630	630	630
	[A]	1000	1000	2000	1250	1000	1600	3200	1250	1000	1250	2500		4000	4000	5000	4000	800	800	800
	[A]	1250	1250		1600	1250			1600	1250	1600					6300	5000	1000	1000	1000
	[A]	1600	1600		2000	1600			2000	1600	2000						6300	1250	1250	1250
	[A]					2000			2500	2000	2500							1600	1600	
	[A]								3200	2500	3200									
	[A]									3200										
Rated ultimate breaking capacity under short-circuit **Icu**																				
220-230-380-400-415V 50-60Hz	[kA]	42	50	42	65	85	130	65	75	100	130	130	75	100	150	100	150	42	65	150
440V 50-60Hz	[kA]	42	50	42	65	85	110	65	75	100	130	110	75	100	150	100	150	42	65	130
500V 50-60Hz	[kA]	42	50	42	65	65	85	65	75	100	100	85	75	100	130	100	130	42	55	100
690V 50-60Hz	[kA]	42	50	42	65	65	85	65	75	85(*)	100	85	75	85(*)	100	100	100	42	55	60
Rated short-time withstand current for 1s, **Icw**	[kA]	42	50	42	55	65	-	65	75	75	85	-	75	100	100	100	100	42	42	15
Utilization category (IEC 60947-2)		B	B	B	B	B	A	B	B	B	B	A	B	B	B	B	B	B	B	A
Isolation behaviour		■		■				■					■			■		■		■
Versions		F-W		F-W				F-W					F-W			F-W		F-W		F-W

(*) The performance at 600V is 100kA

9.1.6 Air circuit-breakers for applications up to 1150V AC

Emax circuit-breakers can be supplied, in a special version, for rated service voltages up to 1150V in alternating current. Circuit-breakers in this version are identified by the letters of the standard range plus "/E" and are derived from the corresponding standard SACE Emax circuit-breakers, of which they maintain the same versions and accessories. They can be either fixed or withdrawable, in both three- and four-pole versions. This range of circuit-breakers has been tested at a voltage of 1250V AC.

		E2B/E	E2N/E	E3H/E	E4H/E	E6H/E	X1B/E
Rated service voltage, **Ue**	[V]	1150	1150	1150	1150	1150	1000
Rated impulse withstand voltage, **Uimp**	[kV]	12	12	12	12	12	12
Rated insulation voltage, **Ui**	[V]	1250	1250	1250	1250	1250	1000
Poles	[Nr.]	3/4	3/4	3/4	3/4	3/4	3/4
Rated uninterrupted current **Iu**	[A]	1600	1250	1250	3200	4000	630
	[A]	2000	1600	1600	4000	5000	800
	[A]		2000	2000		6300	1000
	[A]			2500			1250
	[A]			3200			1600
Rated ultimate breaking capacity under short-circuit **Icu**							
1000V 50-60Hz	[kA]	20	30	50	65	65	20
1150V 50-60Hz	[kA]	20	30	30	65	65	-
Rated short-time withstand current for 1s **Icw**	[kA]	20	30	50(*)	65	65	20

(*) 30 kA @ 1150 V

Rated currents available for air circuit-breakers with the different typologies of electronic trip units

	In [A]	400	630	800	1000	1250	1600	2000	2500	3200	4000	5000	6300
PR121/P PR122/P PR123/P	E1	■	■	■	■	■	■						
	E2	■	■	■	■	■	■	■					
	E3	■	■	■	■	■	■	■	■	■	■		
	E4			■	■	■	■	■	■	■	■		
	E6			■	■	■	■	■	■	■	■	■	■
PR331/P PR332/P PR333/P	X1	■	■	■	■	■	■						
		■	■	■	■	■	■						
		■	■	■	■	■	■						

9.1.7 Air switch-disconnectors

The switch-disconnectors are derived from the corresponding standard circuit-breakers, of which they maintain the overall dimensions and the possibility of mounting the accessories. They only differ from the standard circuit-breakers in the absence of the electronic overcurrent trip units. They are available in both fixed and withdrawable, three- and four-pole versions; they are identified by the letters "/MS" and can be used in category of use AC-23A (switching of motor loads or other highly inductive loads) in compliance with the Std. IEC 60947-3.

		E1B/MS	E1N/MS	E2B/MS	E2N/MS	E2S/MS	E3N/MS	E3S/MS	E3V/MS	E4S/MS	E4H/MS	E6H/MS	X1B/MS
Rated service voltage **Ue**	[V ~]	690	690	690	690	690	690	690	690	690	690	690	690
	[V -]	250	250	250	250	250	250	250	250	250	250	250	250
Rated impulse withstand voltage **Uimp**	[kV]	12	12	12	12	12	12	12	12	12	12	12	12
Rated insulation voltage **Ui**	[V ~]	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Poles	[Nr.]	3/4	3/4	3/4	3/4	3/4	3/4	3/4	3/4	3/4	3/4	3/4	3/4
Rated uninterrupted current **Iu**	[A]	800	800	1600	1000	1000	2500	1000	800	4000	3200	4000	1000
	[A]	1000	1000	2000	1250	1250	3200	1250	1250		4000	5000	1250
	[A]	1250	1250		1600	1600		1600	1600			6300	1600
	[A]	1600	1600		2000	2000		2000	2000				
	[A]							2500	2500				
	[A]							3200	3200				
	[A]												
Rated short-time withstand current for 1s **Icw**	[kA]	42	50	42	55	65	65	75	85	75	100[1]	100	42

Note: The breaking capacity Icu, by means of external protection relay, with 500ms maximum timing, is equal to the value of Icw (1s).
[1] Icu = 85 kA @ 690 V

9.1.8 Air switch-disconnectors for applications up to 1150V AC

Emax switch-disconnectors can be supplied, in a special version, for rated service voltages up to 1150V in alternating current (AC). Circuit-breakers in this version are identified by the letters of the standard range plus “/E” and are derived from the corresponding standard switch-disconnectors.

They are available in the three-pole and four-pole, fixed and withdrawable versions in the same sizes, with accessory options and installations as per the corresponding standard circuit-breakers.

		E2B/E MS	E2N/E MS	E3H/E MS	E4H/E MS	E6H/E MS	X1B/E MS
Rated service voltage **Ue**	[V]	1150	1150	1150	1150	1150	1000
Rated impulse withstand voltage **Uimp**	[kV]	12	12	12	12	12	12
Rated insulation voltage **Ui**	[V]	1250	1250	1250	1250	1250	1000
Poles	[Nr.]	3/4	3/4	3/4	3/4	3/4	3/4
Rated uninterrupted current **Iu**	[A]	1600	1250	1250	3200	4000	1000
	[A]	2000	1600	1600	4000	5000	1250
	[A]		2000	2000		6300	1600
	[A]			2500			
	[A]			3200			
Rated short-time withstand current for 1s **Icw**	[kA]	20	30	30(*)	65	65	20

Note: The breaking capacity Icu, by means of external protection relay, with 500ms maximum timing, is equal to the value of Icw (1s).
(*) 50 kA @ 1000 V

9.1.9 Tmax molded-case circuit-breakers for direct current applications

Tmax molded-case circuit-breakers complying with the Std. IEC 60947-2, are equipped with thermomagnetic trip units, have an application range from 1.6A to 800A and breaking capacities from 16kA to 150kA (@ 250V with two poles in series). The minimum rated operating voltage is 24V DC.

The available circuit-breakers are[1]:

- Tmax T1, 1p, equipped with thermomagnetic trip unit type TMF with fixed thermal and magnetic thresholds[2];
- Tmax T1, T2, T3 and T4 circuit-breakers (up to 50A) equipped with thermomagnetic trip units type TMD with adjustable thermal threshold (I_1 = 0.7..1 x I_n) and fixed magnetic threshold (I_3 = 10 x I_n);
- Tmax T4, T5 and T6 circuit-breakers equipped with thermomagnetic trip units type TMA with adjustable thermal (I_1 = 0.7..1 x I_n) and magnetic threshold (I_3 = 5..10xI_n)[2].

T2, T3 and T4 circuit-breakers in three-pole version can be provided with magnetic only trip units type MF and MA.

1 As regards the modality of pole connection according to the network typology and to the service voltage, please refer to the tables shown in the QT5 "ABB circuit-breakers for direct current applications".

2 The value of the trip threshold undergoes a variation depending on the pole connection mode. For further details see the technical catalogue of the product.

		T1 1P	T1			T2						T3		T4					T5					T6			
Rated uninterrupted current **Iu**	[A]	160	160			160						250		250/320					400/630					630/800/1000			
Poles	[Nr.]	1	3/4			3/4						3/4		3/4					3/4					3/4			
Rated service voltage **Ue**	[V] (DC)	125	500			500						500		750					750					750			
Rated impulse withstand voltage **Uimp**	[kV]	8	8			8						8		8					8					8			
Rated insulation voltage **Ui**	[V]	500	800			800						800		1000					1000					1000			
Test voltage at industrial frequency for 1 min.	[V]	3000	3000			3000						3000		3500					3500					3500			
Rated ultimate short-circuit breaking capacity **Icu**		B	B	C	N	B	C	N	S	H	L	N	S	N	S	H	L	V	N	S	H	L	V	N	S	H	L
(DC) 250V - 2 poles in series	[kA]	25 (a 125V)	16	25	36	16	25	36	50	70	85	36	50	36	50	70	100	150	36	50	70	100	150	36	50	70	100
(DC) 250V - 3 poles in series	[kA]		20	30	40	20	30	40	55	85	100	40	55	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(DC) 500V - 2 poles in series	[kA]		-	-	-	-	-	-	-	-	-	-	-	25	36	50	70	100	25	36	50	70	100	20	35	50	65
(DC) 500V - 3 poles in series	[kA]		16	25	36	16	25	36	50	70	85	36	50	-	-	-	-	-	-	-	-	-	-	-	-	-	-
(DC) 750V - 3 poles in series	[kA]		-	-	-	-	-	-	-	-	-	-	-	16	25	36	50	70	16	25	36	50	70	16	20	36	50
Utilization category (IEC 60947-2)		A	A			A						A		A					B (400A)(1) A (630A)					B (630A-800A)(2) A (1000A)			
Isolation behaviour		■	■			■						■		■					■					■			
Trip units: thermomagnetic																											
T fixed, M fixed	TMF	■	-			-						-		-					-					-			
T adjustable, M fixed	TMD	-	■			■						■		■ (up to 50A)					-					-			
T adjustable, M adjustable (5..10 x In)	TMA	-	-			-						-		■ (up to 250A)					■ (up to 500A)					■ (up to 800A)			
magnetic only	MA	-	-			■ (MF up to 12.5A)						■		■					-					-			
Interchangeability		-	-			-						-		■					■					■			
Versions		F	F			F-P						F-P		F-P-W					F-P-W					F-W			

* The breaking capacity for settings In = 16 A and In = 20 A is 16 kA
(1) Icw = 5kA
(2) Icw = 7.6kA (630A) - 10kA (800A)

9.1.10 SACE Tmax XT molded-case circuit-breakers for direct current applications

In addition ABB offers SACE Tmax XT family, a new range of molded-case circuit-breakers up to 250A.

As regards the protection of the DC section of the PV installations the following circuit-breakers are available:

- XT1 160 and XT3 250 equipped with thermomagnetic trip units TMD with adjustable thermal threshold (I_1 = 0.7..1 x I_n) and fixed magnetic threshold (I_3 = 10 x I_n);
- XT2 160 and XT4 250 equipped with thermomagnetic trip units TMA (for I_n ≥ 40A) with adjustable thermal threshold (I_1 = 0.7..1 x I_n) and magnetic threshold I3 adjustable in the range 8..10 x I_n for 40A, 6..10 x I_n for 50A and 5..10 x I_n for I_n ≥ 63A.

	XT1					XT2					XT3		XT4				
Size [A]	160					160					250		160/250				
Poles [Nr.]	3/4					3/4					3/4		3/4				
Rated service voltage Ue [V] (DC)	500					500					500		750				
Rated impulse withstand voltage Uimp [kV]	8					8					8		8				
Rated insulation voltage Ui [V]	800					1000					800		1000				
Rated ultimate short-circuit breaking capacity Icu	B	C	N	S	H	N	S	H	L	V	N	S	N	S	H	L	V
(DC) 250V-2 poles in series [kA]	18	25	36	50	70	36	50	70	120	150	36	50	36	50	70	120	-
(DC) 500V-3 poles in series [kA]	18	25	36	50	70	36	50	70	120	150	36	50	36	50	70	120	-
Utilization category (IEC 60947-2)	A					A					A		A				
Isolation behaviour	■					■					■		■				
Trip units: thermomagnetic																	
T adjustable, M fixed TMD	■					■ (up to 32A)					■		■ (up to 32A)				
T adjustable, M adjustable TMA	-					■					-		■				
magnetic only MF/MA						■					■		■				
electronic Ekip	-					■					-		■				
Versions	F-P					F-P-W					F-P		F-P-W				

(1) For XT4 160A
(2) For XT4 250A

9.1.11 Molded-case circuit-breakers for applications up to 1000V DC

The range of T4, T5 and T6 circuit-breakers for applications in direct current up at 1000V also comes into the panorama of the Tmax proposals.

These circuit-breakers are available in the three-pole and four-pole version with TMD or TMA thermomagnetic trip units.

These circuit-breakers are available in the fixed, plug-in and withdrawable version (for which the use of the 1000 V fixed parts supplied only by upper terminals is mandatory) and they are compatible with all the accessories except for the residual current release.

