**Solar PV plant as Distributed Generation (DG)**

## 1.5 Types of photovoltaic plants

### 1.5.1 Off-grid plants

Off-grid plants are plants which are not connected to the grid and consist of PV modules 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 since they can replace motor generator sets whenever the electric network is not present or whenever it is not easy to reach. Besides, in an off-grid 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.

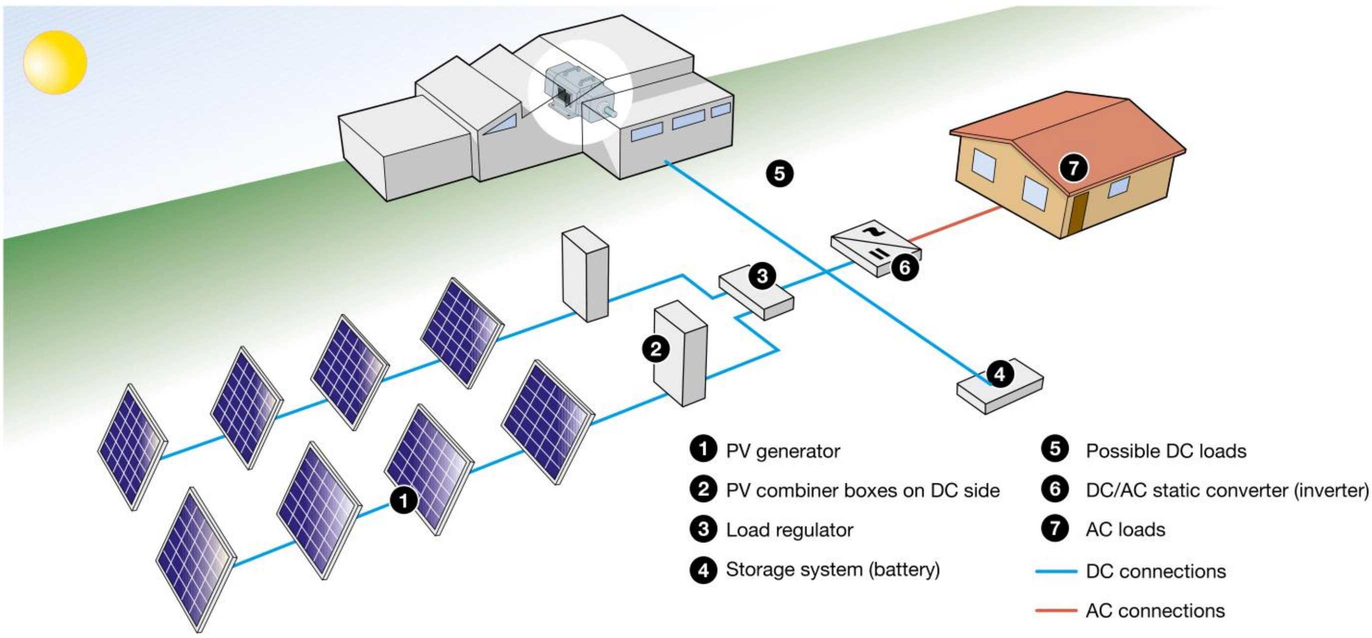
At present the most common applications are used to supply (Figure 1.20):

- 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 a principle diagram of a PV plant working off-grid.

*Figure 1.21*

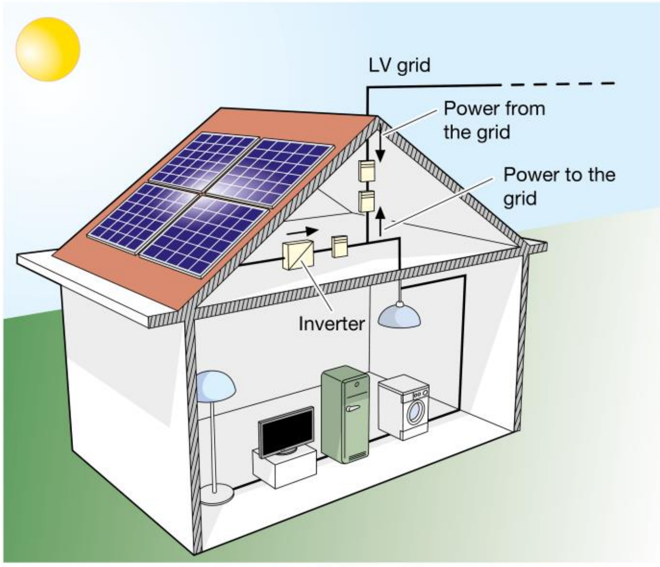


### 1.5.2 Grid-connected plants

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 do not need accumulator banks (Figure 1.22).

