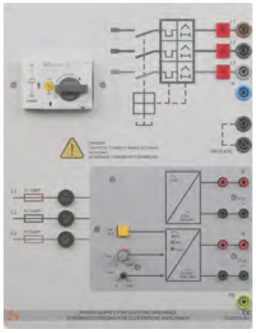
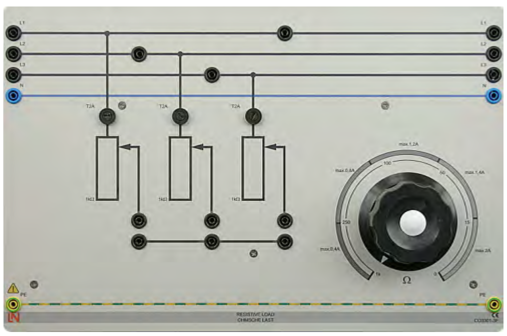
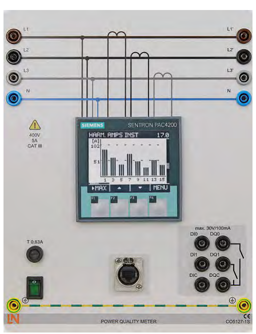
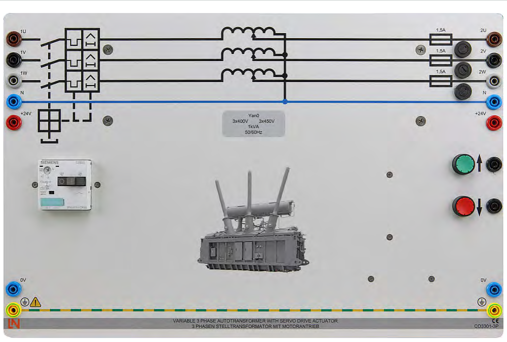
Modern Professional Photovoltaics Systems in Grid-coupled Operation

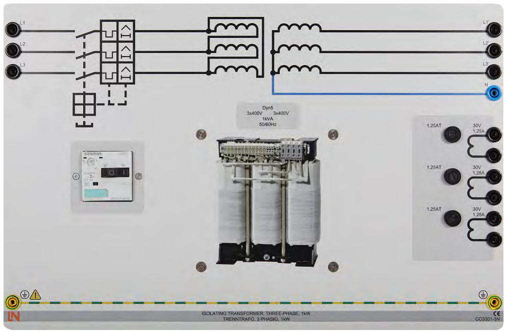
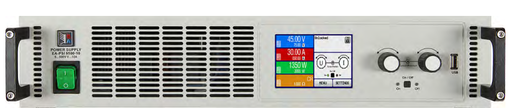
Experiment Objectives

This training system permits a realistic simulation of the sun's path. Thus, it is also possible to perform the experiments in the laboratory without real sunlight using the emulators. The design of photovoltaic systems connected to the grid is realistically conveyed. In order to stabilize the power grid, techniques such as de-rating the inverter power and a variable local network power transformer are employed. Transfer of knowledge, know-how and PC supported evaluation of measurement data are made possible by the multimedia course with the help of the SCADA PowerLab software.

- Introduction to solar radiation.
- Introduction to the fundamentals of photovoltaics.
- Planning and dimensioning grid-coupled photovoltaic systems.
  - MPP tracking of the inverter's operating point at different shadings of the solar generator.
  - The characteristic of the inverter's conversion efficiency.
  - The California Energy Commission (CEC) and European efficiencies.
  - The inverter's power losses.
  - Power reduction effects on MPP regulation and inverter's behavior.
  - The behavior of the reactive power (Q) at different settings of the displacement factor.
  - The characteristic of the PV inverter's displacement factor cos φ in dependence on relative power.
  - The photovoltaic facility's behavior in the event of a grid failure.
  - Record the photovoltaic facility's solar yield data obtained over a period of one week.
  - Visualize the daily and weekly yields.
- Commissioning photovoltaic systems.
- Local network voltage regulation.
  - Examine the voltage of the local network transformer at different loads.
  - The behavior of the voltage at the local network transformer in case of automatic adjustment, under load, and during feed-in.
  - The influence of derating on the voltage in the local network.
  - The influence of a combination of derating and variable local network transformer on voltage.