	T4	T5	T6
Rated uninterrupted current **Iu** [A]	250	400/630	630/800
Poles	4	4	4
Rated service voltage **Ue** [V]	1000	1000	1000
Rated impulse withstand voltage **Uimp** [kV]	8	8	8
Rated insulation voltage **Ui** [V]	1150	1150	1000
Test voltage at industrial frequency for 1 min. [V]	3500	3500	3500
Rated ultimate short-circuit breaking capacity **Icu**	V(1)	V(1)	L(1)
(DC) 4 poles in series [kA]	40	40	40
Utilization category (IEC 60947-2)	A	B (400A)(2) - A (630A)	B(3)
Isolation behaviour	■	■	■
Trip units: thermomagnetic			
T adjustable, M fixed TMD	■	-	-
T adjustable, M adjustable (5..10 x In) TMA	■	■	■
Versions	F	F	F(4)

(1) Power supply only from the top
(2) Icw = 5kA
(3) cw = 7.6 kA (630A) - 10kA (800A)
(4) For T6 in the withdrawable version, please ask ABB SACE

Molded-case circuit-breakers for applications up to 1000V DC - TMD and TMA

	T4 250	T5 400-630	T6 630-800
In [A]	**TMD/TMA**	**TMA**	**TMA**
32	■		
50	■		
80	■		
100	■		
125	■		
160	■		
200	■		
250	■		
320		■	
400		■	
500		■	
630			■
800			■

9.1.12 Molded-case switch-disconnectors for direct current applications

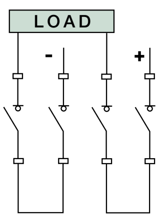
Tmax PV is a new range of T Generation; these are four-pole switch-disconnectors, fixed version, for applications with high DC values, suitable for photovoltaic installations.

They comply with the Std. IEC 60947-3, have a rated insulation voltage up to 1150V DC, service currents up to 1600A and a rated short-time withstand current Icw for 1 s up to 19.2 kA.
Tmax PV range includes six different sizes: from the compact T1D PV (which can be mounted on a DIN rail) to the T7D PV available in two versions, either with operating lever or motor operated mechanism. The accessories are the same as the standard series. The whole range can be remote-controlled by adding the motor operators.

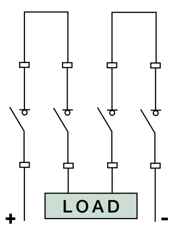
Available size and main characteristics Tmax PV

	T1D PV	T3D PV	T4D PV	T5D PV	T6D PV	T7D PV
Conventional thermal current Ith [A]	160	250	250	630	800	1600
Rated service current in category DC22 B, Ie [A]	160	200	250	500	800	1600
Rated service voltage Ue [V]	1100 V DC	1100 V DC	1100 V DC	1100 V DC	1100 V DC	1100 V DC
Rated impulse withstand voltage Uimp [kV]	8	8	8	8	8	8
Rated insulation voltage Ui [V]	1150 V DC	1150 V DC	1150 V DC	1150 V DC	1150 V DC	1150 V DC
Test voltage at industrial frequency for 1 minute [V]	3500	3500	3500	3500	3500	3500
Rated short-time withstand current for 1s, Icw [kA]	1.5	2.4	3	6	9.6	19.2
Versions	F	F	F	F	F	F
Terminals	FC Cu	FC Cu	FC Cu	FC Cu	FC CuAl	FC CuAl
Mechanical life [No. of operations]	25000	25000	20000	20000	20000	10000

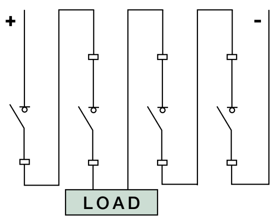
The connection diagrams valid for networks insulated from earth are shown hereunder:



Valid for T1D PV, T3D PV, T6D PV e T7D PV



Valid for T4D PV e T5D PV



Valid for all Tmax PV

9.1.13 Emax air circuit-breakers for direct current applications

Air circuit-breakers of Emax series comply with the Std. IEC 60947-2 and are equipped with DC electronic trip units type PR122/DC and PR123/DC.

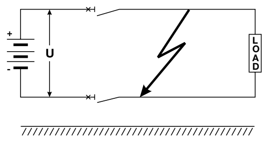
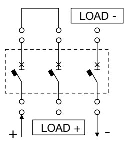
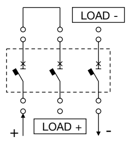
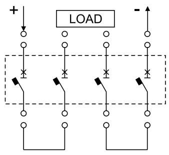
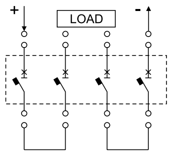
They have an application range from 800A (with E2) to 5000A (with E6) and breaking capacities from 35kA to 100kA (at 500V DC).
By connecting three breaking poles in series, it is possible to achieve a rated voltage of 750V DC, while with four poles in series the limit rises to 1000V DC[3].

The minimum operating voltage (through the dedicated low voltage measuring module PR120/LV) is 24V DC. Thanks to their exclusive technology, the trip units type PR122/DC-PR123/DC allow to carry out the protection functions already available in alternating current.
The Emax DC range maintains the same electrical and mechanical accessories in common with the Emax range for alternating current applications.

[3] *As regards the compulsory modality of pole connection according to the network typology and to the service voltage, please refer to the schemes shown in the QT5 "ABB circuit-breakers for direct current applications".*

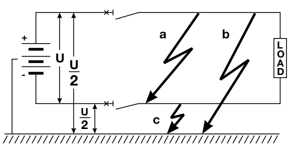
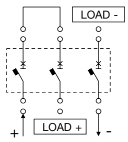
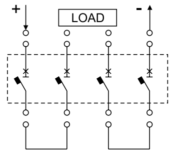
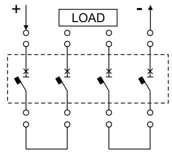
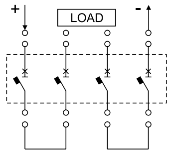
		E2		E3		E4		E6
Rated service voltage Ue	[V]	1000		1000		1000		1000
Rated impulse withstand voltage Uimp	[kV]	12		12		12		12
Rated insulation voltage Ui	[V]	1000		1000		1000		1000
Poles	[Nr.]	3/4		3/4		3/4		3/4
Rated uninterrupted curent Iu		B	N	N	H	S	H	H
	[A]	800		800				
	[A]	1000		1000				
	[A]	1250		1250				
	[A]	1600	1600	1600	1600	1600		
	[A]			2000	2000	2000		
	[A]			2500	2500	2500		
	[A]					3200	3200	3200
	[A]							4000
	[A]							5000
Rated short-time withstand current for (0.5s) Icw	[kA]							
500V DC (III)		35	50	60	65	75	100	100
750V DC (III)		25	25	40	40	65	65	65
750V DC (III)		25	40	50	50	65	65	65
1000V DC (IV)		25	25	35	40	50	65	65
Utilization category (IEC 60947-2)		B	B	B	B	B	B	B
Isolation behaviour		■		■		■		■
Versions		F-W		F-W		F-W		F-W

Network insulated from earth [(1)]

Rated voltage (Un)			≤ 500	≤ 750		≤ 1000
						
isolation			■	■	■	■
protection			■	■	■	■
PR122/DC			■	■	■	■
PR123/DC			■	■	■	■
Icu[(2)]			[kA]	[kA]	[kA]	[kA]
E2	B	800	35	25	25	25
		1000				
		1250				
		1600				
	N	1600	50	25	40	25
E3	N	800	60	40	50	35
		1000				
		1250				
		1600				
		2000				
		2500				
	H	1600	65[(3)]	40	50	40
		2000				
		2500				
E4	S	1600	75	65	65	50
		2000				
		2500				
		3200				
	H	3200	100	65	65	65
E6	H	3200	100	65	65	65
		4000				
		5000				

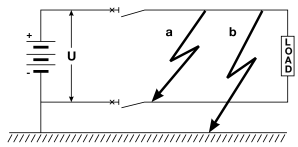
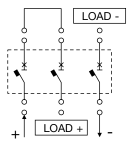
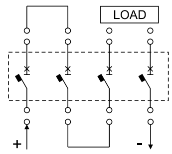
(1) with this typology of pole connection the possibility of a double earth-fault is considered unlikely.
For further information see the QT5 "ABB circuit-breakers for direct current applications".
(2) Icu with L/R = 15ms in compliance with the Std. IEC 60946-2. For Icu with L/R = 5ms and L/R = 30ms ask ABB.
(3) 85kA only if bottom-supplied and by specifying when ordering the following extracode: 1SDA067148R1. Ics=65kA.

Network with the median point connected to earth

Rated voltage (Un)			≤ 500			≤ 500			≤ 750			≤ 1000		
														
PR122/DC			-			-			-			-		
PR123/DC			■			■			■			■		
fault typology			a	b	c	a	b	c	a	b	c	a	b	c
poles in series affected by the fault			3	2 (U/2)	1 (U/2)	3	2 (U/2)	2 (U/2)	3	2 (U/2)	2 (U/2)	3	2 (U/2)	2 (U/2)
Icu(1)			[kA]			[kA]			[kA]			[kA]		
E2	B	800	35	35	18	35	35	35	25	25	25	25	25	25
		1000												
		1250												
		1600												
	N	1600	50	50	25	50	50	50	40	40	40	25	25	25
E3	N	800	60	60	30	60	60	60	50	50	50	35	35	35
		1000												
		1250												
		1600												
		2000												
		2500												
	H	1600	65(2)	65	40	65(2)	65(2)	65(2)	50	50	50	40	40	40
		2000												
		2500												
E4	S	1600	75	75	35	75	75	75	65	65	65	50	50	50
		2000												
		2500												
		3200												
	H	3200	100	100	50	100	100	100	65	65	65	65	65	65
E6	H	3200	100	100	65	100	100	100	65	65	65	65	65	65
		4000												
		5000												

(1) Icu with L/R = 15ms in compliance with the Std. IEC 60946-2. For Icu with L/R = 5ms and L/R = 30ms ask ABB.
(2) 85kA only if bottom-supplied and by specifying when ordering the following extracode: 1SDA067148R1. Ics=65kA.

Network with one polarity connected to earth [1]

Rated voltage (Un			≤ 500[2]			
						
isolation			■		■	
protection			■		■	
PR122/DC			■		■	
PR123/DC			■		■	
fault typology[3]			a	b	a	b
poles in series affected by the fault			3	2	4	3
Icu[4]			[kA]		[kA]	
E2	B	800	35	20	25	25
		1000				
		1250				
		1600				
	N	1600	50	25	40	25
E3	N	800	60	30	50	35
		1000				
		1250				
		1600				
		2000				
		2500				
	H	1600	65[5]	40	65[5]	65[5]
		2000				
		2500				
E4	S	1600	100	50	100	100
		2000				
		2500				
		3200				
	H	3200	100	65	100	100
E6	H	3200	100	65	100	100
		4000				
		5000				

[1] for networks with positive polarity connected to earth ask ABB.
[2] for higher voltages ask ABB.
[3] for further information see the QT5 “ABB circuit-breakers for direct current applications”.
[4] Icu with L/R = 15ms in compliance with the Std. IEC 60946-2. For Icu with L/R = 5ms and L/R = 30ms ask ABB.
[5] 85kA only if bottom-supplied and by specifying when ordering the following extracode: 1SDA067148R1. Ics=65kA.

9.1.14 Air switch-disconnectors for applications up to 1000V DC

Emax /E MS are switch-disconnectors for applications up to 1000V DC at 6300A DC. They are available either fixed or withdrawable, in both three- and four-pole versions.

By connecting three breaking poles in series, it is possible to achieve a rated voltage of 750V DC, while with four poles in series the limit rises to 1000V DC.

		E1B/E MS		E2N/E MS		E3H/E MS		E4H/E MS		E6H/E MS	
Rated service voltage **Ue**	[V]	750	1000	750	1000	750	1000	750	1000	750	1000
Rated impulse withstand voltage **Uimp**	[kV]	12	12	12	12	12	12	12	12	12	12
Rated insulation voltage **Ui**	[V]	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Poles	[Nr.]	3	4	3	4	3	4	3	4	3	4
Rated uninterrupted current **Iu**	[A]	800		1250		1250		3200		4000	
	[A]	1250		1600		1600		4000		5000	
	[A]			2000		2000				6300	
	[A]					2500					
	[A]					3200					
Rated short-time withstand current for (1s) **Icw**	[kA]	20	20*	25	25*	40	40*	65	65	65	65

Note: The breaking capacity Icu, by means of external protection relay, with 500 ms maximum timing, is equal to the value of Icw (1s).
*The performances at 750V are:
for E1B/E MS Icw = 25 kA
for E2N/E MS Icw = 40 kA
for E3H/E MS Icw = 50 kA

9.2 Residual current releases Type B

9.2.1 Residual current releases RC223 and RC Type B

The RC223 residual current release, which can be combined with Tmax T3 and T4 four-pole circuit-breakers in the fixed, withdrawable or plug-in version (withdrawawble and plug-in for T4 only), and the residual current release RC Type B, which can be combined with Tmax T3 four-pole circuit-breaker are the most advanced solution in the whole residual current release family for the Tmax range.
It can boast conformity with Type B operation, which guarantees sensitivity to residual fault currents with alternating, alternating pulsating and direct current components.
Apart from the signals and settings typical of the "basic" residual current release, RC223 and RC Type B releases also allow the selection of the maximum threshold of sensitivity at the residual fault frequency (3 steps: 400 – 700 – 1000 Hz).
It is therefore possible to adapt the residual current device to the different requirements of industrial plants according to the prospective fault frequencies generated on the load side of the release.

The rated supply frequency is always 50-60 Hz; by selecting 400-700-1000 Hz, the device becomes sensitive to the detection of the fault currents up to these frequencies.