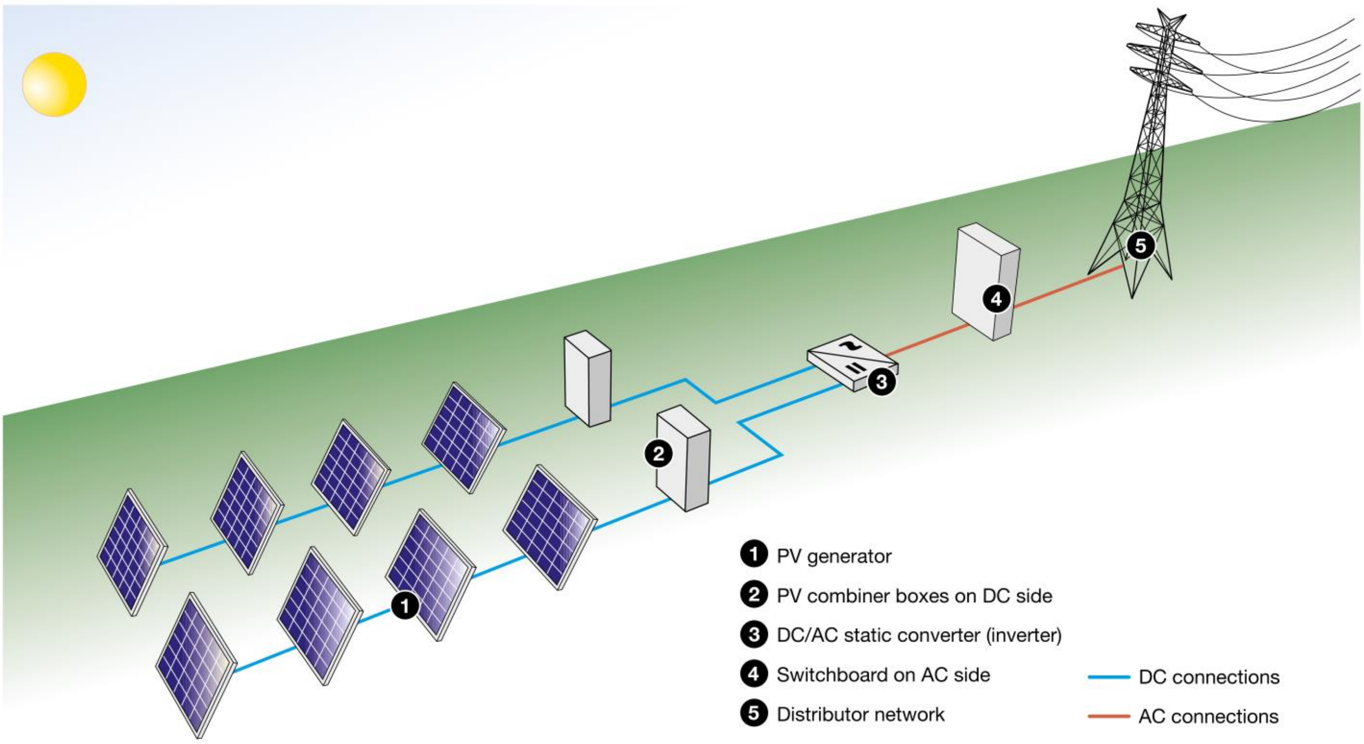
*Figure 1.22*

*Figure 1.23*




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



## 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. off-grid 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

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

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

where:

$\eta_{BOS}$ (*Balance Of System*) is the overall efficiency of all the components of the PV plant on the load side of the modules (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, the following is obtained:

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

**Example 2.1**

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

From the Table in the Std. UNI 10349, an annual mean radiation of 1276 kWh/m$^2$ is obtained. Assuming to be under the standard conditions of 1 kW/m$^2$, the expected annual mean production 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/m$^2$) | Site | Annual solar radiation (kWh/m$^2$) | Site | Annual solar radiation (kWh/m$^2$) | Site | Annual solar radiation (kWh/m$^2$) |
|---|---|---|---|---|---|---|---|
| **Agrigento** | 1923 | **Caltanisetta** | 1831 | **Lecce** | 1639 | **Pordenone** | 1291 |
| **Alessandria** | 1275 | **Cuneo** | 1210 | **Livorno** | 1511 | **Prato** | 1350 |
| **Ancona** | 1471 | **Como** | 1252 | **Latina** | 1673 | **Parma** | 1470 |
| **Aosta** | 1274 | **Cremona** | 1347 | **Lucca** | 1415 | **Pistoia** | 1308 |
| **Ascoli Piceno** | 1471 | **Cosenza** | 1852 | **Macerata** | 1499 | **Pesaro-Urbino** | 1411 |
| **L'Aquila** | 1381 | **Catania** | 1829 | **Messina** | 1730 | **Pavia** | 1316 |
| **Arezzo** | 1329 | **Catanzaro** | 1663 | **Milan** | 1307 | **Potenza** | 1545 |
| **Asti** | 1300 | **Enna** | 1850 | **Mantova** | 1316 | **Ravenna** | 1411 |
| **Avellino** | 1559 | **Ferrara** | 1368 | **Modena** | 1405 | **Reggio Calabria** | 1751 |
| **Bari** | 1734 | **Foggia** | 1630 | **Massa Carrara** | 1436 | **Reggio Emilia** | 1427 |
| **Bergamo** | 1275 | **Florence** | 1475 | **Matera** | 1584 | **Ragusa** | 1833 |
| **Belluno** | 1272 | **Forlì** | 1489 | **Naples** | 1645 | **Rieti** | 1366 |

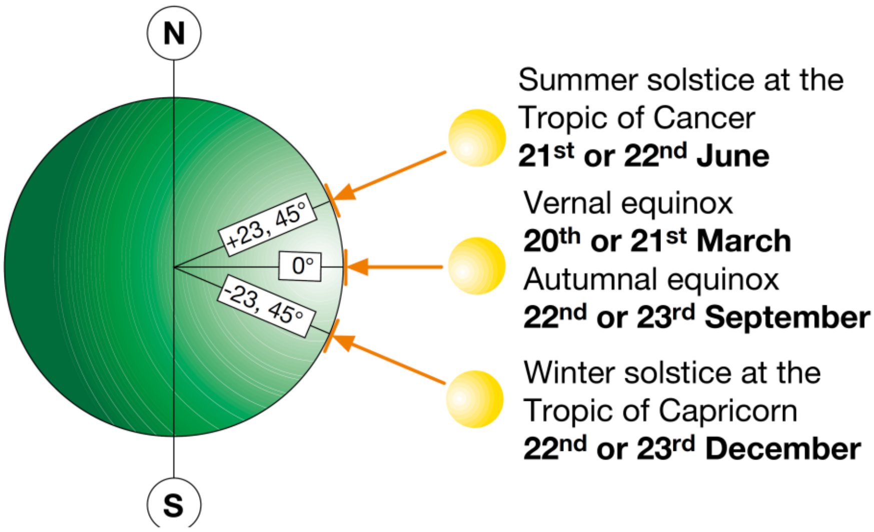
*Table 2.2*

| 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 |

## 2.6 Inclination and orientation of the modules

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 the 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*




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;

$\delta$ is the angle of solar declination [23.45°]

Finding the complementary angle of $\alpha$ (90°-$\alpha$), it is possible to obtain the tilt angle $\beta$ of the modules 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].