Equipment

Equipment	Part Number	Description
	**CO3212-5U**	Universal power supply for electric machines Manual
	**CO3301-3F**	Variable Ohmic Load, three-phase, 1 kW
	**CO5127-1S**	Power Quality Meter Manual
	**CO3301-3P**	Variable 3-phase Transformer with Motor Drive

	**CO3301-3N**	Isolating Transformer, 3-phase, 1 kW
	**CO3208-1N**	3-phase Industrial Photovoltaic Converter Manual
	**CO3208-1P**	Solar Panel Emulator, 1.5 kW, 500 V Operating instructions. (English version from page 93)

CO3208-1N*

This transformerless PV-inverter is designed specially for three-phase power supply. The device has a graphical display for visualizing energy yield values, current power and operating parameters of the photovoltaic system.

Technical data - CO3208-1N (* CO3208-1N7) 3-phase industrial photovoltaic inverter

- DC-PV Input
    - Voltage: 250 - 1000 V
    - MPP voltage: 300 - 800 V
    - Maximum current: 11A
- AC Output
    - Voltage: 3 x 230, 50/60 Hz
    - Power factor: 0.8 - 1
    - Max. Current: 7A
    - Maximum Power : 3200 W

- Maximum efficiency: 98.6%
- European efficiency: 97.9%
- CEC efficiency: 98.3%
- MPP-efficiency: >99.8% (static), > 99% (dynamic)
- De-rating/ power limiting occurs automatically when:
    - input power > max. recommended PV power
    - cooling is inadequate
    - input current is too high
    - grid current is too high
    - internal or external de-rating is performed
    - grid frequency is too high (according to country setting)
    - limiting signal is received via an external interface
    - output power is limited (set at the inverter)
- Communication interfaces:
    - 1 x RJ45 socket (RS485)
    - 2 x RJ45 socket (Meteocontrol WEB log or solar log; Ethernet interface)
- Feed-in management as per EEG 2012: Ready for feed-in management via RS485 interface

Time / Date

Note:
If the inverter was disconnected from the grid for too long, it loses the time and date settings. Yield data and error messages cannot be stored and the inverter shows error messages. These can be deleted only after correcting the time and date.

- Correct the time and date under *Settings* → *Time / Date*. (See page 34 of the Installation and operating manual).
- Delete the Event log under *Settings* → *Clear event log*. .

DC-Circuit breaker

The DC-Circuit breaker interrupts the plus and minus inputs simultaneously.

Make sure that the switch is always in position "I".

The manufacturer's instructions can be viewed here: Installation and operating manual

CO3208-1P*

Technical data CO3208-1P (*CO3208-1P7) Solar Panel Emulator, 1.5 kW / 500 V

- AC-Input
  - Input voltage 90...264 V AC
  - Input frequency 50/60 Hz

- DC-Output
  - Output voltage: 0...500 V DC
  - Output current: 0...10 A
  - Maximal power: 1500 W

Click here to view the operating instructions. (English version from page 93)