RC223

RC B Type

Electrical characteristics		RC223	RC B Type
Primary service voltage	[V]	110…500	110…500
Rated frequency	[Hz]	45…66	45…66
Fault current frequency	[Hz]	0-400-700-1000	0-400-700-1000
Rated service current	[A]	fino a 250A (225 per T3)	fino a 225A
Adjustable trip thresholds	[A]	0.03-0.05-0.1-0.3-0.5-1	0.03-0.05-0.1-0.3-0.5-1
Adjustable time limits for non-trip at 2·IΔn	[s]	ist-0.1-0.2-0.3-0.5-1-2-3	ist-0.1-0.2-0.3-0.5-1-2-3
Absorbed power		<10W @ 400V	<10W @ 500V

9.2.2 Residual current devices

F204 B type B
Rated current I_n: 40, 63, 125 A
Rated sensitivity I_{dn}: 30, 300, 500 mA
Rated voltage: 230÷400 V
Poles: 4 in 4 modules
Type: B, B selective
Reference Standards: EN 61008, IEC 60755, IEC 62423
Accessories for F204 type B
- signal/auxiliary contact

F202 PV B
Rated current I_n: 25, 63 A
Rated sensitivity I_{dn}: 30, 300 mA
Rated voltage: 230 V
Poles: 2 in 4 modules
Type: B
Reference Standards: EN 61008, IEC 60755, IEC 62423
Accessories for F202PV B
- signal/auxiliary contact

9.3 Contactors

A Series
Rated operating voltage max 1000 V AC
Rated current:
- three-pole contactors: from 25 A to 2050 A (in AC-1 - 40°C)
- four-pole contactors: from 25 A to 1000 A (in AC1- 40°C)

Compact design for the whole range
Range:
- three-pole contactors
- four-pole contactors
- auxiliary contactors

9.4 Switch-disconnectors

OT Series
Rated current I_n: from 15 to 125 A
Poles: 3, 4, 6 and 8 poles according to the operating voltage
Characteristics:
- mechanism with quick closing / opening operation and independent snap function (versions OT 45...125)
- accessories for snap-on mounting on circuit-breakers
- mechanism for OT 45...125 switch-disconnectors for DIN rail mounting, padlockable through a blocking adapter

Reference Standard: IEC 60947-3

S800 PV-M
Rated current I_n: 32, 63, 125 A
Rated voltage U_e:
- 2 poles, up to 800 V DC
- 4 poles, up to 1200 V DC

Rated short-time withstand current I_{cw}: 1.5 kA
Temperature range: –25 °C...+60 °C
Utilization category: DC-21A
Reference Standard: IEC 60947-3
Accessories for S800 PV-M
- shunt opening releases
- undervoltage releases
- signal/auxiliary contacts
- rotary drive adapter and rotary handle

9.5 Miniature circuit-breakers

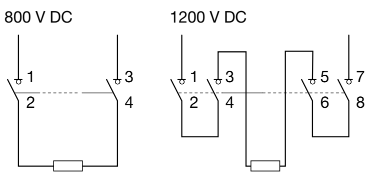
S284 UC Z
Rated current In: 6...63 A
Poles: 4
Rated voltage U_e: 500 V DC
Ultimate short-circuit breaking capacity I_{cu}: 4.5 kA
Temperature range: –25 °C...+55 °C
Reference Standard: IEC 60947-2
Accessories for S284 UC Z
- shunt opening releases
- undervoltage releases
- signal/auxiliary contacts
- rotary drive adapter and rotary handle

S800 PV-S
Rated current I_n: 10...125 A
Rated voltage U_e:
- 2 poles, up to 800 V DC (100÷125 A, up to 600 V DC)
- 4 poles, up to 1200 V DC

Ultimate short-circuit breaking capacity I_{cu}: 5 kA
Temperature range: –25 °C...+60 °C
Reference Standard: IEC 60947-2
Accessories for S800 PV-S
- shunt opening releases
- undervoltage releases
- signal/auxiliary contacts
- rotary drive adapter and rotary handle

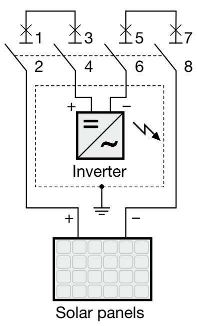
Use of S800 PV-M switch-disconnectors in DC

Layout of PV panels in earth-insulated systems



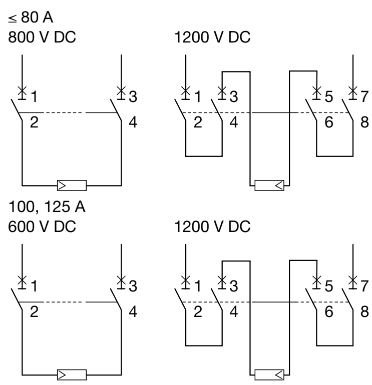
Wiring diagram of a PV plant downstream the strings

S 284 UC - IT system



Use of S800 PV-S thermal magnetic CBs in DC

Layout of PV panels in earth-insulated systems



9.6 Surge protective devices, Type 2

OVR PV
Protection of the DC side
Maximum continuously applied voltage up to 1120 V DC
Rated discharge current for pole: 20 kA
Maximum discharge current for pole: 40 kA

Other characteristics:
- integrated thermal protection with breaking capacity 25 A DC
- pluggable cartridges
- remote signalling contact in TS (remote indicator) versions
- no follow-up short-circuit current
- no risk in case of polarity inversion
- back-up protection with fuse 4A gR (or 16A gR only if installed in IP65 enclosure)

9.7 Fuse disconnectors and fuse holders

E 90 PV
Rated voltage: 1000 V DC
Rated current: up to 32 A
Fuse dimensions: 10.3 mm x 38 mm
Utilization category: DC-20B
Reference Standard: CEI EN 60947-3

Other characteristics:
- one module per pole
- available in single-pole and two-pole versions
- compatible with PS bars
- terminal cross section of 25mm^2
- sealable when closed and lockable when open
- available versions with signalling LED for fuse interruption

9.8 Electronic energy meters

Single-phase active energy meters ODINsingle
Voltage: 230 V AC
Maximum inrush current: 65 A
Display: 6-digit LCD with backlight
Impulse output for the remote control of energy consumption
Operating temperature: from –25 °C up to +55 °C
Reference Standards: IEC 62052-11, IEC 62053-21
Compliance with the MID (European Directive for Measuring Instruments) for the fiscal use of energy metering
Reset possibility

Three-phase active and reactive energy meters DELTAplus
Voltage: direct measure up to 500 V AC; for higher voltages, with voltage transformer
Current: direct insertion up to 80 A; for higher currents, with current transformer .../5 A
Display: 7-digit LCD
Impulse output for the remote control of energy consumption
Reference Standards: IEC 62052-11, IEC 62053-21
Compliance with the MID (European Directive for Measuring Instruments) for the fiscal use of energy metering
Reset possibility

Serial communication adapters
Communication modules for electronic energy meters:
- M-bus
- Ethernet
- GSM/GPRS
- RS 232
- EIB/KNX
- LonWorks PLC

9.9 Switchboards

Gemini series
Degree of protection: IP 66
Insulation in class II
Rated insulation voltage: 1000 V AC, 1500 V DC
Thermoplastic co-injection material, 100% recyclable
GWT: 750 °C
Temperature range: from –25 °C up to +100 °C
Shock resistance: up to 20 J (degree IK 10)
For indoor/outdoor use
Suitable for the installation of circuit-breakers and other components on DIN rail, molded-case circuit-breakers, contactors and other automation products
Reference Standards: CEI EN 50298, CEI EN 50439-1, CEI 23-48, CEI 23-49, IEC 60670
IMQ approved

9.10 Wall-mounted consumer units

Europa series
Degree of protection: IP 65
Insulation class: II
Available in self-extinguishing thermoplastic material, resisting to anomalous heat and fire up to 650 °C (glow-wire test) in compliance with the Std. IEC 60695-2-11
Installation temperature: from –25 °C up to +60 °C
Rated insulation voltage: 1000 V AC, 1500 V DC
Shock resistance: 6 J (degree IK 08)
Extractable DIN rail frame, to facilitate bench wiring, it can also be dismantled (and snapped-on) to make the cable connection of the single rows easier
Possibility of installing equipment with depth 53, 68 and 75 mm
Units with 8 or more modules, equipped with flanges in bi-material and rigid to facilitate the input of conduits and cables
Reference Standards: CEI 23-48, CEI 23-49, IEC 60670
IMQ approved

9.11 Junction boxes

Degree of protection: IP 65
Insulation class: II
Available in self-extinguishing polycarbonate material, resisting to anomalous heat and fire up to 960 °C (glow-wire test) in compliance with the Std. IEC 60695-2-11
Installation temperature: from –25 °C up to +60 °C
Shock resistance: 20 J (degree IK 10)
Reference Standards: CEI 23-48, IEC 60670
IMQ approved

9.12 Terminal blocks

Compliance with the Standards IEC 60947-7-1, IEC 60947-7-2
Parallel interconnections available
Self-extinguishing material V0

Screw connection
Voltage: max 1000 V
Current: max 415 A
Cross sectional area: max 240 mm2

Self-stripping connection (ADO system)
Voltage: max 1000 V
Current: max 32 A
Cross sectional area: max 4 mm2
Available also in the version ADO screw-clamp

Spring connection
Voltage: max 800 V
Current: max 125 A
Cross sectional area: max 35 mm^2

New SNK Series
Screw connection
Voltage: max 1.000 V
Current: max 232 A
Cross sectional area: max 95 mm^2

9.13 Motors

Low Voltage asynchronous motors
Aluminum motors
Available both in standard as well as in self-braking version
Power: from 0.06 kW to 1.1 kW
Poles: 2, 4, 6, 8
Voltage: up to 690 V
Protection: IP 55

Main advantages:
- high reliability
- reduced maintenance
- designed to operate under critical environmental conditions

Brushless motors Series 9C
Absolute feedback transducer
Emergency brake
Overload: up to 4 times the rated value
Inrush torque: up to 90 Nm
Compact overall dimensions

Main advantages:
- compact dimensions
- sturdy construction in IP 65
- uniformity of rotation al low rpm
- high inrush torques

9.14 Frequency converters

ACS355 – General machinery drive
Power: 0.37... 22 kW

ACSM1 – High performance machinery drive
Power: 0.75... 110 kW

9.15 Programmable Logic Controllers

AC500 CPU
2 serial interfaces integrated, RS232/RS485 configurable
Integrated display for diagnosis and status control
Centrally expandable with up to 10 expansion modules locally and up to 4 external communication modules simultaneously, in any desired combination
Optional: SD card for data storage and program backup
It can also be used as slave on Profibus DP, CANopen and DeviceNet via FieldBusPlug
Available with integrated Ethernet ports

9.16 Sub-switchboards

ABB offer for PV applications is completed with a range of sub-field and field switchboards ready to be installed. These switchboards consist of enclosures of insulation class II and are equipped with all the necessary protective and disconnecting devices.

Consumer unit Europe series, 8 modules, IP65
1 string

10 A, 500 V	
Miniature circuit-breaker	S284 UC Z10
Surge protective device	OVR PV 40 600 P
16 A, 500 V	
Switch-disconnector	OT16F4N2
Surge protective device	OVR PV 40 600 P
Fuse disconnector	E 92/32 PV
	10 A, 800 V
Miniature circuit-breaker	S802PV-S10
Surge protective device	OVR PV 40 1000 P

Consumer unit Europe series, 12 modules, IP65
2 strings
16 A, 500 V
Miniature circuit-breaker S284 UC Z16
Surge protective device OVR PV 40 600 P

16 A, 500 V
Switch-disconnector OT16F4N2
Surge protective device OVR PV 40 600 P
Sezionatori fusibili E 92/32 PV for each string

16 A, 800 V
Miniature circuit-breaker S802PV-S16
Surge protective device OVR PV 40 1000 P

Consumer unit Europe series, 18 modules, IP65
3 strings

25 A, 750 V	
Switch-disconnector	OT25F8
Surge protective device	OVR PV 40 1000 P
Fuse disconnectors	E 92/32 PV for each string
32 A, 800 V	
Miniature circuit-breaker	S802PV-S32
Surge protective device	OVR PV 40 1000 P
Fuse disconnectors	E 92/32 PV

Gemini switchboard, size 1 IP66
5 strings

50 A, 800 V	
Switch-disconnector	T1D 160 PV
Surge protective device	OVR PV 40 1000 P
Fuse disconnectors	E 92/32 PV for each string
50 A, 800 V	
Miniature circuit-breaker	S802PV-S50
Surge protective device	OVR PV 40 1000 P
Fuse disconnectors	E 92/32 PV for each string

Consumer unit Europe series, 36 modules, IP65
4 strings

32 A, 750 V	
Switch-disconnector	OT40F8
Surge protective device	OVR PV 40 1000 P
Fuse disconnectors	E 92/32 PV for each string
32 A, 800 V	
Switch-disconnector	S802PV-M32
Surge protective device	OVR PV 40 1000 P
Fuse disconnectors	E 92/32 PV for each string
40 A, 800 V	
Miniature circuit-breaker	S802PV-S40
Surge protective device	OVR PV 40 1000 P
Fuse disconnectors	E 92/32 PV for each string

Gemini switchboard, size 2 IP66
6 strings

63 A, 800 V	
Switch-disconnector	T1D 160 PV
Surge protective device	OVR PV 40 1000 P
Fuse disconnectors	E 92/32 PV for each string
63 A, 800 V	
Miniature circuit-breaker	S802PV-S63
Surge protective device	OVR PV 40 1000 P
Fuse disconnectors	E 92/32 PV for each string

8 strings

80 A, 1000 V	
Switch-disconnector	T1D 160 PV
Surge protective device	OVR PV 40 1000 P
Fuse disconnectors	E 92/32 PV for each string
80 A, 1000 V	
Miniature circuit-breaker	S804PV-S80
Surge protective device	OVR PV 40 1000 P
Fuse disconnectors	E 92/32 PV for each string

Annex A: New panel technologies

A.1 Emerging technologies

New different technologies are being the subject of research and development activities. These emerging technologies can be divided into two typologies on the ground of their inspiring concept:

- low cost, which includes "dye sensitized" cells, organic cells and hybrid cells based on inorganic-organic nanocompounds (DSSC);
- high efficiency, which involves different approaches to get some cells which can exceed the theoretical limit of solar conversion efficiency for a single junction, that is 31% without concentration 40.8% at the maximum possible concentration (OSC).

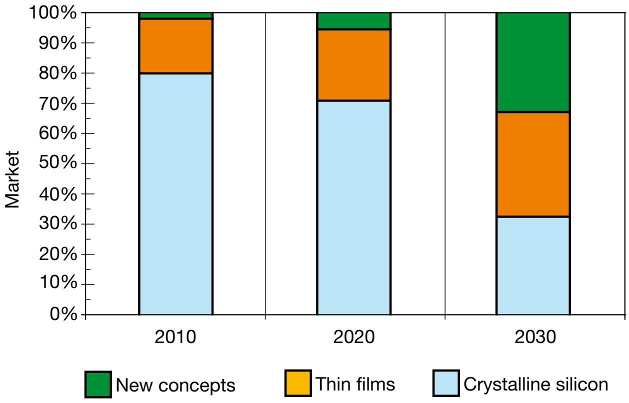
Dye sensitized solar cells (DSSC – also known as Grätzel cells from the name of their inventor) consist of a glass or plastic sub-layer with the following elements deposited one upon the other: a thin film conductive transparent electrode, a porous nanocrystal layer of the semiconductive titanium dioxide ($Ti0_2$), dye molecules (metal-organic complexes of ruthenium) distributed on the $Ti0_2$ surface, an electrolyte formed by an organic solvent and a redox pair as iodide/trioxide and a platinum-catalyzed counter electrode. Unlike traditional cells, the function of sunlight absorption and generation of electric charges is separated from the transportation function of charges. In fact the dye molecules absorb light and create the electron-hole pairs, the electrons are injected into $Ti0_2$ and transported up to the contact area, the redox pair provide the dye with the yielded electron by closing the internal circuit with the rear electrode (where the electrons from the external circuits are drawn). The main advantage of such technology is represented by the possibility of depositing the different materials on a large area by low-cost processes, but this type of cells has limited conversion efficiencies (<11%) and above all has a stability against exposure to atmospheric agents and to solar radiation of few years.
Production costs are expected to reach about 0.5 €/W.