*Figure 2.9*

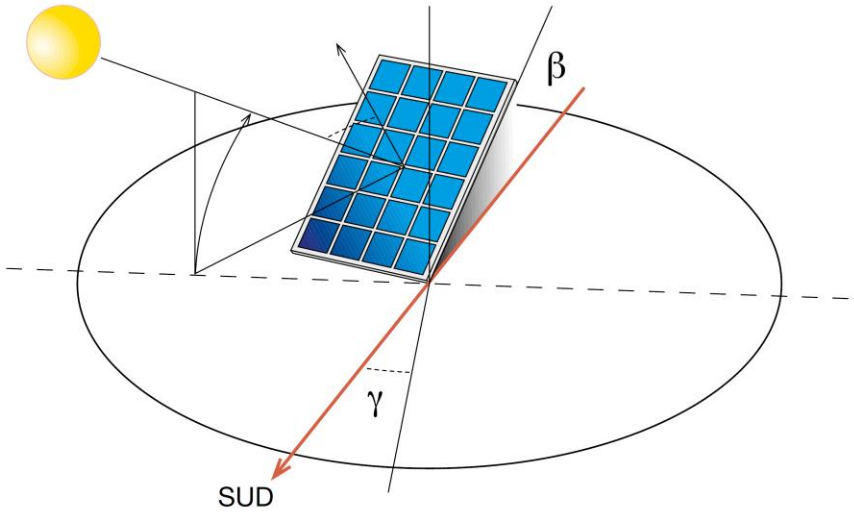
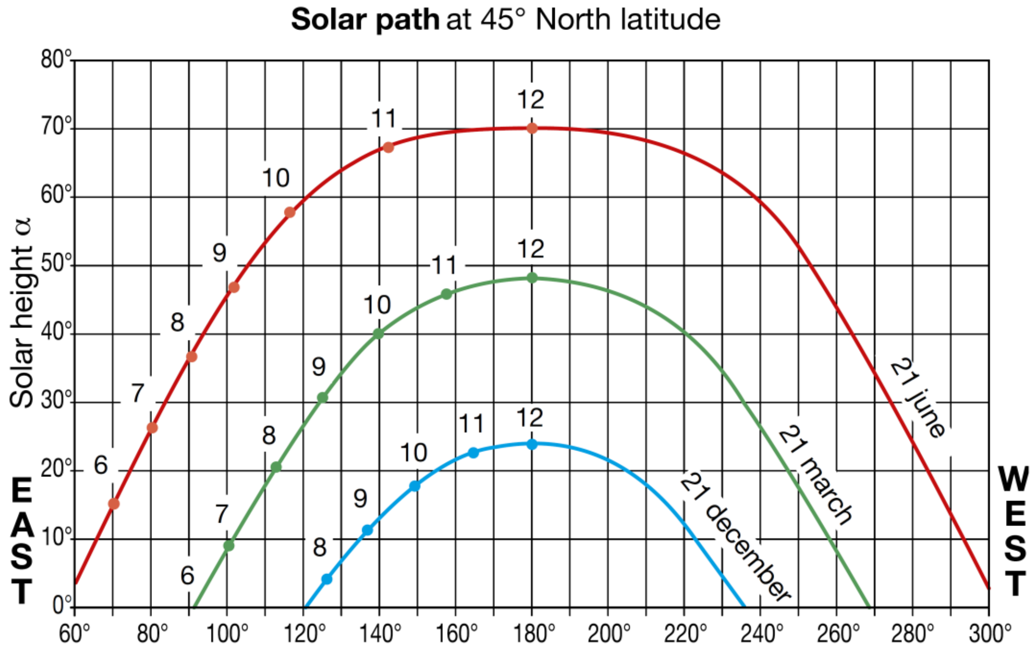



*Figure 2.8*




The fixed modules should be oriented as much as possible to south in the northern hemisphere[4] to get a better insolation of the panel surface at noon local hour and a better global daily insolation of the modules.
The orientation of the modules 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).

Positive values of the Azimuth angles show an orientation to west, whereas negative values show an orientation to east (IEC 61194).

**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 the horizontal plan and obtained in the previous example, the expected production capability becomes:

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

*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 |

## 3.2 PV plant layout

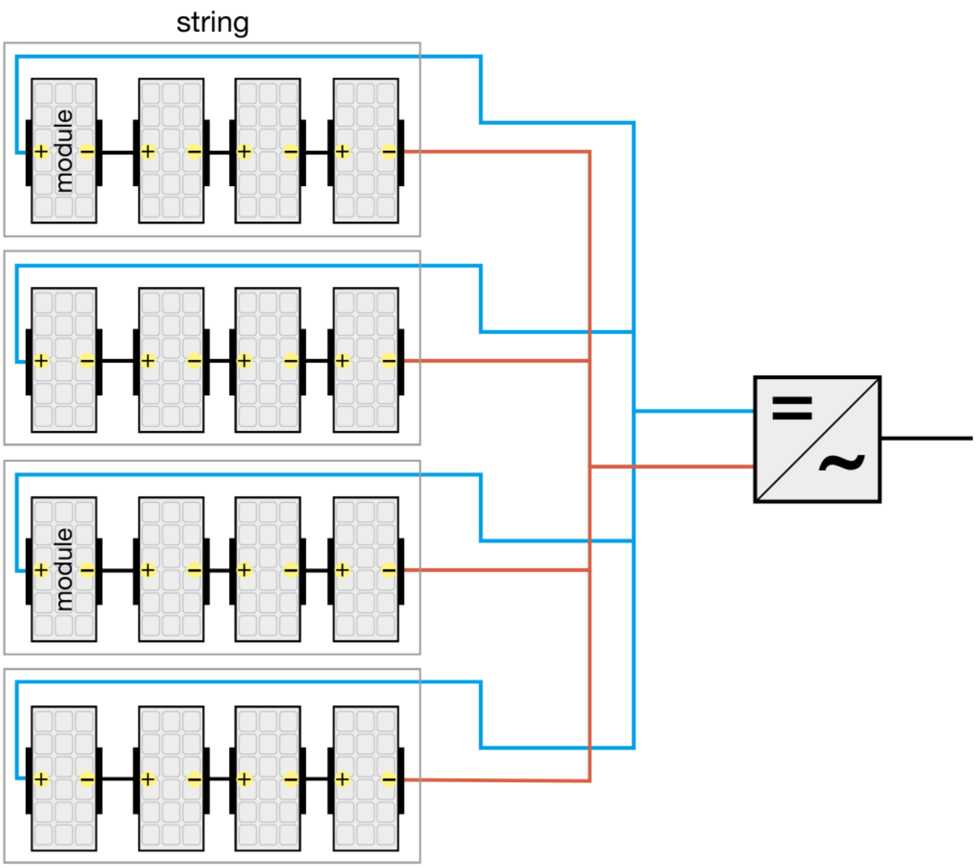
The connection of the strings forming the solar field of the PV plant can chiefly occur by providing:

- one single inverter for the whole plant (single-inverter or central inverter) (Figure 3.4)
- one inverter for each string (Figure 3.5)
- one inverter for more strings (multi-inverter plant) (Fig-

### 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 maintenance costs. However, a failure of the single inverter causes the stoppage of the production of the whole plant.
Besides, this solution is not very suitable as the size of the PV plant (and with it also the peak power) increases, since this raises 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 , 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 in the electrical performances of the plant in comparison with the other layouts.

*Figure 3.4*



### 3.2.2 Plant with one inverter for each string

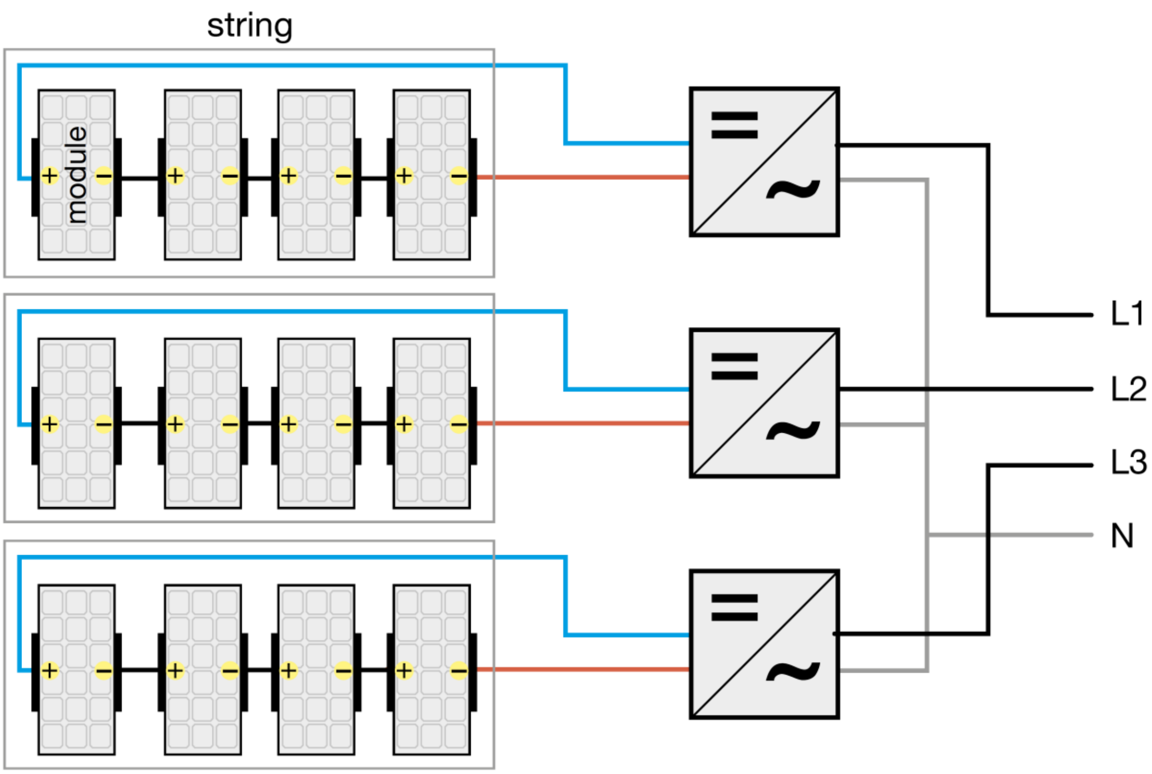
In a medium-size plant, each string may be directly connected to its own inverter and thus it operates according to its own maximum power point.

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 in 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*