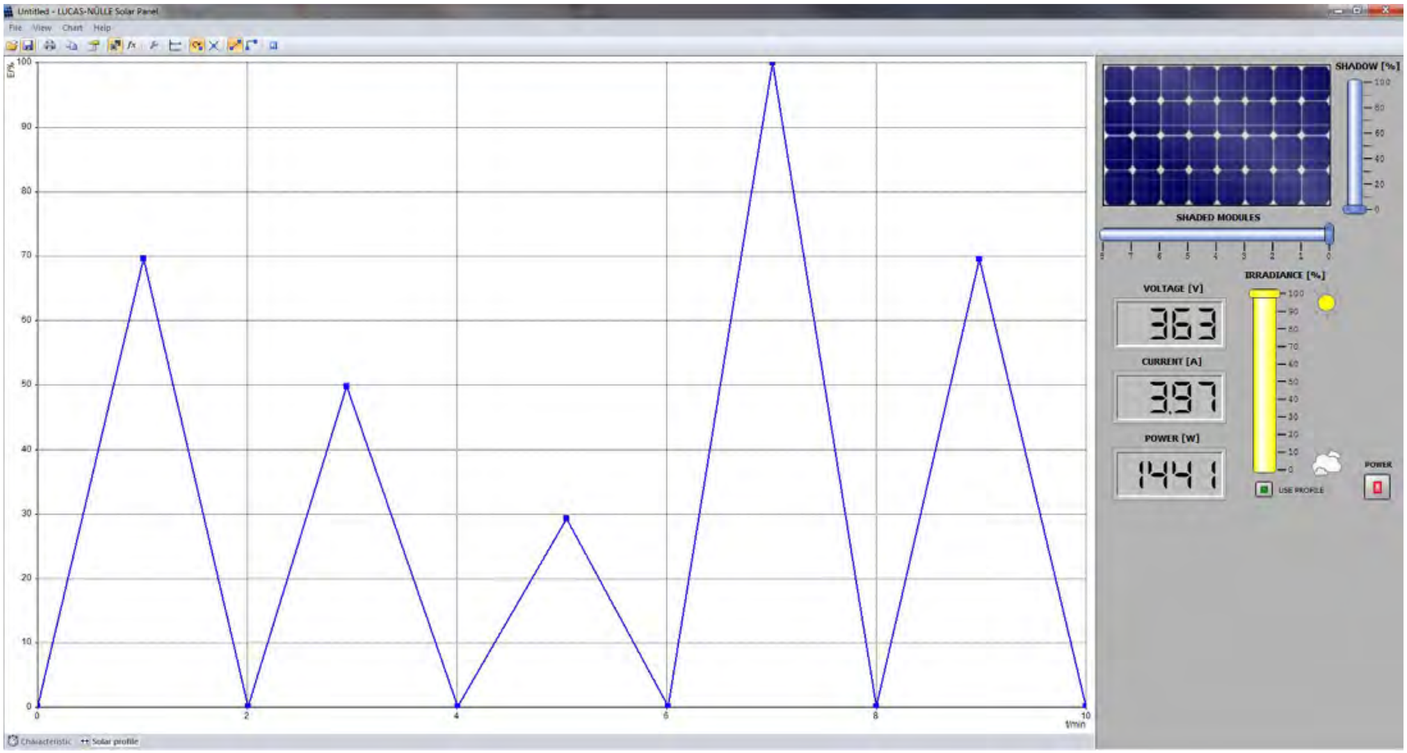
Lucas Nülle Solar panel emulator and Solar Panel

The **solar panel emulator** consists of a controlled DC power supply source. A special control algorithm ensures that the current and voltage behave analogously to PV modules. For the PV inverter, it behaves like a real solar system.

The "**Solar Panel**" application makes it possible to emulate the behaviour of a photovoltaic system.

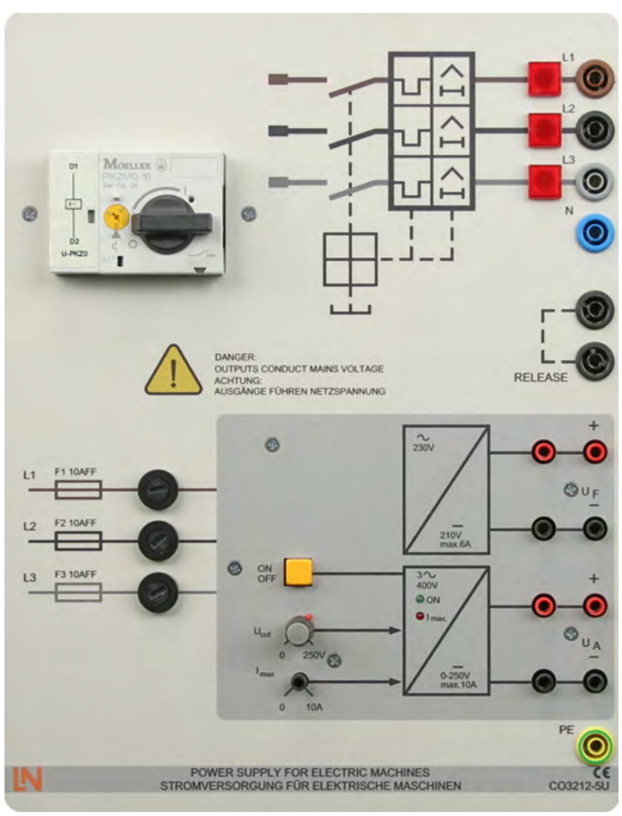
Via the user panel (right), the irradiance, shading of modules and number of shaded modules can be adjusted.

In addition, the behavior of the solar panel can be simulated in a specific period of time by means of the sun path profile.