Organic solar cells (OSC) consist of a conductive transparent electrode (ITO on glass or plastic), an active material constituted by organic molecules or polymers and a metallic counter-electrode. In the OSC the absorption of the sunlight and the liberation of electric charges occur through the organic material which is responsible also for transporting the charges generated by PV effect to the electrodes. The most efficient organic cells (but they reach only some percentage point) are inspired by the chlorophyll photosynthesis process: they use a mixture of compounds as the vegetal pigments, e.g. the anthocyanins derived from the fruits of the forest, or the polymers and the molecules synthesized in order to maximize the absorption of solar radiation.

In the *hybrid cells* the active material can be a mixture of organic molecules and of nanoparticles of inorganic compounds (e.g. carbon nanotubes).
Organic semiconductors have the capabilities necessary to reach in the medium-long term the aim of producing PV panels at low cost, since they can be synthesized and then deposited, at low temperature and with a low industrial cost, on a large area also on flexible sub-layers. For the time being the main limit of this typology is its conversion efficiency (<7%). Moreover, further studies on the stability and life time of these devices should be carried out.
The activities in progress for the high efficiency are aimed above all at producing multiple devices positioned in series, in which each of the junctions is designed and realized with a specific material for photogeneration in a specific interval of the solar radiation spectrum.
Since each single junction needs a different energy to determine the transfer of the electrons from the valence band to the conduction band, it is possible to use the energy of a greater number of photons than solar radiation, with a conversion efficiency higher than 30% (theoretical limit 50%). Among the most promising solutions there is the realization of quantum dot (QD) silicon based cells. In this case the photoactive material consists of silicon nanocrystals with nearly spherical form and diameter smaller than 7 nm, embedded in a matrix of silicon-based dielectric material, such as silicon oxide, silicon nitride or silicon carbide. By controlling the dimensions and density of the dots it is possible to provide the material with the most suitable characteristics to exploit part of the solar spectrum. A material suitable for photovoltaics shall consist of a more or less regular lattice of silicon QD with some nm diameter at a distance of about 1 nm in a silicon nitride or carbide matrix.
An alternative approach for high efficiency is using concentration systems able to separate, through dichroic materials, the different chromatic components of the incident solar radiation, sending it to different physically separated cells, each able to exploit at the best a part of the solar spectrum. This approach avoids the use of the expensive multijunction cells and reduces the problem of the temperature rise of the PV cells present in the traditional concentration systems.
By far the modules based on such technologies are not available on the market even if the first pilot production lines are being set up. The estimated time to have organic cells with commercial diffusion is around ten years.
Figure A.1 shows the forecast of the market share for

these technologies considered in the short, medium and long time. The new concepts include, in addition to the emerging technologies, also the concentrated photovoltaics.

Figure A.1



In the field of distributed generation through concentrated PV systems, there is the possibility to add, to the electric power production, the recovery of the heat necessary for cogenerative applications since the heat due to the cooling of cells (60° to 120°C, according to the concentration factor) becomes available to be used for air-conditioning or hot sanitary water.
However, the cogenerative solution has the drawback of having the cells work at a higher temperature for the heat production, which causes a reduction in the PV efficiency.
Concentrated photovoltaics is still in a demonstrative phase but a gradual passage to the industrial production phase has been noticed in the last years. Therefore, the cost of this technology (3.5 to 5 €/W) is still due to the pre-industrial development; however a reduction to 2-3€/W is foreseen for the next 5 years and a further halving in the following 5 years, also thanks to new solar tracking systems and to the research on high concentration systems (1000x).

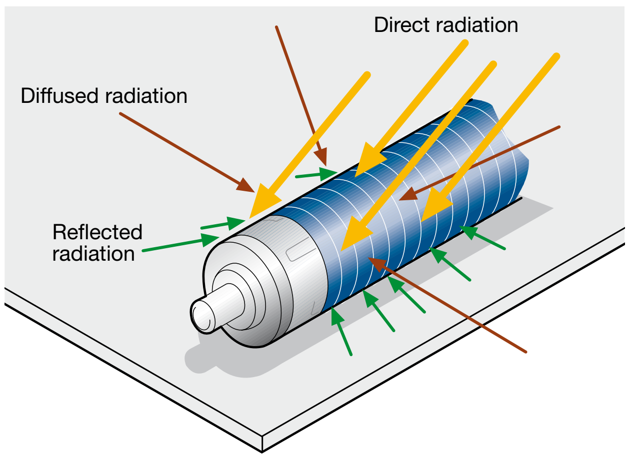
A.2 Concentrated photovoltaics

Concentrated solar plants use the principle of solar radiation concentration by means of suitable optical systems to strike the PV cells with light. Keeping constant the peak power of the system, the semiconductor area used is reduced by a factor equal to the optical concentration. This factor ranges from the value of 30x in the systems with less concentration up to a value next to 1000x for higher concentration systems. However, unlike the usual PV panels, concentrated photovoltaics can convert into electric energy only the direct solar radiation and consequently such systems need a sun tracking system (heliostat).
The concentrators currently used are both refractive (Fresnell or prismatic lens) as in the “Point-focus“ type solutions (in which each cell has a dedicated optics), as well as reflective in the dish solutions of “Dense Array” type (in which there is a single focal optics for an assembly of cells positioned in the focal point, that is along the line where the solar radiation concentrates).
The efficiency of concentrated solar panels ranges from the 12% of the single-crystalline silicon (concentration 20x) to about 20% (concentration 200x), with peaks of 40% when multi-junction cells with germanium (Ge) or gallium arsenide (GaAs) sub-layer are used.

A.3 Photovoltaics with cylindrical panels

These semi-integrated solar power plants use cylindrical panels coated at 360° with thin films, thus exploiting the solar radiation all day long as well as the light reflected by the surface on which they lie (Figure A.2).
The cylindrical panels work in the optimum way when they are horizontally mounted one next to the other; the system is light and unlike the traditional panels it is not subject to the “sail effect” and therefore it does not need that the modules are fixed by means of ballasted weights.

Figure A.2



Annex B: Other renewable energy sources

B.1 introduction

Renewable energies are those forms of energy generated by sources which due to their intrinsic characteristic are regenerated or are not “exhaustible” in a “human” time scale and whose use does not jeopardize the natural resources for the future generations.

As a consequence, the sun, the sea, the Earth’s heat are usually considered as "renewable power sources", that is sources whose present use does not jeopardize their availability in the future; on the contrary, the “non renewable” ones are limited for the future, both since they have long formation periods, higher than those of effective consumption (in particular, fossil fuels such as petroleum, coal, natural gas), and since they are present in reserves which are not inexhaustible on a human time scale.

If the strict definition of “renewable energy” is the above mentioned one, as a synonym also the expressions “sustainable energy” and ”alternative energy sources" are often used. However, there are slight differences; as a matter of fact sustainable energy is a method of production and use of energy allowing a sustainable development, thus including also the aspect of efficiency of energy uses. Instead alternative energy sources are all the sources different from hydrocarbons, that is deriving from non fossil materials.
Therefore, there is not a single definition of the whole of renewable sources, since in different circles there are different opinions as regards the inclusion of one or more sources in the group of the "renewable” ones.

B.2 Wind power

Eolic energy is the product of the conversion of the kinetic energy of wind into other energy forms, mainly into electric energy. The devices suitable for this type of transformation are called aerogenerators or wind turbines.
An aerogenerator requires a minimum wind velocity (cut-in) of 3-5 m/s and deliver the nameplate capacity at a wind velocity of 12-14 m/s. At high speeds the generator is blocked by the braking system for safety reasons. The block can be carried out by means of real brakes which slow down the rotor or with methods based on the stall phenomenon, “hiding” the blades from the wind. There are also aerogenerators with variable pitch blades which adjust to the wind direction, thus keeping constant the power output. The revolutions per minute (RPM) of the aerogenerator are very variable since the wind speed is variable; however, since the network frequency must be constant, the rotors are connected to inverters for the control of the voltage and frequency at which the energy is put into the network. Kinematics of the wind generator is characterized by low frictions and with them by low overheating, therefore no refrigeration system (oil and water) is needed with a remarkable reduction in the maintenance cost.

The environmental impact has always been an important deterrent to the installation of these plants. In fact, in most cases, the windiest places are the peaks and the slopes of the mountain relieves, where wind-powered plants are visible also from a great distance, with a landscape impact not always tolerable.

Another problem, which is quite important when considering large scale production, is the intermittency of the generated electric power. As a matter of fact, the wind, similarly to the sun and contrary to the conventional power sources, doesn’t deliver power in a homogeneous and continuative way and, in particular, it cannot be controlled so that the produced power can be adapted to the load requirement. Moreover, the authorities charged with the control of the air traffic in some countries have recently raised doubts about the installation of new wind plants since these could interfere with radars, which cannot easily eliminate the echoes due to the wind towers because of their high RCS (Radar Cross Section)[1].

In spite of all these ties, in many European countries the spreading of eolic parks is increasing just thanks to their ease of installation and reduced maintenance, and the possibility of exploiting not only the mainland, but also the open sea, with the so-called off-shore plants.

B.3 Biomass energy source

Biomass usable for energy production purposes consists of all those living materials which can be used directly as fuels or transformed into liquid or gaseous fuels, in the conversion plants, for a more convenient and wider usage. The term biomass includes heterogeneous materials, from the forest residues to the wastes of the wood transformation industry or of the zoo technical farms. Generally speaking all the organic materials deriving from photosynthetic reactions may be defined as biomass.

[1] Radar cross section (RCS) is a measure of how detectable an object is with a radar since when radar waves are beamed at a target, only a certain amount are reflected back. A number of different factors determine how much electromagnetic energy returns to the source, such as the angles created by surface plane intersections. For example, a stealth aircraft (which is designed to be undetectable) will have design features that give it a low RCS, as opposed to a passenger airliner that will have a high RCS.

In Italy biomasses cover about the 2.5% of the energy demand, with a carbon dioxide contribution to the atmosphere which can be virtually considered as null since the quantity of CO_2 released during combustion is equivalent to that absorbed by the plant during the growth process. Biomasses can be used in thermal generation plants with different dimensions, dimensions strictly connected to the characteristics of the territory and to the availability of this fuel in neighbouring zones.

B.4 Geothermal power

Geothermal power is a form of energy using the heat sources in the most inner areas of the earth, the subsoil. It is naturally linked to those regions where geothermal phenomena are present (in Italy Tuscany, Latium, Sardinia, Sicily and other areas in Veneto, Emilia Romagna and Lombardy can be pointed out as "hot areas"), where the heat spreading to the rocks next to the surface can be exploited to generate electricity through steam turbines, or used for heating in residential and industrial applications[2].

There are also technologies (geothermal sensor heat pumps) able to exploit the latent energy stored in the soil: in this case we speak of low temperature geothermal energy. These pumps are electrical heating (and also cooling) systems which take advantage of the relatively constant temperature of the soil during the whole year and can find an application in a wide range of buildings, all over the world. Geothermal sensors are heat exchangers (of the tubes) vertically (or horizontally) grounded in which a thermally conducting fluid flows. During winter, the environment is heated transferring the energy from the ground to the house, whereas during summer the system is reversed by drawing the heat from the ambient and transferring it to the ground.

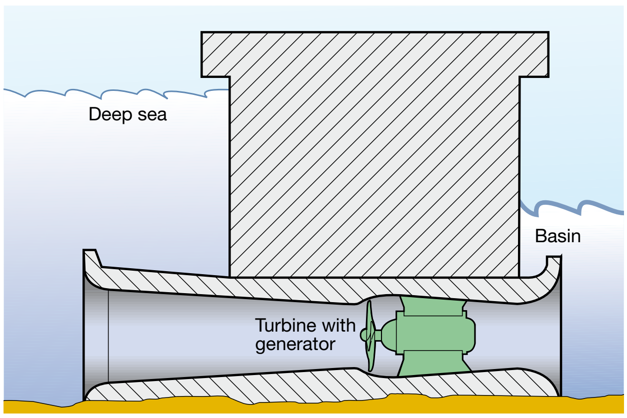
B.5 Tidal power and wave motion

The huge energy reserve offered by the sea (over 70% of the Earth surface is constituted by the ocean expanses with an average depth of 4000 m) is suitable to be exploited in different ways. In fact, in addition to the heat due to the thermal gradient (difference in temperature between two points), the sea has a kinetic energy due to the presence of currents, waves and tides.

Where there is a wide range between high and low tide it is possible to foresee the construction of a tidal stream energy power plant; on the coasts of Canada or on the English Channel coastline the difference in height (or head) between high and low tides reaches 8-15 m; on the contrary, in the Mediterranean Sea the tidal range does not usually exceed 50 cm.

In a tidal power plant the water flows in and out of a basin of a few square kilometers, passing through a series of pipes in which it gains speed and drives some turbines connected to generators (alternators). During the ebb tide the water flows from the basin to the deep sea, thus driving the turbine; when the sea level begins to rise and the tide is sufficiently high, the sea water is made to flow into the basin and the turbine is powered again. A peculiarity of this system is the reversibility of the turbines which therefore can run both as the tide rises and falls (Figure B.1).

Figure B.1



Generally speaking, the exploitation of tides to generate electricity is little effective; so far only two installations of this type were built: the most important is on the estuary of the Rance River in Brittany (France) and has a total power capacity of 240 MW, the other one is in Russia.