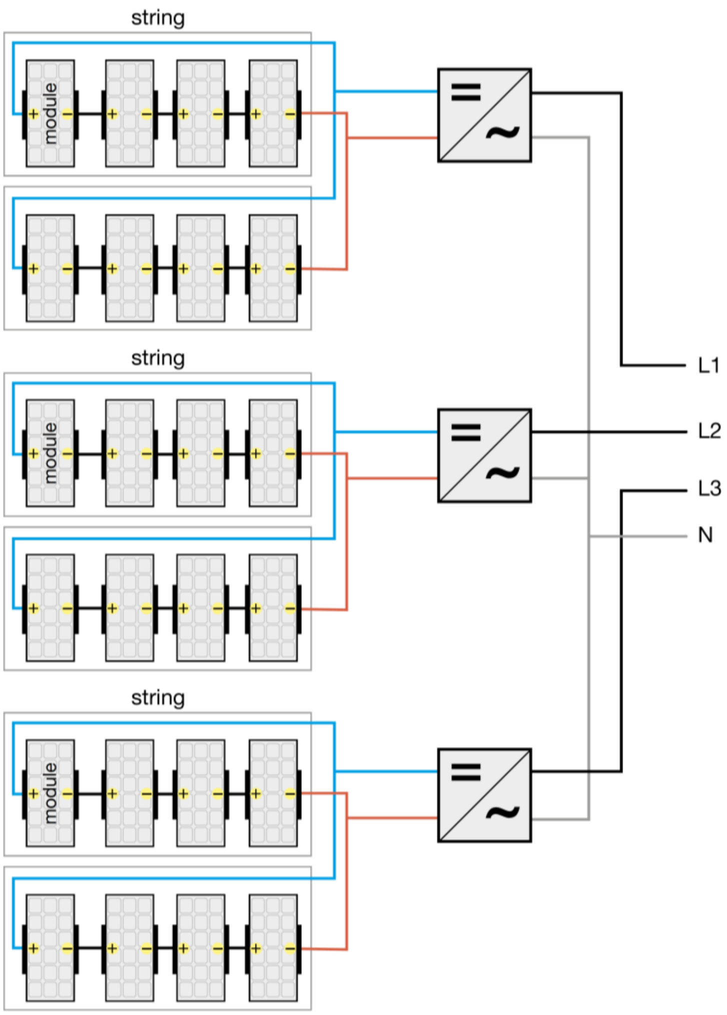
### 3.2.3 Multi-inverter plant

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, the benefit of the reduction in the problems due to shading, different exposition of the strings and also to the use of modules different from one another remains, provided that the 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 of single-inverter), but of the relevant subfield only.



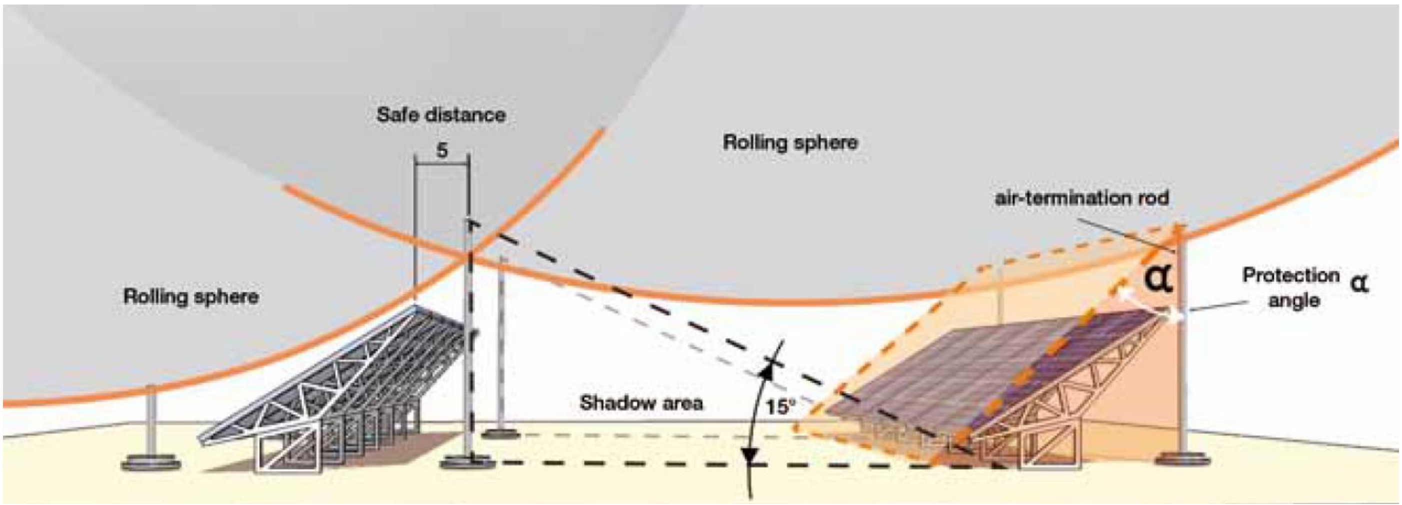
**PV plant on ground (rural and remote area)**

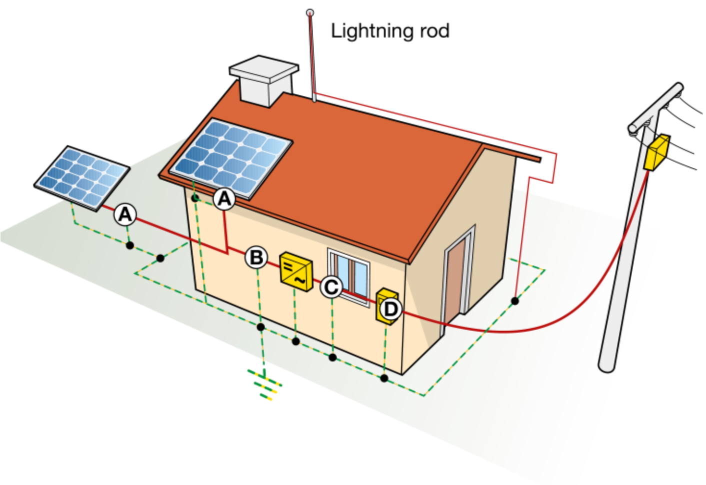
They are typically supplied by a MV three-phase line, which is unshielded and may be many kilometers long. Such line arrives at a MV/LV transformer, on the load side of which there are the inverters, whose withstand voltage is generally equal to 4 kV; the PE conductor, instead, is usually distributed in the same cable of the phase conductors.