CO3212-5U*

Mains power supply for DC, AC and three-phase machines and for synchronous machine excitation. The power supply unit is especially designed for the operation with electrical machines.



Specification:

- Three-phase: L1, L2, L3, N accessible via 4 mm (0.157 in) safety sockets.
- DC current: 0...240 V DC variable, constant and electronically protected against overload and short-circuit.
- Output current: 3...10 A (adjustable current limitation setting).
- Second DC voltage 210 V DC, 6A fixed

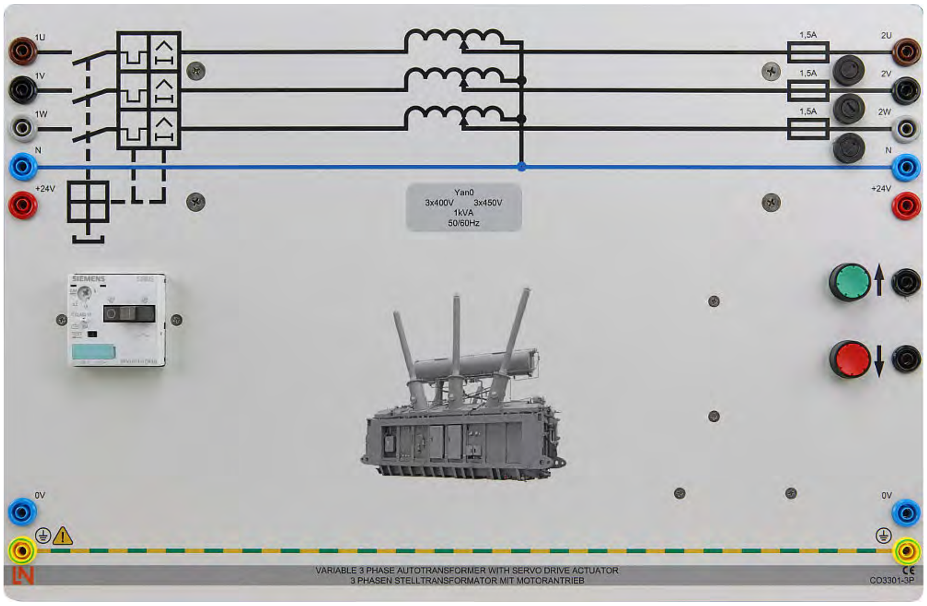
Protective devices:

- Motor protection CB switch, adjustable from 6.3...16 A Under-voltage trip.
- Emergency OFF switch.
- Mains connection:
    - **CO3212-5U:** 3 x 230/400 V, 50 Hz
    - **CO3212-5U7:** 3 x 120/208 V, 60 Hz
- Dimensions: 11.7 x 9 x 5.5 in (HxWxD).
- Weight: 3 kg

The manufacturer's instructions can be viewed here: Manufacturer's instructions.

CO3301-3P

The purpose of this variable transformer CO3301-3P is to compensate voltage fluctuations in the event of changes in load by modifying the transformation ratio. The component can be used as a step-up or step-down transformer. Control is performed via the inputs of power quality meter CO5127-1S.