The sea waves are a store of energy taken from the wind. The longer is the wavelength, the more energy can be stored. Given the expanse of the sea and the energy contained in a single wave, there is a huge reserve of renewable energy which can be used. The average total amount of energy contained in the wave motion (travelling for hundreds of kilometers also without wind and with a little dispersion) offshore the coasts of the United States, calculated with a water depth of 60 m (the energy starts dissipating at about 200 m and at 20 m depth it becomes a third) has been esteemed to be about 2.100

[2] In Italy the exploitation of the geothermal power is today limited to Tuscany and high Lazio with a total capacity of 681 MW in 2004, and a production of 5.4 billion kWh equal to 1.55% of the national electric production.

terawatthour (TWh/year) (2100×10^{12} Wh).
The production of tidal energy is already a reality which arouses a remarkable interest. In countries such as Portugal, United Kingdom, Denmark, Canada, USA, Australia, New Zealand, and others there are dozens of companies and research institutes exclusively involved in the matter. The cost per KWh, when using this resource, is already close to that of eolic power generation.
The technologies under testing and those being used are different and numerous: floating devices anchored by means of a cable unrolled and wrapped up, piezoelectric pads, caissons filled with water and emptied, various floating systems and fixed systems both on the shore as well as on the sea floor.
The first installations were fixed structures with high environmental impact. The first floating project has been the project Kaimei in which a pool of nations (United States, United Kingdom, Ireland, Canada, and Japan) started in 1978 the construction of a ship whose power generation is 2 MWh. Another similar project is the Japanese Mighty Whale. The Italian project Sea Breath belongs to this family.

B.6 Mini-hydroelectric power

With the term mini-hydroelectric reference is usually made to hydroelectric generating stations with power lower than 10 MW, reduced dimensions and low environmental impact. The energy is obtained through hydraulic plants which utilize the water flow to drive turbines. Mini-hydroelectric technology can represent an important resource for many agricultural and mountain areas, and can be exploited both by recovering the structures existing along the rivers (conduits, purification plants, aqueducts) as well as, in the presence of interesting water flow, by forming water leaps and realizing interventions of limited impact on catchment basins.

B.7 Solar thermal power

Solar thermal plants are the most widespread ones and those which can more easily find an application on roofs in Italy. They use solar radiation, through a solar collector, mainly for water heating, for sanitary uses and after a careful evaluation also for the heating of rooms and swimming pools. The technology is ripe and reliable, with installations having an average life of over 20 years and a payback period which can be very short. A family of 4 people using 75 liters of hot water per person/day, combining the conventional gas boiler with a solar plant (typical plant: 4 m^2 panels and tank of 300 liters), can amortize the necessary investment, about 4,000 Euros, in a three-year period.
This calculation takes into account the existing incentives which allow part of the purchase and installation costs to be deducted from the taxes (55% tax deduction for the energy requalification of the buildings).

The technological solutions currently available can be distinguished in three categories:

- *unglazed collectors*, based on a vary simple operating principle: the water flows through pipes generally made of plastic material directly exposed to solar radiation and, by heating, the pipes allow the increase in the temperature of the water circulating inside them;

- *flat plate collectors*, which are based on the same principle of the unglazed collectors, but use materials with a higher thermal conductivity (copper, stainless steel, aluminum, ….) and are enclosed in cases (panels) constituted by a flat plate absorber on the rear part (aimed at retaining heat and maximizing radiation) and by a glass (or plastic material) plate in the upper part, in order to prevent the loss of heat in the environment through convection;

- *evacuated tube collectors*, in which the pipe containing the convector fluid is enclosed in a glass pipe with higher diameter and whose internal surface is coated with absorbing material and where vacuum is created in order to obtain thermal insulation to reduce heat loss due to convection.

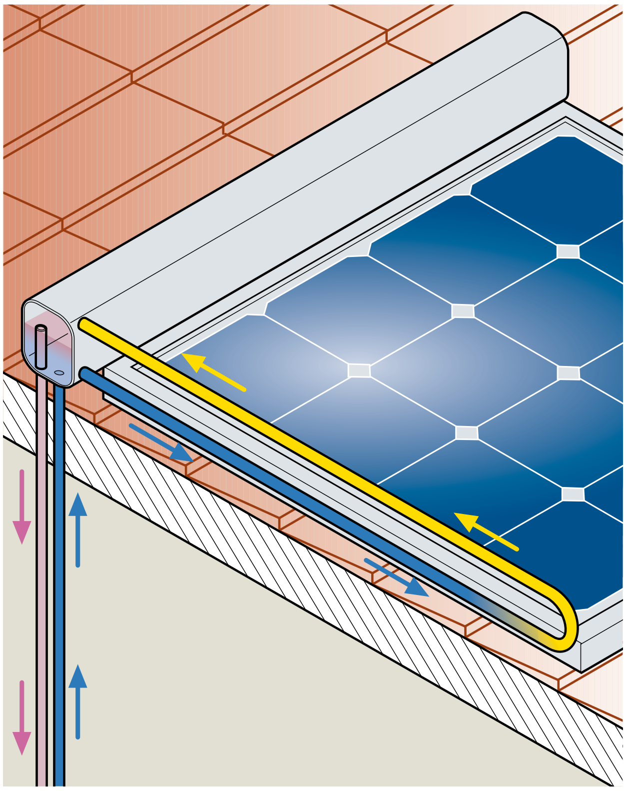
The heat collected by the convector fluid is transferred to the sanitary water contained in a particular storage tank in different ways according to the installation typology.
The hot water produced by a solar thermal plant can be used:

1. for sanitary uses (bathroom, cooking, washing machine, dishwasher)
2. to integrate space heating (better if combined with radiant systems such as radiant underfloor and wall panels because they require water at a lower temperature than the radiators normally used and cause less heat loss)
3. to maintain temperature in the swimming pools
4. both for families as well as in larger structures (leisure centers, hospitals, hotels, etc….)

By simplifying the classification, three alternative types of solar thermal plants can be identified:

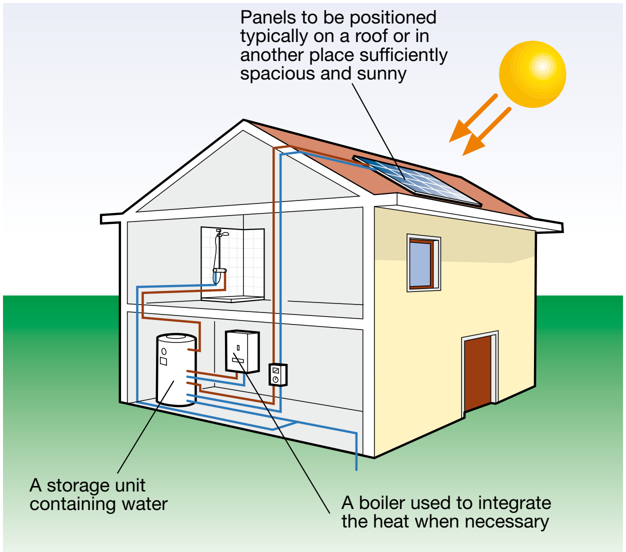
- *natural circulation*. These are the systems which exploit the natural principle according to which a hotter fluid tends to rise, whereas a cooler fluid tends to move downwards. In this case the thermal store unit is positioned above the panel (mounted on the roof as in Figure B.2a or placed in the attic as in Figure B.2b). The thermo-vector fluid, once it has been heated by the solar radiation, rises directly in the storage unit and transfers its own heat to the water contained in it. Once the fluid has cooled it flows downwards into the panels and the cycle starts again. This technology simply needs some solar collectors and a store unit/ heat exchanger. Surfaces and sizes vary according to the thermal requirements. The advantages of this type of plant are the cheapness, the possibility of functioning without electric pumps and control units, the inclination given by the slope of the roof, quick and economical installation, minimum maintenance and high efficiency strengthen by the natural circulation of the thermo-vector fluid. But there are also some disadvantages, from the slightest ones of aesthetic nature to the most important ones such as the exposure of the storage unit to atmospheric agents and to adverse environmental conditions and to the necessity that the roof is able to support the weight from a structural point of view.

Figure B.2



- *forced circulation*. Unlike natural convection, by forced circulation the storage unit can be positioned also at a lower level than the collectors and therefore also inside the house. In this type of installations, the presence of an electric pump allows the thermo-vector fluid to circulate from the collectors (higher position) to the thermal store unit (lower). With respect to natural circulation systems, this typology of plants needs a circulation pump, a control unit, temperature sensors and expansion vessels, with a usually higher costs and higher maintenance requirements. However, people who live in prestigious historic centers (and therefore in buildings subject to architectonic ties) and do not have an attic available to "hide" the storage unit of the natural circulation system, can solve the problem of the overall dimensions of the storage unit on the roof thanks to forced circulation (Figure B.3).

Figure B.3 - Scheme of a forced circulation plant



- *"drain back" forced circulation*. This technology represents an evolution of the traditional forced circulation and eliminates the possible inconvenience of stagnation of the thermo-vector fluid inside the collectors, which can occur when the pump is blocked or if other problems typical of forced circulation have occurred. "Stagnation" may cause overheating of the fluid with consequent serious damages to the solar plant. On the contrary, with this type of plant, when the pump stops, the panels empty and the liquid flows inside the drain storage unit thus preventing the collectors from breaking because of stagnation.

A 2-3 m^2 natural circulation plant with a 150/200 liter storage unit for hot sanitary water (useful to satisfy the requirements of 2-4 people) has an average cost of

2,000-3,000 €, installation, labor and VAT included. For a bigger plant, always with natural circulation, 4 m^2 of size, with 300 liter storage unit (useful to satisfy the requirements of 4-6 people) an indicative cost of about 4,000-4,500 € may be considered. A bigger plant - 15 m^2 with a 1,000 liter storage unit (for a 5 member family in a house with a floor heating system) with forced circulation contributing also to the heating of rooms - has an indicative cost of about 12,000 €. A solar thermal plant allows savings on the electricity and/or on the gas bills with favorable investment return times. Solar panels satisfy about 70% of the requirements for sanitary hot water of a dwelling house. When using solar power also as integration to domestic heating, the total requirement satisfied could also reach 40%. A solar thermal system installed according to the state of the art may be guaranteed up to fifteen years and with proper maintenance it might have longer endurance.
For solar thermal plants (only when installed in buildings already registered at the land-registry office) it is possible to obtain a fiscal exemption equal to 55% of the costs of plant purchase and installation, to be divided into 5 years as established by the Law no. 2 dated 28th January 2009 for the conversion of the anti-crisis DL (Legislative Decree) 185/2008. This deduction has been extended for three years in the Financial Act 2008. The VAT for solar plants is 10%. Besides, in many Regions, Provinces and Communes, incentives and loans are provided, which usually reach 25% to 30% of the total expenses.

B.8 Solar thermodynamic power

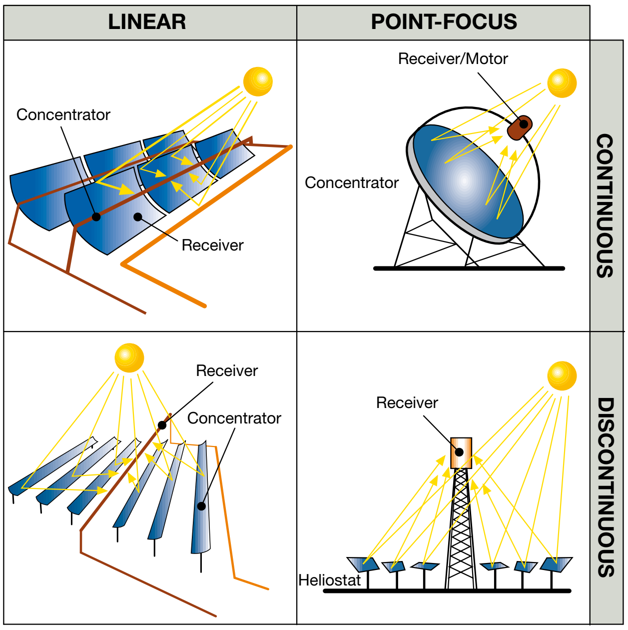
The conversion of solar energy into electricity is carried out in a solar thermodynamic plant in two phases:

- firstly solar radiation is converted into thermal energy;
- successively the thermal energy is converted into electrical power through a thermodynamic cycle.

The thermodynamic conversion of the second phase is completely analogous to what occurs in conventional thermal power stations and therefore it is necessary that the thermal power is available at high temperature to obtain high efficiency. As a consequence, in solar thermodynamic systems it is generally necessary to concentrate the solar radiation by means of a concentrator, constituted by suitably-designed mirrors allowing collection and focusing of the solar radiation onto a receiver which absorbs it and transforms it into thermal energy. The whole of concentrator and receiver forms the solar collector.
In the installation technologies currently available, the concentrator can be linear or point-focus, of continuous or discontinuous type (Figure B.4):

- solution a), parabolic trough collectors;
- solution b), parabolic dish concentrators;
- solution c), linear Fresnel reflectors;
- solution d), solar tower systems.

Figure B.4 - Typologies of solar collectors



Every technology allows reaching of different concentration factors, i.e. different values of maximum temperature and with it of thermodynamic cycle typologies most suitable for the conversion of thermal energy into electrical energy.
As a consequence, a solar thermal power station can be considered as the grouping of two sub-assemblies:

- one constituted of the solar collector which carries out the first phase of energy conversion;
- one converting thermal energy into electrical energy and which is constituted of the energy conversion equipment and of the transport and storage system which transfers heat from the collector to the thermodynamic cycle.

The thermal store unit has the purpose of storage of the generated heat to ensure the proper operation of the plant in case of sudden variations in the irradiation due to weather phenomena.
According to the maximum temperature of the convector

fluid, as thermodynamic cycle, the following typologies can be adopted: the water steam Rankine cycle (for temperatures in the range from 400° to 600°C) typical for plants with parabolic trough collectors, the Stirling cycle (for temperatures up to 800°C) in small parabolic dish plants and the Joule-Brayton cycle (for temperatures up to 1000°C) either in simple configuration or with combined cycle, typically in tower plants.

In the plants with parabolic trough concentrators (Figure B.5), the mirrors are used to focus the sunlight on thermal-efficient receiving tubes running along the focal line of the parabolic trough. A heat-conducting fluid (synthetic oil or a mixture of molten salts) circulates through these tubes taking away the heat from the receiver and transferring it through heat exchangers to the water of the thermodynamic cycle, thus generating superheated steam to drive a standard steam turbine.

These types of plants have an average annual net conversion output of about 12 to 14% and constitute almost the whole of the existing thermodynamic solar plants.