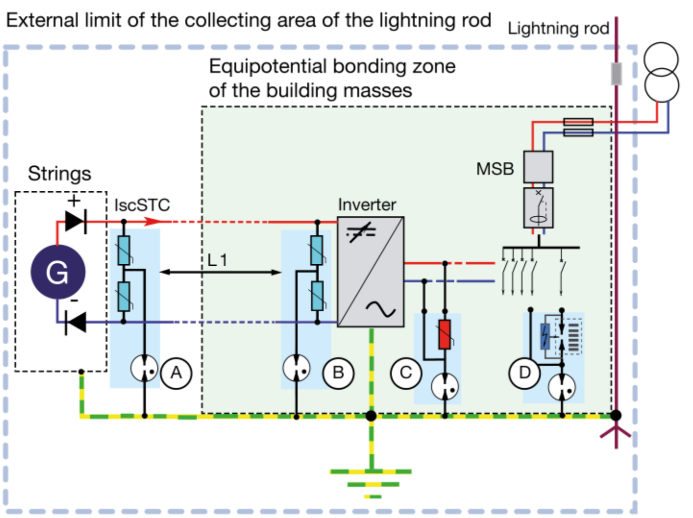
Attention shall be paid since a telecom line often enters the PV plant, for the control and monitoring of the plant itself.

First of all, analogously to what is done for the buildings, the collection area is analyzed to determine whether the structure is exposed.

Also when the structure is not exposed, the DC lines must be protected following the same criteria considered for the structures on the roof.



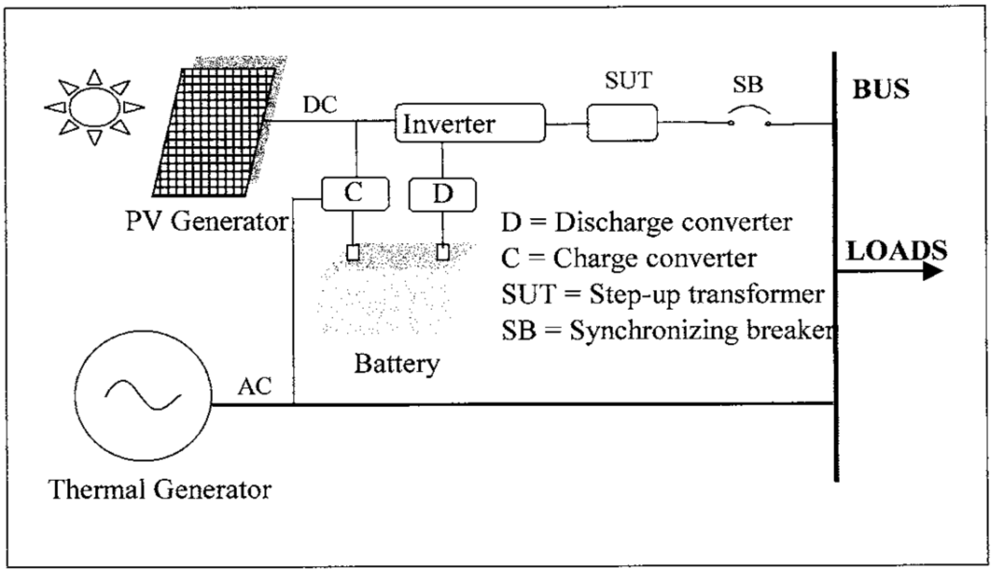
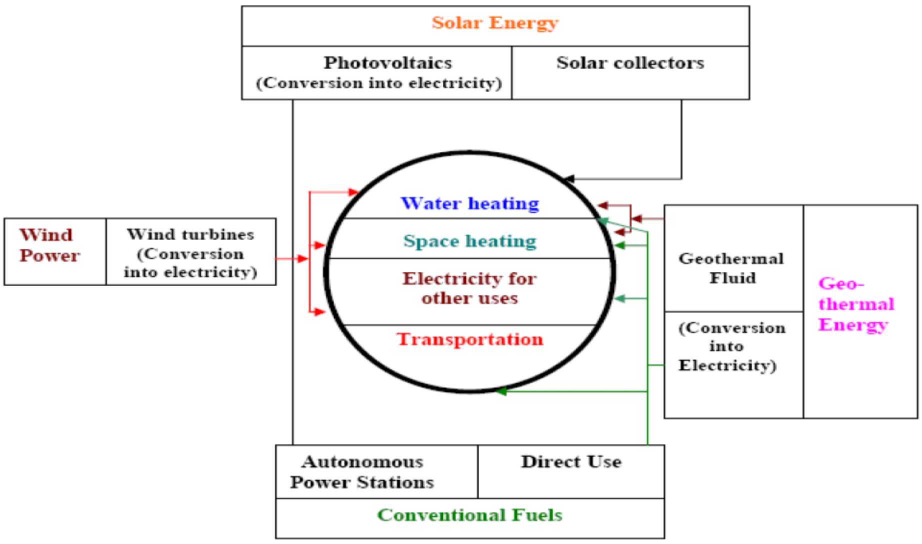



**FIGURE 13-1**
Electrical schematic of the grid-connected photovoltaic system.

**Appendix (1) Energy sources their final uses**

Different sources of energy, which can be used for different final uses. Those sources are: wind power, solar energy, geothermal energy, the existing electricity production system and the conventional fuels with direct use. The main categories of final uses are: transportation, space heating, water heating and electricity for other uses.



SOLAR RESOURCE MAP

# PHOTOVOLTAIC POWER POTENTIAL

# IRAQ

### DESCRIPTION

This solar resource map provides a summary of estimated solar photovoltaic (PV) power generation potential. It represents the average daily/yearly totals of electricity production from a 1 kW-peak grid-connected solar PV power plant, calculated for a period of 20 recent years (1999-2018).

The PV system configuration consists of ground-based, free-standing structures with crystalline-silicon PV modules mounted at a fixed position, with optimum tilt to maximize yearly energy yield. The optimum tilt ranges from 26° to 35° towards the equator. Use of high efficiency inverters is assumed. The solar electricity calculation is based on high-resolution solar resource data and PV modeling software provided by Solargis. The calculation takes into account solar radiation, air temperature, and terrain, to simulate the energy conversion and losses in the PV modules and other components of a PV power plant. In the simulation, losses due to dirt and soiling was estimated to be 3.5%. The cumulative effect of other conversion losses (inter-row shading, mismatch, inverters, cables, transformer, etc.) is assumed to be 7.5%. The power plant availability is considered to be 100%.