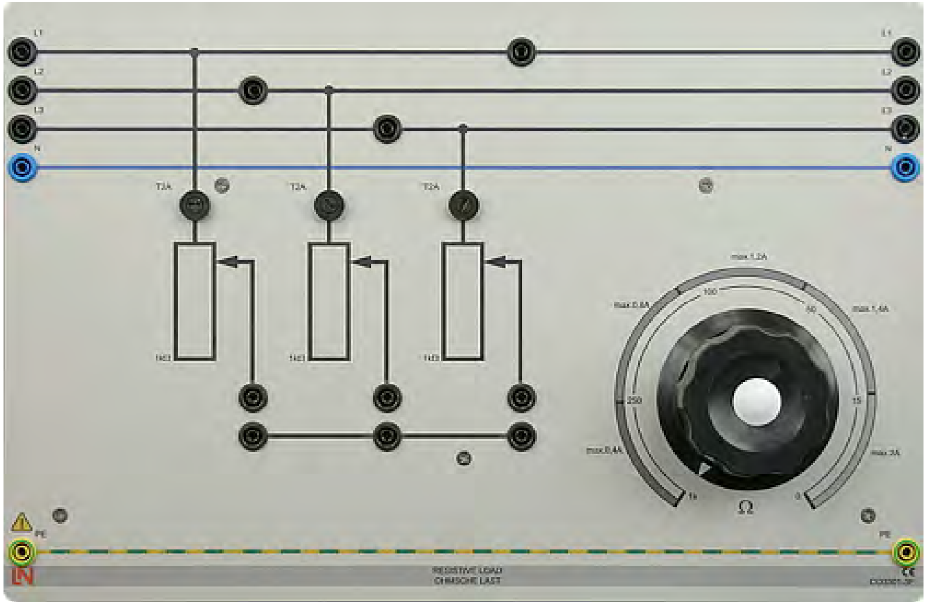


Technical data - C03301-3P 3-phase Variable Transformer with Motor Drive

- Primary: 3x 400 V windings.
- Secondary: 3x 0 ... 450 V, 2 A windings.
- Nominal power: 1000 VA.
- Frequency: 50/60 Hz.
- Switching group: Yan0.
- 24 V input/"Increase voltage" button.
- 24 V input/"Decrease voltage" button.
- Protection: 1 automatic circuit breaker (adjustable).
- Inputs/outputs: 4mm (0.157 in) safety sockets.
- Dimensions: 11.7 x 18 x 5.9 in.

CO3301-3F

CO33301-3F has three synchronously adjustable ring rheostats (bank winding) with scale 100 - 0% and a fuse in the sliding-contact connection.



Technical data - CO3301-3F Variable ohmic load, three-phase

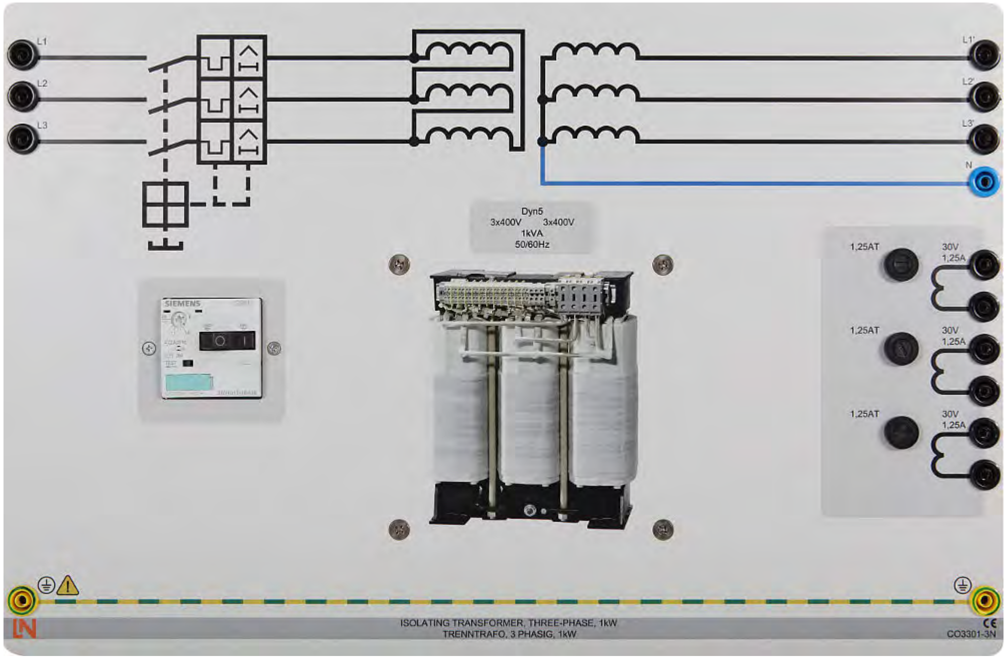
- Suitable for parallel, series, star and delta circuits.
- Resistance: 3 x 750 ohms.
- Current: 3 x 2 A.
- Inputs / outputs: 4mm (0.157 in) safety sockets.
- Dimensions: 11.7 x 18 x 4.9 in (HxWxD).

CO3301-3N

This transformer is meant for feeding the transmission line model; scale factor 1:1000 for secondary current and voltage.