Figure B.5 - Parabolic trough concentrators

In the plants with parabolic dish concentrators (Figure B.6), solar radiation is concentrated onto a collector positioned in the focus of a parabolic dish reflector. The collector absorbs the radiation heat and heats a fluid which is used to generate electrical energy directly in the receiver through a small Stirling engine or a small gas turbine.

These types of plants have an average annual net conversion output of about 18% with daily peaks of 24%, but they are suitable for the generation of low powers (some dozens of kWs).

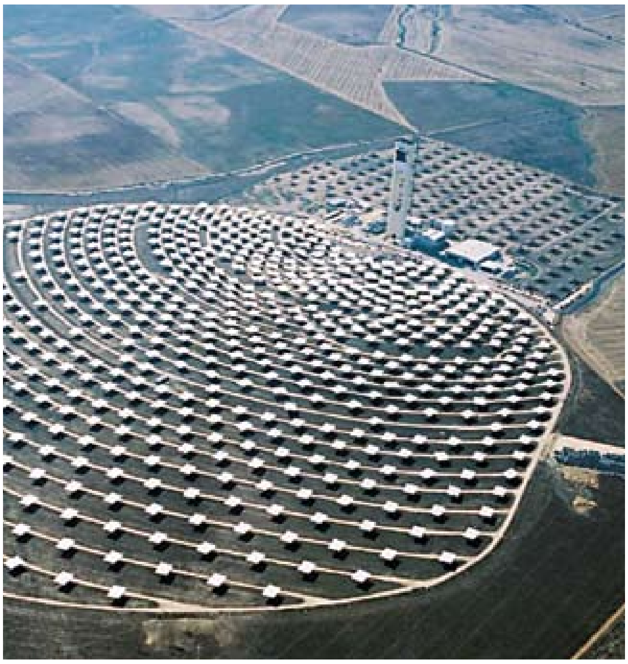
Figure B.6 – Parabolic dish plant

The plants with *linear Fresnel* concentrators (Figure B.7) are conceptually similar to linear trough plants, have slightly lower optical returns but have simpler tracking systems for the mirrors and lighter structures since they are less exposed to wind. They are still being tested but according to evaluations based on the manufacturing costs of the collectors they result to be more profitable compared with other technologies.

Figure B.7 – Linear Fresnel concentrator plant

In the central receiver plants (Figure B.8), the solar radiation coming from flat mirrors (heliostats) positioned on the ground in circles is focused on the central receiver mounted on a tower. In the receiver there is an exchanger which absorbs the reflected radiation and converts it into thermal energy for the subsequent generation of superheated steam to be sent to turbines or for the heating of either air or gas duly pressurized and used directly in open- or closed-cycle gas turbines.

Figure B.8 – Central receiver plant



B.9 Hybrid systems

In the next future it will be possible to think not only of a renewable source applied to a building or a site, but hybrid solutions will be taken into consideration to allow a source to back up the other. Such integration has already found applications in the residential buildings where it is possible to find more and more thermal solar systems coupled with PV plants, or geothermal systems combined with solar thermal systems.
Moreover, nowadays DC cogeneration is already present in the case of cogeneration plants producing heat and DC electric energy which is converted into alternating current by an inverter analogously to PV plants. This type of plants offers two advantages: the first one is linked to the possibility of modulating the electric production from 15% to 100% of the maximum power according to the usage requirements; the second one is allowing the connection to a PV system, as a temporary replacement for the cogenerator, so that panels can be exploited when insolation is at its maximum and the cogenerator in the night hours or with low irradiation. The flexibility of DC cogeneration, applicable also to small users with an efficiency which can get to 90%, is well adapted to the intermittency of the renewable sources, thus allowing a constant supply also in stand-alone systems which do not turn to the grid for electric energy storage.
Besides, more complex hybrid systems are coming out: they allow the energy to be stored in the hydrogen produced by electrolysis using the electric energy generated in excess by photovoltaic or wind-powered systems when consumption from the loads and the grid is low[3]. The hydrogen produced is stored in tanks at high pressure and then used to generate electric energy through fuel cells or by biogas mixing[4]. But these systems still have a low total efficiency in the conversion chain of the electric energy into hydrogen and then again into electricity through the fuel cells, and moreover these devices are still quite expensive. However, there are technical solutions aimed at reducing these disadvantages; their use on a big scale shall allow a reduction in costs and a rise in the system integration with an ever increasing spread, looking forward to the introduction of the Smart Grids, that is "smart distribution networks" able to shunt the electric power from one point of the grid to another in a scenario characterized by a variety of producers who, at the same time, are also self-consumers.

B.10 Energy situation in Italy

The gross national electrical energy demand in 2007 was about 360170 GWh. When not considering the self-consumption of the generation stations necessary for its own operation and the energy losses in the national distribution network, the energy consumption of the final users results to be 318952 GWh.

73.8% of the gross national electricity demand is covered by the big thermal power stations which burn mainly fossil fuels mostly imported from abroad. Biomasses (industrial or civil waste materials) and fuel of national origin must be considered as small part - lower than 2% - of the fuel used in thermal power stations.

[3] This is the typical case of wind-powered systems in northern Europe, where too much wind often blows in comparison with the real demands of the grid, and, as a consequence, wind turbines must be stopped, thus losing that production quota which could be used. In order to get round this, hydrogen-storage systems are being realized to store the energy produced by the wind blades in the windiest days, that is when the plants generate more energy than required by the grid.

[4] Or heat generation for district heating and sale of possible residual biogas as fuel for transport means.

Other important energy sources are the renewable ones (hydroelectric, geothermal, wind and photovoltaic sources) which contribute to the national demand with a share equal to 13.4% of the total amount.
These are the main sources for the national production of energy; they allow to generate a gross amount of energy equal to about 313887GWh per year.
The remaining part necessary to cover the national needs is imported from abroad and is 12.8% of the total amount.

B.10.1 Non renewable energies

As already seen, most part of the national demand is covered by the production of the thermal power stations with the aid of fossil fuel. Italy cannot count on a remarkable reserve of this type of fuel and consequently almost the total amount of the raw material is imported from abroad approximately according to the following percentages:
- natural gas about 65.2%;
- coal about 16.6%;
- petroleum products about 8.6%;
- minor fuel sources, prevalently of fossil nature (petroleum coke), about 7.3%.

The above data depict Italy as the fourth international importer of natural gas (mainly from Russia and Algeria and for lower amounts from Norway, Libya and the Netherlands). Although the energy amount produced from petroleum is remarkably decreased in favor of that derived from natural gas, Italy remains the European country depending most on petroleum for the production of electrical energy.

B.10.2 Renewable energies

A national plan providing for the establishment of renewable energy sources which can guarantee optimum performances and at the same time reduce pollution risks is fundamental to comply with the dictates of the Kyoto Protocol.
In Italy most generation of electricity through renewable sources derives from the hydroelectric plants (defined as classic renewable sources) located mainly in the Alps and in some Apennine areas; they generate about 10.7% of the gross national energy demand.
Other renewable energy sources are geothermal generating stations (essentially in Tuscany), which produce 1.5% of the electricity required.
“New” renewable sources such as wind technology (with eolic parks spread above all in Sardinia and in the Southern Apennine Mountains) generate about 1.1% of the required electric power, whereas lower percentages of about 0.01%, which correspond to about 39 GWh of the total amount, are produced by solar technology in grid-connected or stand-alone systems. A higher percentage with a production of about 2.3% of the total energy demand is covered by thermal power stations or incinerators through the combustion of biomasses, industrial or urban waste materials, gases derived by primary industrial processes (steelworks, blast furnaces, and refineries).

Annex C: Dimensioning examples of photovoltaic plants

C.1 Introduction

Here are two dimensioning examples of a photovoltaic power plant grid-connected in parallel to a preexisting user plant. The first example refers to a small grid-connected PV plant typical of a familiar end user, whereas the second one refers to a higher power plant to be installed in an artisan industry. In both cases the user plants are connected to the LV public utility network with earthing systems of TT type; the exposed conductive parts of the PV plants shall be connected to the already existing earthing system, but the live parts of the PV plant shall remain isolated. Finally, the prospective short-circuit current delivered by the distribution network is assumed to be 6kA line-to-neutral in the first example and 15kA three-phase in the second one.

C.2 3kWp PV plant

We wish to carry out dimensioning of a PV plant for a detached house situated in the province of Bergamo; the plant shall be connected to the LV public utility network based on net metering. This house is already connected to the public network with 3kW contractual power and an average annual consumption of about 4000 kWh.

The side of the roof (gabled roof) in which the panels shall be partially integrated has a surface of 60 m², is sloped with a tilt angle β of 30° and is +15° (Azimut angle γ) south oriented.

3 kWp is the power plant size decided, so that the power demand of the user is satisfied as much as possible; with reference to the example 2.2 of Chapter 2, the expected production per year, considering an efficiency of the plant components of 0.75, is about 3430 kWh.

Choice of panels

By using polycrystalline silicon panels, by 175 W power per unit, 17 panels are needed, a value obtained by the relation 3000/175=17. The panels are assumed to be all connected in series in a single string.

The main characteristics of the generic panel declared by the manufacturer are:

- Rated power P_{MPP}[1] — 175 W
- Efficiency — 12.8 %
- Voltage V_{MPP} — 23.30 V
- Current I_{MPP} — 7.54 A
- No-load voltage — 29.40 V
- Short-circuit current Isc — 8.02 A
- Maximum voltage — 1000 V
- Temperature coefficient P_{MPP} — -0.43%/°C
- Temperature coefficient U — -0.107 V/°C
- Dimensions — 2000 x 680 x 50 mm
- Surface — 1.36 m²
- Insulation — class II

Therefore the total surface covered by the panels shall be equal to 1.36 x 17 ≈ 23 m², which is smaller than the roof surface available for the installation.

By assuming -10°C and +70°C as minimum and maximum temperatures of the panels and by considering that the temperature relevant to the standard testing conditions is about 25°C, with the formula [2.13] the voltage variation of a PV module, in comparison with the standard conditions, can be obtained.

- Maximum no-load voltage — 29.40+0.107 · (25+10) = 33.13V
- Minimum voltage MPP — 23.30+0.107 · (25-70) = 18.50V
- Maximum voltage MPP — 23.30+0.107 · (25+10) = 27.03V

For safety purpose and as precautionary measures, for the choice of the plant components the higher value between the maximum no-load voltage and the 120% of the no-load voltage of the panels (note 7, Chapter 3) is considered. In this specific case, the reference voltage results to be equal to 1.2 · 29.40 = 33.28V, since it is higher than 33.13V.

Electrical characteristics of the string:

- Voltage MPP — 17 x 23.30 = 396 V
- Current MPP — 7.54 A
- Maximum short-circuit current — 1.25 x 8.02 = 10 A
- Maximum no-load voltage — 17 x 35.28 = 599.76 V
- Minimum voltage MPP — 17 x 18.50 = 314.58 V
- Maximum voltage MPP — 17 x 27.03 = 459.50 V

Choice of the inverter

Due to the small power of the PV plant and to carry out the direct connection with the LV single-phase network, a single-phase inverter is chosen which converts direct current to alternating current thanks to the PWM control and IGBT bridge. This inverter is equipped with an output toroidal transformer to guarantee the galvanic isolation between the electric grid and the PV plant; it has input and output filters for the suppression of the emission disturbances - both conducted as well as radiated - and an isolation sensor to earth for the PV panels.

It is equipped with the Maximum Power Point Tracker (MPPT), and with the interface device with the relevant interface protection.

[1] *MPP identifies the electrical quantities at their maximum power point under standard radiance conditions.*

Technical characteristics:

• Input rated power	3150 W
• Operating voltage MPPT on the DC side	203-600 V
• Maximum voltage on the DC side	680 V
• Maximum input current on the DC side	11.5 A
• Output rated power on the AC side	3000 W
• Rated voltage on the AC side	230 V
• Rated frequency	50 Hz
• Power factor	1
• Maximum efficiency	95.5%
• European efficiency	94.8%

To verify the correct connection string-inverter (see Chapter 3) first of all it is necessary to verify that the maximum no-load voltage at the ends of the string is lower than the maximum input voltage withstood by the inverter:

$$599.76 \text{ V} < 680 \text{ V (OK)}$$

In addition, the minimum voltage MPP of the string shall not to be lower than the minimum voltage of the inverter MPPT:

$$314.58 \text{ V} > 203 \text{ V (OK)}$$

whereas the maximum voltage MPP of the string shall not be higher than the maximum voltage of the inverter MPPT:

$$459.50 \text{ V} < 600 \text{ V (OK)}$$

Finally, the maximum short-circuit current of the string shall not exceed the maximum short-circuit current which the inverter can withstand on the input:

$$10 \text{ A} < 11.5 \text{ A (OK)}$$

Choice of cables

The panels are connected one to another in series through the cables L1* and the string thus obtained is connected to the field switchboard immediately on the supply side of the inverter using solar single-core cables L2 having the following characteristics:

- cross-sectional area 2.5 mm²
- rated voltage U_o/U 600/1000V AC – 1500V DC
- operating temperature -40 +90 °C
- current carrying capacity in free air at 60°C (two adjacent cables) 35 A
- correction factor of current carrying capacity at 70°C 0.91
- maximum temperature of the cable under overload conditions 120 °C

The current carrying capacity I_z of the solar cables installed in conduit at the operating temperature of 70°C results to be equal to (see Chapter 3):

$$I_z = 0.9 \cdot 0.91 \cdot I_0 = 0.9 \cdot 0.91 \;.\; 35 \approx 29\text{A}$$

where 0.9 represents the correction factor for installation of the solar cables in conduit or in cable trunking.

The carrying capacity is higher than the maximum short-circuit current of the string:

$$I_z > 1.25 \cdot I_{sc} = 10\text{A}$$

The frames of the panels and the supporting structure of the string are earthed through a cable N07V-K, yellow-green with 2.5 mm² cross-section. The connection of the field switchboard to the inverter is carried out using two single-core cables N07V-K (450/750V) with 2.5 mm² cross-sectional area and length L3=1m in conduit, with current carrying capacity of 24A, that is higher than the maximum string current.