The underlying solar resource database is calculated from atmospheric and satellite data with a 30-minute time step, and a spatial resolution of 1000 m.

### ABOUT

The World Bank Group has published this solar resource map using data from the **Global Solar Atlas** (GSA), to support the scale-up of solar power in our client countries. This work is funded by the Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund administered by The World Bank and supported by 18 donor partners. It is part of a global ESMAP initiative on Renewable Energy Resource Mapping that covers biomass, hydropower, solar and wind. This map has been prepared by Solargis, under contract to The World Bank, based on a solar resource database that Solargis owns and maintains.

To obtain additional maps and information, please visit:
http://globalsolaratlas.info



Map data sources:
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Source: Global Solar Atlas 2.0 • Solargis database version: 2.1 • Map issue date: 2019-10-17

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ESMAP

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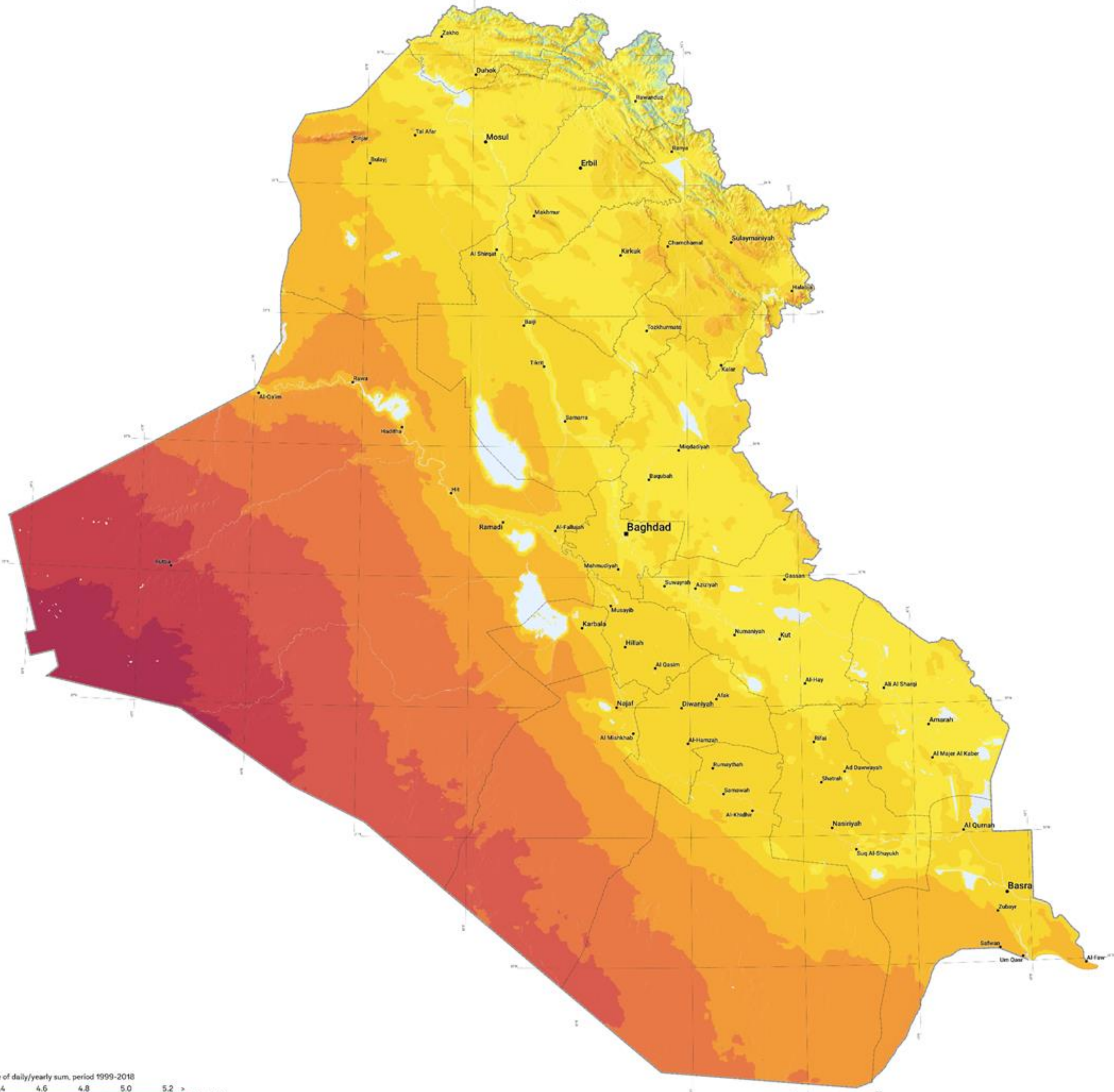


Long term average of daily/yearly sum, period 1999-2018

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Daily sum: | < 4.2 | 4.4 | 4.6 | 4.8 | 5.0 | 5.2 > | kWh/kWp |
| Yearly sum: | < 1534 | 1607 | 1680 | 1753 | 1826 | 1899 > | |

0 50 km

SOLAR RESOURCE MAP

# GLOBAL HORIZONTAL IRRADIATION

## IRAQ

### DESCRIPTION

This solar resource map provides a summary of the estimated solar energy available for power generation and other energy applications. It represents the average daily/yearly sum of global horizontal irradiation (GHI) covering a period of 20 recent years (1999-2018). The underlying solar resource database is calculated by the Solargis model from atmospheric and satellite data with 30 minute time step. The effects of terrain are considered at nominal spatial resolution of 250 m.

There is some uncertainty in the yearly GHI estimate as a result of limited potential for regional model validation due to a lack of high quality ground measurement data, which is estimated to vary regionally from approx. 5% to 7%.

GHI is the most important parameter for energy yield calculation and performance assessment of flat-plate photovoltaic (PV) technologies.