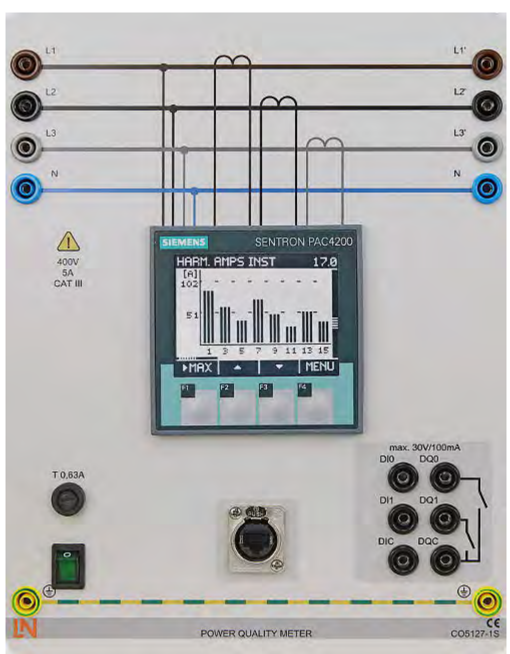
Technical data - CO3301-3N Isolating transformer, 3-phase

- Primary: 3 x 400V winding.
- Secondary: 3 x 400V, 2 A; 3 x 30V, 1.25A winding.
- Power rating: 1000 VA; for a short time: 2000 VA.
- Switching group: Dyn5.
- Fuse: 1 circuit breaker 1.6 - 2.5A, adjustable.
- Inputs/outputs: 4mm (0.157 in) safety sockets.
- Dimensions: 11.7 x 18 x 5.9 in.



CO5127-1S

The three-phase power quality meter permits measurement and display of all relevant grid parameters. It is able to carry out single, two-phase or three-phase measurements. Display and operation are performed via menu navigation with an LC display or the integrated Ethernet interface. The optional SCADA software provides for display of all readings and allows implementation and analysis of intelligent power grids (smart grid). The “Smart Meter” acts as a digital electricity meter at the end points of the electricity grid to measure electricity consumption and can be used to turn consumers on or off depending on circumstances.



Technical data - CO5127-1S 3-phase power quality meter

- Supply voltage 95...240 V AC (50/60 Hz).
- Measurement variables:
    - Voltage
    - Current
    - Active power
    - Apparent power
    - Reactive power
    - Cosine φ
    - Active, reactive and apparent work
    - Frequency and distortion factors for current and voltage
- Max. measurement values:
    - Voltage L-L: 690 V.
    - Current: 5 A.
- Protection class II.
- Interface:
    - Ethernet
- Special features:
    - Detection of harmonic network oscillations and neutral conductor currents.
    - Pulse measurement.
    - Peak and mean value detection.
    - Load profile recording and event logging.
    - Real-time clock.
    - Large, high-contrast graphic display with background illumination.
    - Data display in tables, diagrams and vector diagrams.
    - 2 digital inputs and outputs for free assignment of functions.

Click here to view the operating instructions.

Background/Introduction

Renewable Energies

The term "renewable energy" stands for an energy source that is inexhaustible. Energy sources like the sun or the wind are free and unlimited.

In the future it is clear that renewable energy, particularly wind and solar energy, will become more important and over the long term might be able to replace fossil fuels like coal and gas. However, any future energy mix cannot be comprised of just renewable energies, since, apart from environmental factors, economic efficiency as well as reliability are also important factors for a sustainable power supply.