The connections between the inverter and the meter of the produced power (length L4=1m) and between the meter and the main switchboard of the detached house (length L5=5m) are carried out using three single-core cables N07V-K (F+N+PE) with 2.5 mm² cross-sectional area in conduit, with current carrying capacity of 21A, which is higher than the output rated current of the inverter on the AC side:

$$I_z > \frac{P_n}{V_n \cdot \cos\varphi_n} = \frac{3000}{230 \cdot 1} = 13\text{A}$$

Verification of the voltage drop

Here is the calculation of the voltage drop on the DC side of the inverter to verify that it does not exceed 2%, so that the loss of energy produced is lower than this percentage (see Chapter 3).

Length of the cables with 2.5 mm² cross-section:

- connection between the string panels (L1): (17-1) x 1 m = 16 m
- connection between string and switchboard (L2): 15 m
- connection between switchboard and inverter (L3): 1 m
- total length 16 + 15 + 1 = 32 m

Therefore the percentage voltage drop results :

$$\Delta U\% = \frac{P_{max} \cdot (\rho_1 \cdot L_1 \cdot \rho_2 \cdot 2 \cdot L_2 + \rho_2 \cdot 2 \cdot L_3)}{s \cdot U^2} \;.\; 100 = \hookleftarrow$$

$$\rightarrow \frac{3000 \cdot (0.021 \cdot 16 + 0.018 \cdot 2 \cdot 15 + 0.018 \cdot 2 \cdot 1)}{2.5 \cdot 396^2} \;.\; 100 = 0.7\%$$

[2] *The voltage drop of the generated power between inverter and meter is disregarded because of the limited length of the connection cables (1m). For the connection cables string-switchboard and switchboard-inverter the resistivity of copper at 30°C* $\rho_2 = 0.018 \frac{\Omega \cdot mm^2}{m}$, *is considered, whereas for the connection cables between panels an ambient temperature of 70°C is considered; therefore* $\rho_1 = 0.018 \cdot [1+0.004 \cdot (70 - 30)] = 0.021 \frac{\Omega \cdot mm^2}{m}$.

Switching and protection devices

With reference to the plant diagram shown in Figure C.1, the protection against overcurrent is not provided since on the DC side the cables have a current carrying capacity higher than the maximum short-circuit current which could affect them.

On the AC side, in the main switchboard of the detached house there is a thermomagnetic residual current circuit-breaker DS 201 C16 A30 (30mA/typeA I_{cn}= 6kA) for the protection of the connection line of the inverter against overcurrents and for the protection against indirect contacts.

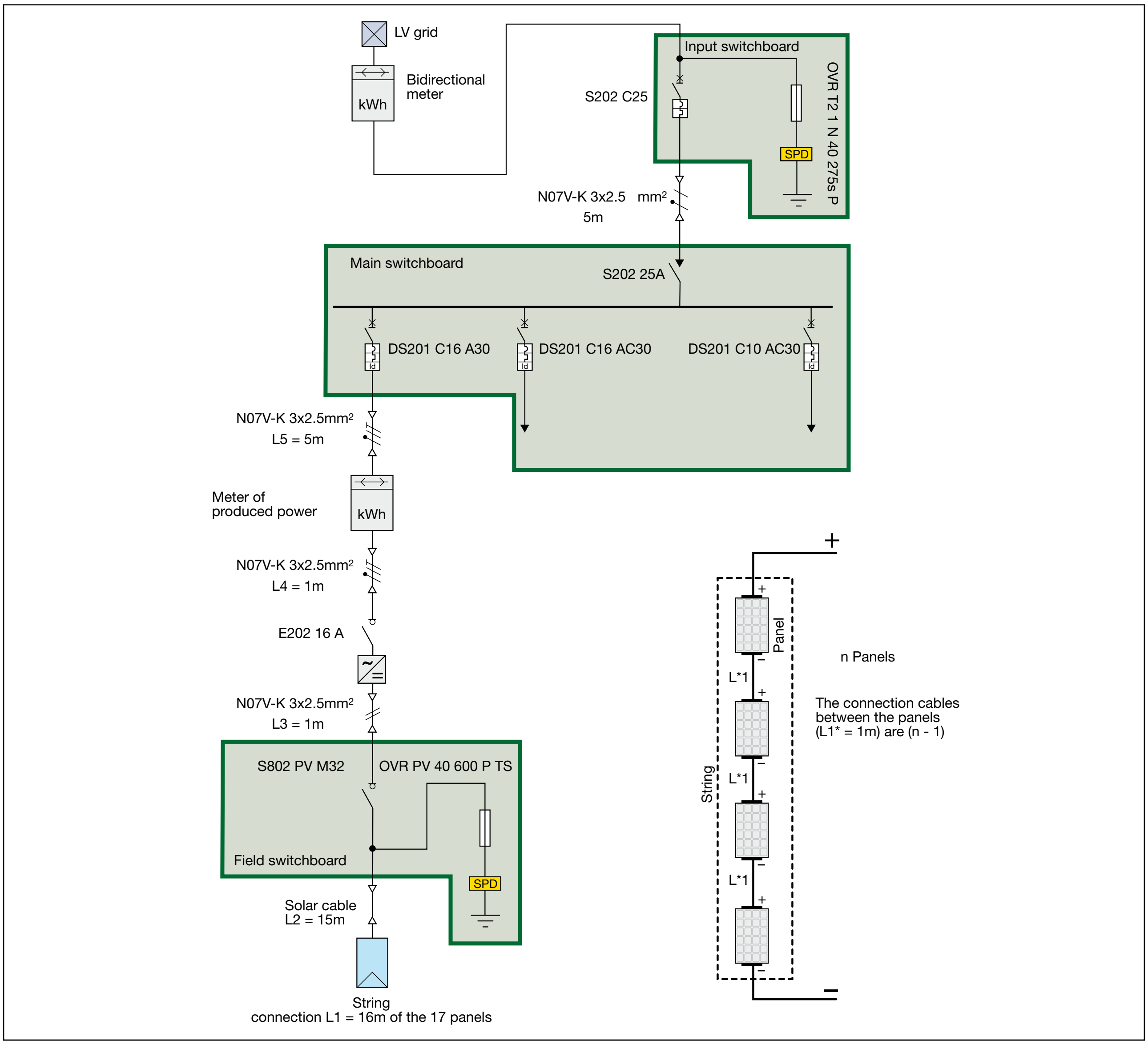
Two switch-disconnectors are installed immediately upstream and downstream the inverter, S802 PV-M32 upstream and E202 I_n=16A downstream respectively, so that the possibility of carrying out the necessary maintenance operations on the inverter itself is guaranteed.

The protection against overvoltages is carried out on the DC side by installing inside the field switchboard a surge protective device type OVR PV 40 600 P TS upstream the switch-disconnector for the simultaneous protection of both inverter and panels; on the AC side instead, an OVR T2 1N 40 275s P is mounted inside the input switchboard.

The SPD type OVR PV on the DC side shall be protected by two 4A fuses 10.3 x 38 mm (or 16A fuses only if installed in IP65 enclosures) mounted on a disconnector fuse holder E 92/32 PV. The SPD type OVR T2 on the AC side shall be protected instead by a fuse 10.3 x 38 mm E9F 16A gG mounted on a fuse holder E 91hN/32.

The other switching and protection devices, that is the input thermomagnetic circuit-breaker S202 C25, the main switch-disconnector E202 In=25A and the two thermomagnetic residual current circuit-breakers DS 201 C10/16, were already installed in the pre-existing user plant and are maintained.

Figure C1



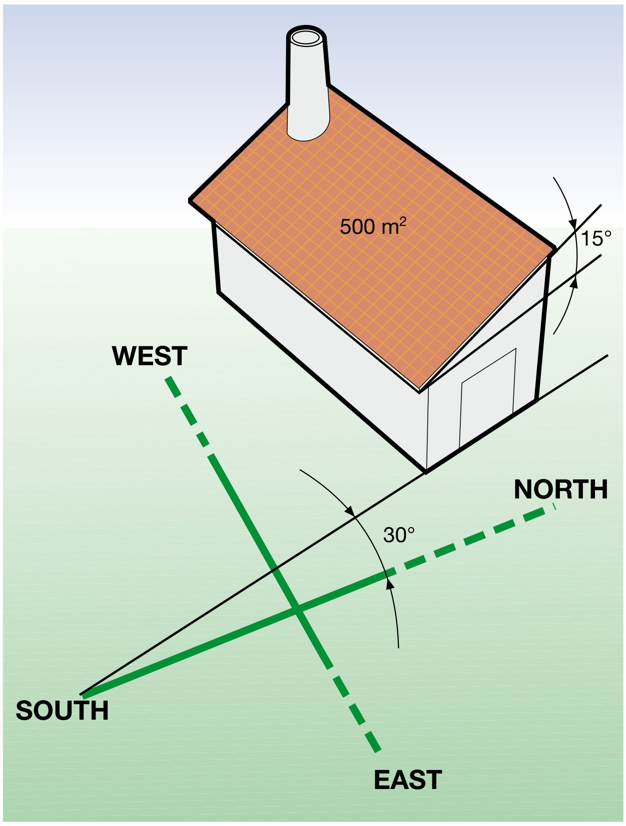
C.3 60kWp PV plant

We wish to carry out dimensioning of a PV plant to be connected to the LV public utility network based on net metering for an artisan manufacturing industry situated in the province of Milan. This industry is already connected to the LV public network (400V three-phase) with 60 kW contractual power and an average annual consumption of about 70 MWh.
The side of the roof (Figure C.2) in which the panels shall be partially integrated has a surface of 500 m^2, is sloped with a tilt angle β of 15° and is -30° (Azimut angle γ) south oriented.

6kWp is the power plant size based on net metering, so that the power demand of the user is satisfied as much as possible (as in the previous example).
From Table 2.1 we derive the value of the solar radiation on a horizontal surface in Milan, which is estimated 1307 kWh/m^2. With the given tilt angle and orientation, a correction factor of 1.07 is derived from Table 2.3. Assuming an efficiency of the plant components equal to 0.8, the expected power production per year results:

$$E_p = 60 \cdot 1307 \cdot 1.07 \cdot 0.8 \approx 67 MWh$$

Figure C2



Choice of panels

By using polycrystalline silicon panels, with 225 W power per unit, 267 panels are needed, number obtained from the relation 60000/225=267.
Taking into account the string voltage (which influences the input voltage of the inverter) and the total current of the strings in parallel (which influences above all the choice of the cables), we choose to group the panels in twelve strings of twenty-two panels each, for a total of $12 \cdot 22 = 264$ panels delivering a maximum total power of $264 \cdot 225 = 59.4$ kWp.
The main characteristics of the generic panel declared by the manufacturer are:

- Rated power P_{MPP} 225 W
- Efficiency 13.5 %
- Voltage V_{MPP} 28.80 V
- Current I_{MPP} 7.83 A
- No-load voltage 36.20 V
- Short-circuit current I_{sc} 8.50 A
- Max voltage 1000 V
- Temperature coefficient P_{MPP} -0.48 %/°C
- Temperature coefficient U -0.13 V/°C
- Dimensions 1680 x 990 x 50 mm
- Surface 1.66 m^2
- Insulation class II

Therefore, the total surface covered by the panels shall be equal to 1.66 x 264 = 438 m^2, which is smaller than the roof surface available for the installation.
By assuming -10°C and +70°C as minimum and maximum temperatures of the panels and by considering that the temperature relevant to the standard testing conditions is about 25°C, with the formula [2.13] the voltage variation of a PV module, in comparison with the standard conditions, can be obtained.

- Maximum no-load voltage $36.20 + 0.13 \cdot (25 + 10) = 40.75V$
- Minimum voltage MPP $28.80 + 0.13 \cdot (25 - 70) = 22.95V$
- Maximum voltage MPP $28.80 + 0.13 \cdot (25 + 10) = 33.35V$

For safety purpose and as precautionary measures, for the choice of the plant components the higher value between the maximum no-load voltage and the 120% of the no-load voltage of the panels (note 7, Chapter 3) is considered. In this specific case, the reference voltage results to be equal to $1.2 \cdot 36.20 = 43.44V$, since it is higher than 40.75V.
Electrical characteristics of the string:

- Voltage MPP 22 x 28.80 = 663.6 V
- Current MPP 7.83 A
- Maximum short-circuit current 1.25 x 8.50 = 10.63 A
- Maximum no-load voltage 22 x 43.44 = 955.68 V
- Minimum voltage MPP 22 x 22.95 = 504.90 V
- Maximum voltage MPP 22 x 33.35 = 733.70 V

Choice of the inverter

Two three-phase inverters are chosen each with 31kW input rated power; therefore six strings in parallel shall be connected to each inverter.

The three-phase inverters which have been chosen convert direct current to alternating current thanks to the PWM control and IGBT bridge. They have input and output filters for the suppression of the emission disturbances, both conducted as well as radiated, and an earth-isolation sensor for the PV panels. They are equipped with the Maximum Power Point Tracker (MPPT).

Technical characteristics:

- Input rated power 31000 W
- Operating voltage MPPT on the DC side 420-800 V
- Maximum voltage on the DC side 1000 V
- Maximum input current on the DC side 80 A
- Output rated power on the AC side 30000 W
- Rated voltage on the AC side 400 V three-phase
- Rated frequency 50 Hz
- Power factor 0.99
- Maximum efficiency 97.5%
- European efficiency 97%

To verify the correct connection string-inverter (see Chapter 3) first of all it is necessary to verify that the maximum no-load voltage at the ends of the string is lower than the maximum input voltage withstood by the inverter:

$$955.68 \text{ V} < 1000 \text{ V (OK)}$$

In addition, the minimum voltage MPP of the string shall not be lower than the minimum voltage of the inverter MPPT:

$$504.90 \text{ V} > 420 \text{ V (OK)}$$

whereas the maximum voltage MPP of the string shall not be higher than the maximum voltage of the inverter MPPT:

$$733.70 \text{ V} < 800 \text{ V (OK)}$$

Finally, the maximum total short-circuit current of the six strings connected in parallel and relevant to each inverter shall not exceed the maximum short-circuit current which the inverter can withstand on the input:

$$6 \times 10.63 = 63.75 \text{ A} < 80 \text{ A (OK)}$$

Choice of cables

The panels are connected in series using the cable L1* and each deriving string is connected to the field switchboard inside the shed and upstream the inverter using solar cables of length L2 in two cable trunkings each containing 6 circuits in bunches.