### ABOUT

The World Bank Group has published this solar resource map using data from the **Global Solar Atlas** (GSA), to support the scale-up of solar power in our client countries. This work is funded by the Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund administered by The World Bank and supported by 18 donor partners. It is part of a global ESMAP initiative on Renewable Energy Resource Mapping that covers biomass, hydropower, solar and wind. This map has been prepared by Solargis, under contract to The World Bank, based on a solar resource database that Solargis owns and maintains.

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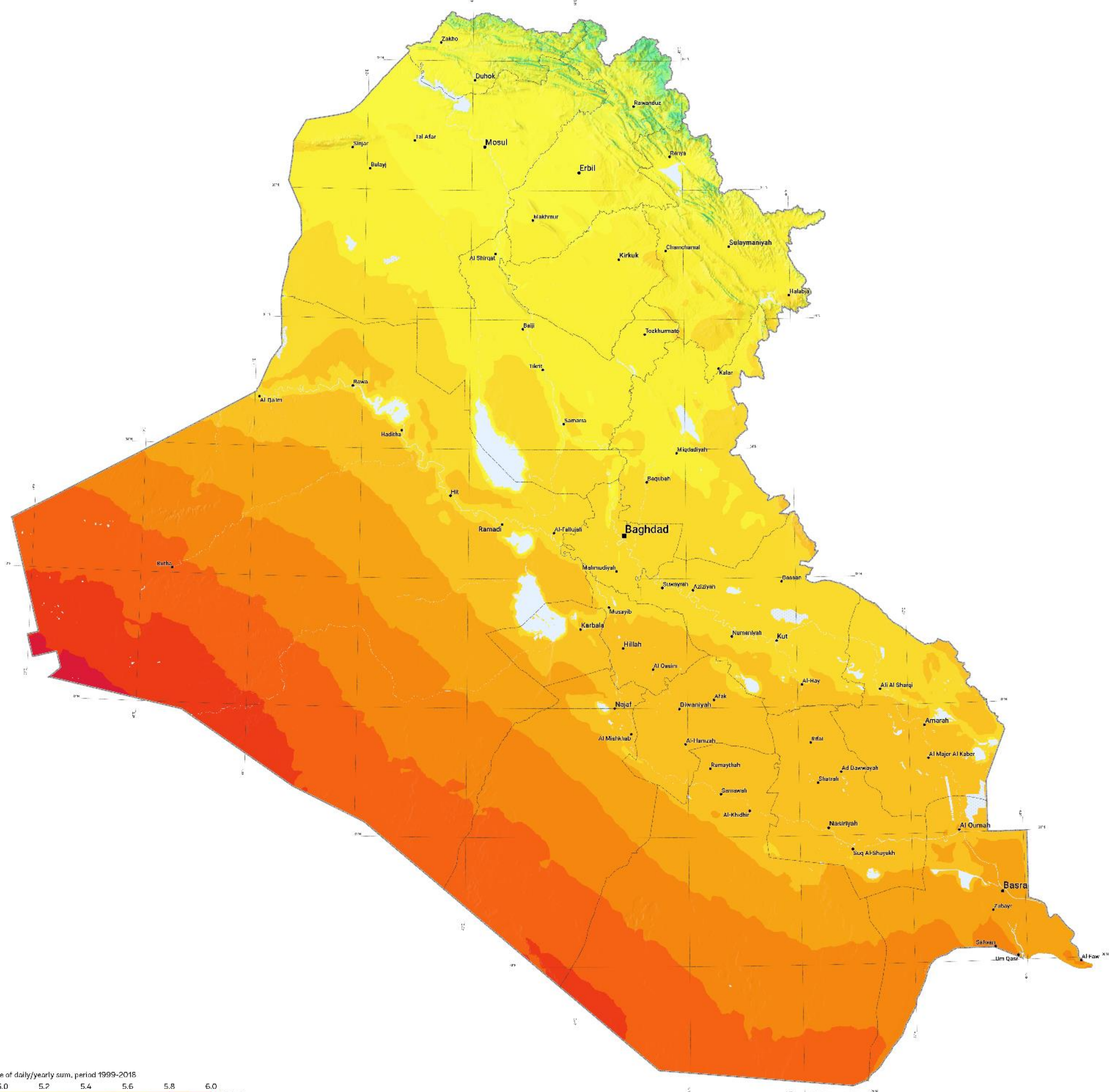


Long term average of daily/yearly sum, period 1999-2018

| Daily sum: | < 4.8 | 5.0 | 5.2 | 5.4 | 5.6 | 5.8 | 6.0 kWh/m² |
|---|---|---|---|---|---|---|---|
| Yearly sum: | < 1753 | 1826 | 1899 | 1972 | 2045 | 2118 | 2191 |

0 50 km

SOLAR RESOURCE MAP

# DIRECT NORMAL IRRADIATION

# IRAQ

**DESCRIPTION**

This solar resource map provides a summary of the estimated solar energy available for power generation and other energy applications. It represents the average daily/yearly sum of direct normal irradiation (DNI) covering a period of 20 recent years (1999-2018). The underlying solar resource database is calculated by the Solargis model from atmospheric and satellite data with 30-minute time step. The effects of terrain are considered at nominal spatial resolution of 250 m.

There is some uncertainty in the yearly DNI estimate as a result of limited potential for regional model validation due to a lack of high quality ground measurement data, which is estimated to vary regionally from approx. 8% to 15%.

DNI is the most important parameter for energy yield calculation and performance assessment of concentrating solar power (CSP) and concentrator solar photovoltaic (CPV) technologies. DNI is also important for the calculation of global irradiation received by tilted or sun-tracking photovoltaic modules.

**ABOUT**

The World Bank Group has published this solar resource map using data from the **Global Solar Atlas** (GSA), to support the scale-up of solar power in our client countries. This work is funded by the Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund administered by The World Bank and supported by 18 donor partners. It is part of a global ESMAP initiative on Renewable Energy Resource Mapping that covers biomass, hydropower, solar and wind. This map has been prepared by Solargis, under contract to The World Bank, based on a solar resource database that Solargis owns and maintains.

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