Advantages

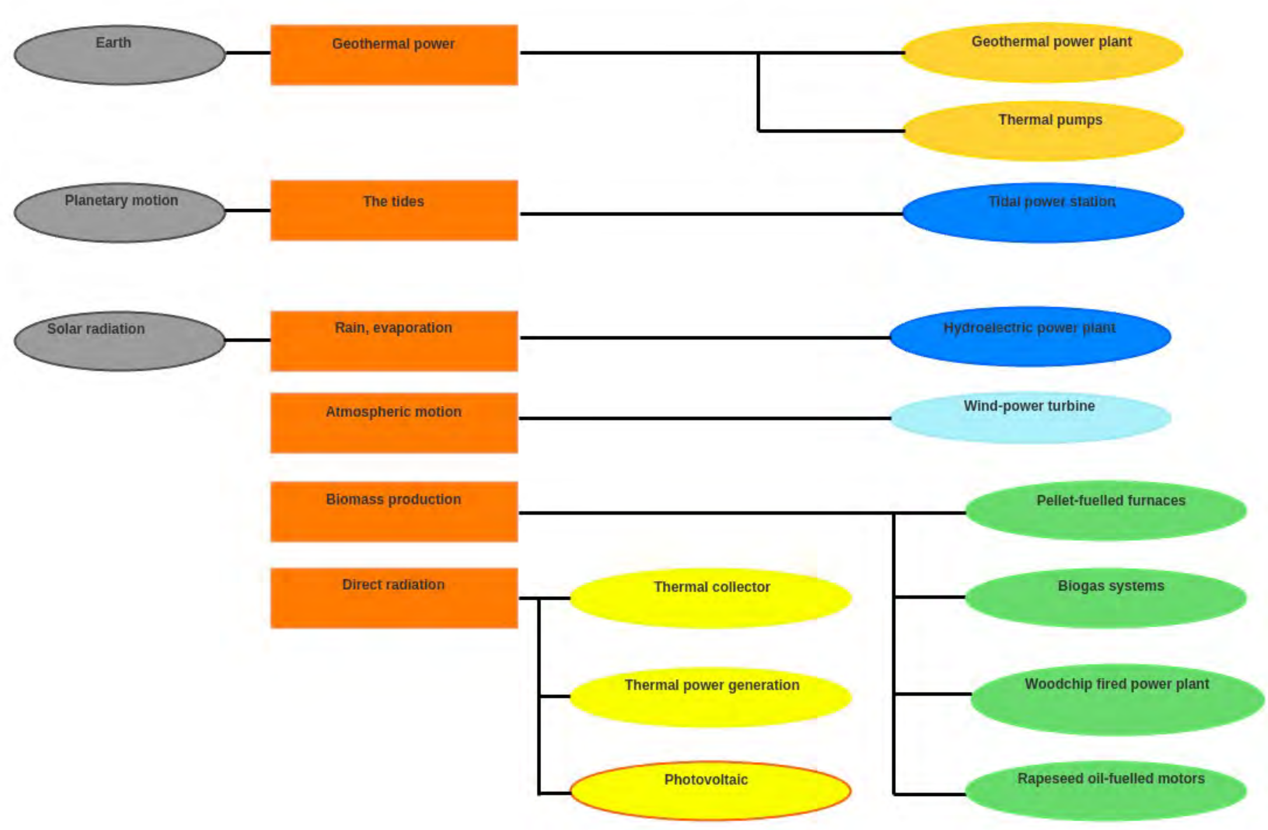
- Inexhaustible supply.
- Environmentally friendly.
- Almost emission free (CO_2).
- No fuel costs.
- Decentralized availability and usability.
- Safe compared to nuclear power (consider accidents in nuclear power plants or natural disasters as in Japan).