The characteristics of the solar panels are:

- cross-sectional area 4 mm^2
- rated voltage Uo/U 600/1000 VAC – 1500 VDC
- operating temperature -40 +90 °C
- current carrying capacity in free air at 60°C 55 A
- correction factor of the carrying capacity at 70°C 0.91
- maximum temperature of the cable under overload conditions 120 °C

The current carrying capacity I_z of the solar cables bunched in conduit at the operating temperature of 70°C results to be equal to (see Chapter 3):

$$I_z = 0.57 \cdot 0.9 \cdot 0.91 \cdot I_0 = 0.57 \cdot 0.9 \cdot 0.91 \; . \; 55 \approx 26\text{A}$$

where 0.9 represents the correction factor for installation of the solar cables in conduit or in cable trunking, whereas 0.57 is the correction factor for 6 circuits in bunches.

The carrying capacity is higher than the maximum short-circuit current of the string:

$$I_z > 1.25 \cdot I_{sc} = 10.63\text{A}$$

The frames of the panels and the supporting structure of each string are earthed through a cable N07V-K, yellow-green with 4 mm^2 cross-section. With reference to the electric diagram of Figure C.2, the connection of the field switchboard to the inverter is carried out using two single-core cables N1VV-K (0.6/1kV sheathed cables) with 16 mm^2 cross-section and length L3=1m in conduit, with current carrying capacity of 76A, a value higher than the maximum total short-circuit current of the six strings connected in parallel:

$$I_z > 6 \cdot 1.25 \cdot I_{sc} = 63.75\text{A}$$

The connection of the inverter to the paralleling switchboard of the inverters is carried out using three single-core cables N1VV-K of 16 mm^2 cross-section and length L4=1m in conduit with current carrying capacity of 69A, which is higher than the output rated current of the three-phase inverter:

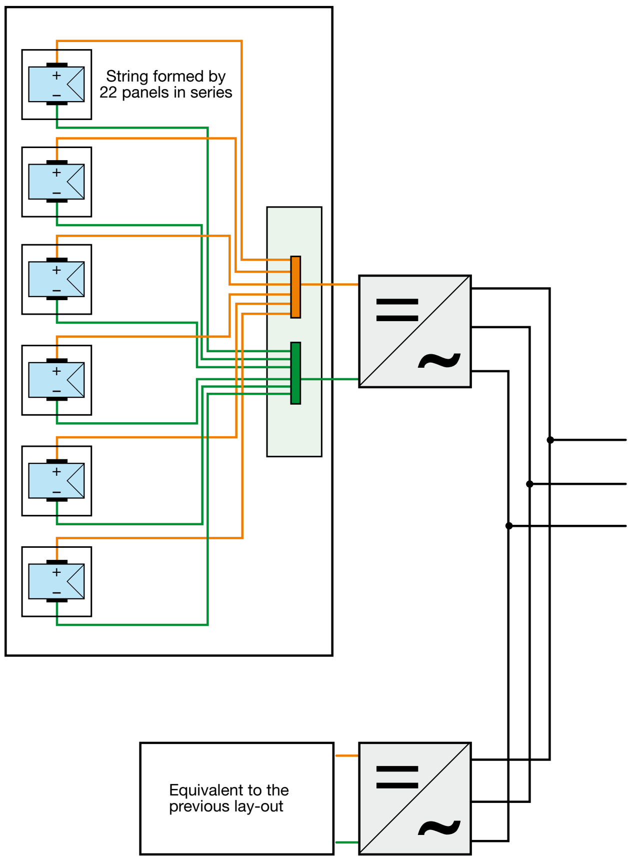
$$I_z > \frac{P_n}{\sqrt{3} \cdot V_n \cdot \cos\varphi_n} = \frac{30000}{\sqrt{3} \cdot 400 \cdot 0.99} = 43.7\text{A}$$

The connections between the inverter paralleling switchboard and LV/lv galvanic isolation transformer (length L5=1m), between the transformer and the meter of the power produced (length L6=2m), between the meter and the interface device (length L7=2m) and between the interface device and the main switchboard of the industry (length L8=5m) are carried out using three single-core cables N1VV-K with 35 mm² cross-sectional area in conduit, with current carrying capacity of 110A, which is higher than the output rated current of the PV plant:

$$I_z > \frac{P_n}{\sqrt{3} \cdot V_n \cdot \cos\varphi_n} = \frac{60000}{\sqrt{3} \cdot 400 \cdot 0.99} = 87.5A$$

The protective conductor PE is realized using a yellow-green single-core cable N07V-K and16 mm² cross-section.

Figure C3



LV/lv isolation transformer

As shown in the clause 4.2, for plants with total generating power higher than 20kW and with inverters without metal separation between the DC and the AC parts it is necessary to insert a LV/lv isolation transformer at industrial frequency with rating power higher or equal to the power of the PV plant.

The characteristics of the three-phase transformer chosen are:

- rated power An 60 kVA
- primary voltage V1n 400V
- secondary voltage V2n 400V
- frequency 50/60Hz
- connection Dy11
- electrostatic screen between the primary and secondary windings
- degree of protection IP23
- insulation class F

Interface device

The interface device is mounted in a suitable panel board and it consists of a three-pole contactor A63 having a rated service current Ie=115A in AC1 at 40°C. To the contactor an interface relay is associated having the protections 27, 59 and 81 and the settings shown in Table 4.1.

Verification of the voltage drop

Here is the calculation of the voltage drop on the DC side of the inverter to verify that it does not exceed 2% (see Chapter 3).

Length of the cables with 4 mm² cross-section, DC side:

- connection between the string panels (L1*): (22-1) x 1 m = 21 m
- connection between string and switchboard (L2): 20 m

Length of the cables with 16 mm² cross-section, DC side:

- connection between switchboard and inverter (L3): 1 m

Total length of the cables on the DC side: 21 + 20 + 1 = 42 m

The average percentage voltage drop up to the field switchboard, when the panels constituting the string deliver the maximum power P_{max} = 22 x 225 = 4950W, with string voltage of 663.6V results to be[3]:

$$\Delta U\% = \frac{P_{max} \cdot (\rho_1 \cdot L_1 \cdot \rho_2 \cdot 2 \cdot L_2)}{s \cdot U^2} \cdot 100 = \hookleftarrow$$

$$\rightarrow \frac{4950 \cdot (0.021 \cdot 21 + 0.018 \cdot 2 \cdot 20)}{4 \cdot 663.6^2} \cdot 100 = 0.326\%$$

The average percentage voltage drop between the field switchboard and the inverter with P_{max} = 6 x 4950 = 29700W results to be:

$$\Delta U\% = \frac{P_{max} \cdot (\rho_2 \cdot 2 \cdot L_3)}{s \cdot U^2} \cdot 100 = \frac{29700 \cdot (0.018 \cdot 2 \cdot 1)}{16 \cdot 663.6^2} \cdot 100 = 0.015\%$$

Therefore the total voltage drop results equal to 0.34%.

Switching and protection devices

PV field switchboards

The current carrying capacity of the string cables is higher than the maximum current which can pass through them under standard operating conditions; therefore it is not necessary to protect them against overload.

Under short-circuit conditions the maximum current in the string cable affected by the fault results (see clause 6.1.3):

$$I_{sc2} = (x - 1) \cdot 1.25 \cdot I_{sc} = (6 - 1) \cdot 1.25 \cdot 8.50 \approx 53A$$

this value is higher than the cable carrying capacity: as a consequence, it is necessary to protect the cable against short-circuit by means of a protective device, which under fault conditions shall let through the power that the cable can withstand. Such device shall also protect the string against the reverse current since x=y=6>3 (see clause 6.1.2).

With reference to the diagram of Figure C.2, the six protection devices in the field switchboard shall have a rated current (see relation [6.3]) equal to:

$$1.25 \cdot I_{sc} \leq I_n \leq 2 \cdot I_{sc} \rightarrow 1.25 \cdot 8.5 \leq I_n \leq 2 \cdot 8.5 \rightarrow I_n=16A$$

Therefore a S804 PV-S16 is chosen, which has a rated voltage U_e=1200VDC and a breaking capacity I_{cu}=5kA > I_{sc2}.

The connection cables between field switchboard and inverter does not need to be protected against overcurrents since their current carrying capacity is higher than the maximum current which may interest them. Therefore a main switch-disconnector circuit-breaker T1D PV 160[4] shall be mounted inside the field switchboard to disconnect the inverter on the DC side.

In the field switchboards also some surge suppressors (SPD) shall be installed for the protection of the inverter on the DC side and of the PV panels: the choice is SPD type OVR PV 40 1000 P TS protected by 4A fuses gR (or 16A fuses only if installed in IP65 enclosures) mounted on fuse holders type E92/32 PV.

Paralleling switchboard

With reference to the plant diagram of Figure C.4, on each of the two lines coming from the three-phase inverters a generator themomagnetic circuit-breaker S203 P - C63[5] (having a breaking capacity equal to the prospective three-phase short-circuit current given by the network) coupled with a residual current device type F204-63/0.03 is installed (I_{dn}=30mA type B, since the installed inverters are not equipped with an internal isolation transformer). A switch disconnector T1D 160 3p for the switchboard is also installed.

Main switchboard

In the main switchboard of the industry, housing the protective devices for the distribution lines of the user's plant, a circuit-breaker T2N 160 PR221DS-LI In=100A combined with a residual current device RC222 (to guarantee time-current discrimination with the F204 B residual current device) is also installed with the purpose of pro-

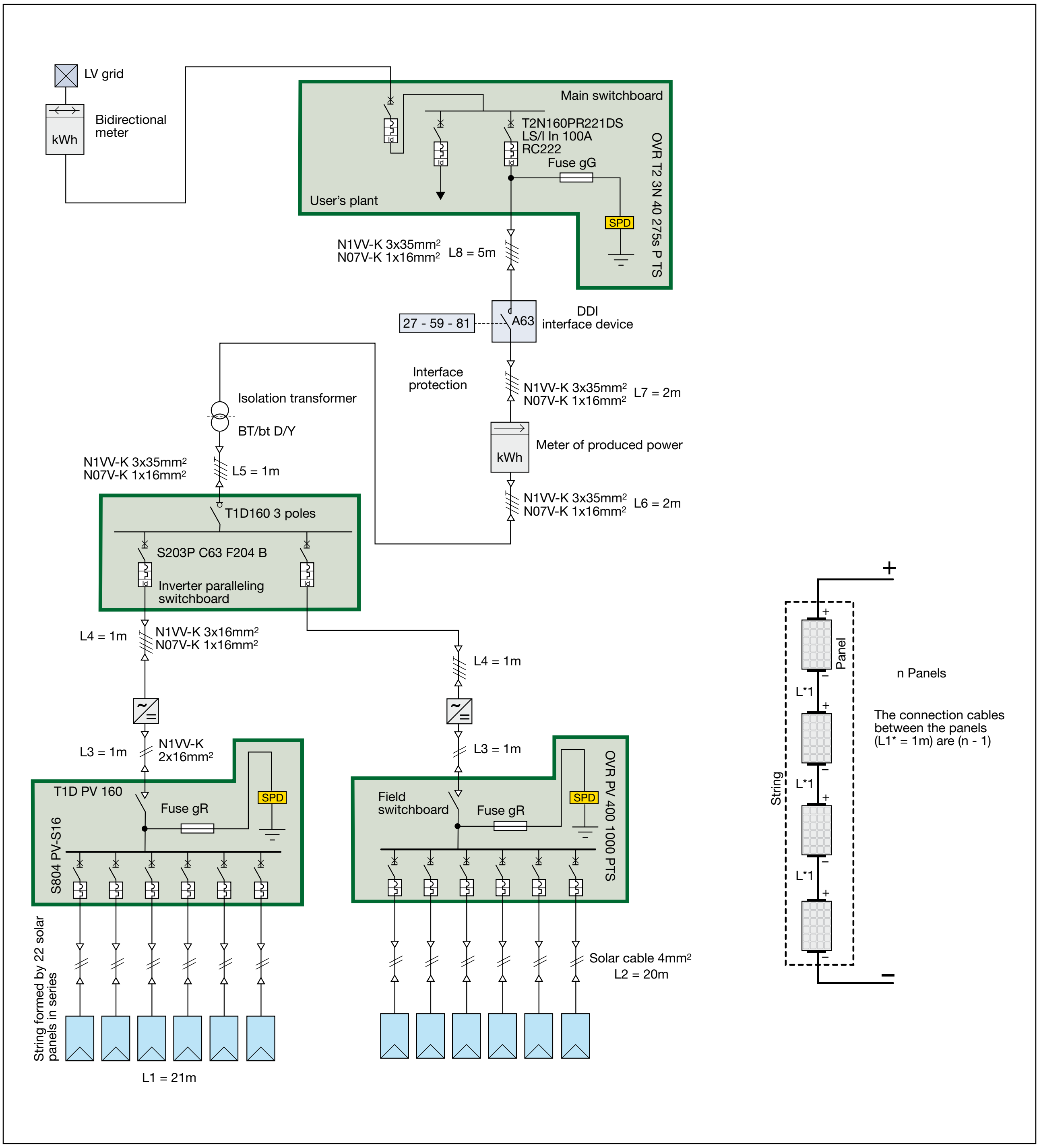
[3] *For the connection cables string-switchboard and switchboard-inverter the resistivity of copper at 30°C* $\rho_2 = 0.018 \frac{\Omega \cdot mm^2}{m}$*, is considered, whereas for the connection cables between panels an ambient temperature of 70°C is considered; therefore* $\rho_1 = 0.018 \cdot [1+0.004 \cdot (70 - 30)] = 0.021 \frac{\Omega \cdot mm^2}{m}$.

[4] *Two poles in series are connected with the positive polarity and two in series on the negative polarity since the PV system is isolated from earth.*

[5] *The neutral pole is not connected.*

tecting against overcurrents the contactor with interface function DDI, the switch-disconnector in the paralleling switchboard, the isolation transformer and the cables for the connection between the paralleling switchboard and the main switchboard. Instead, the RC222, coordinated with the earthing system, protects against indirect contacts with the exposed conductive parts positioned between the paralleling switchboard and the main switchboard, in particular that of the transformer.
For the protection against the input overcurrents of the plant on the network side, a surge suppressor type OVR T2 3N 40 275s P TS is installed, protected by 20A fuses E9F gG mounted on E93hN/32 fuse holders.

Figure C4



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1SDC007109G0201 - 04/2010