Disadvantages

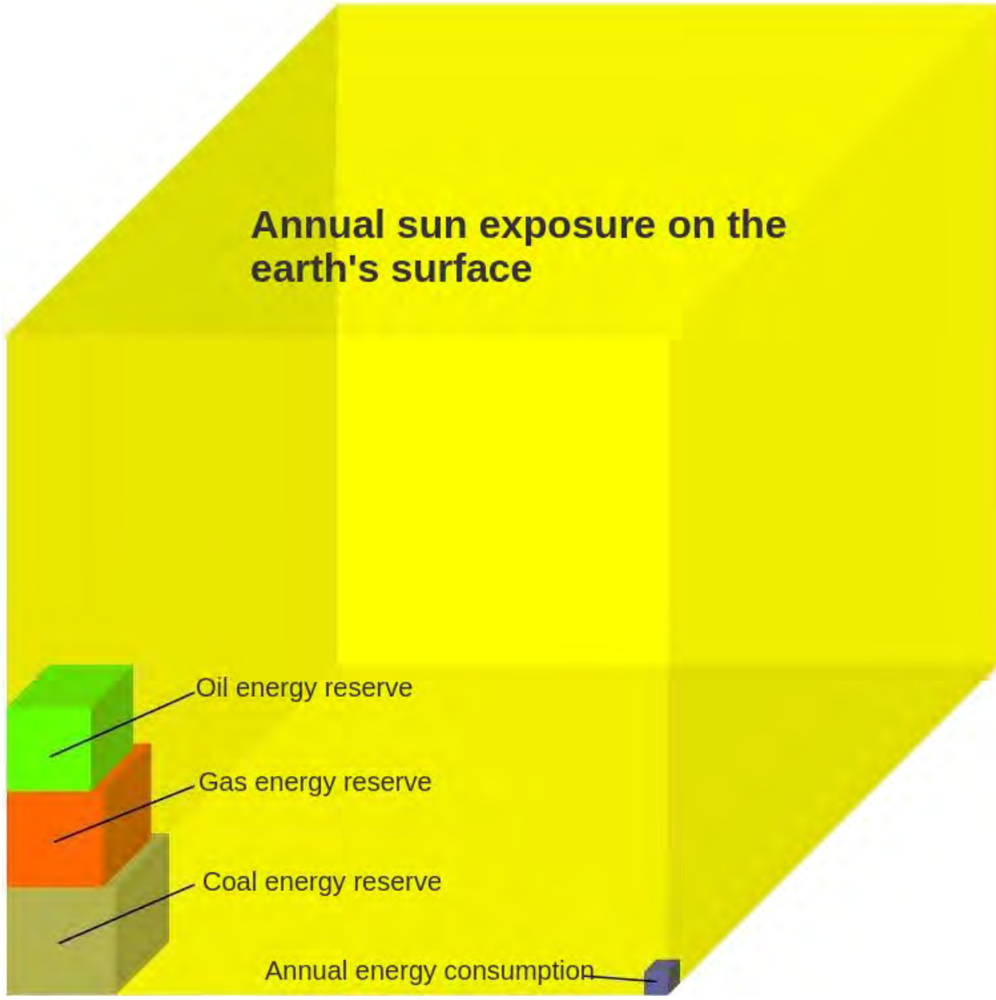
- Generates less power than other energy sources such as fossil fuel.
- Interventions in the environment.
- High investment costs.
- Energy supply fluctuates (photo-voltaic and wind power) requiring back up power sources.

Renewable energy can be divided into 3 areas: solar energy, planetary energy and geothermal energy.

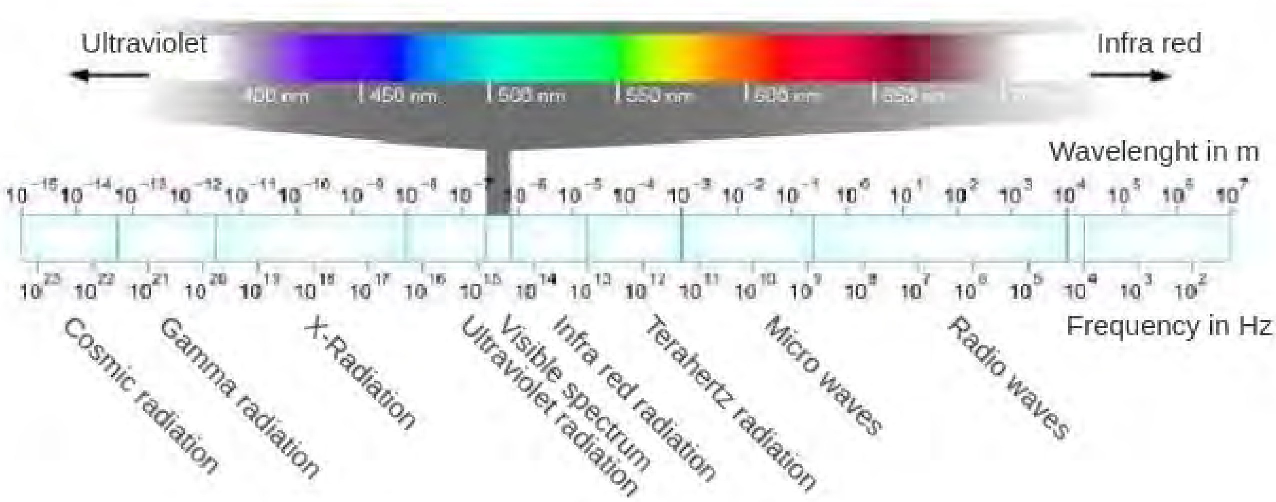
Natural energy conversions cause energy forms such as solar radiation, geothermal and tidal, which can be exploited technically, to produce electricity, heat or fuels.



Solar Radiation



The sun radiates enormous quantities of energy in the form of electromagnetic radiation on a daily basis. A narrow range of this radiation constitutes light visible to humans. The chart below provides an overview of the electromagnetic radiation spectrum.



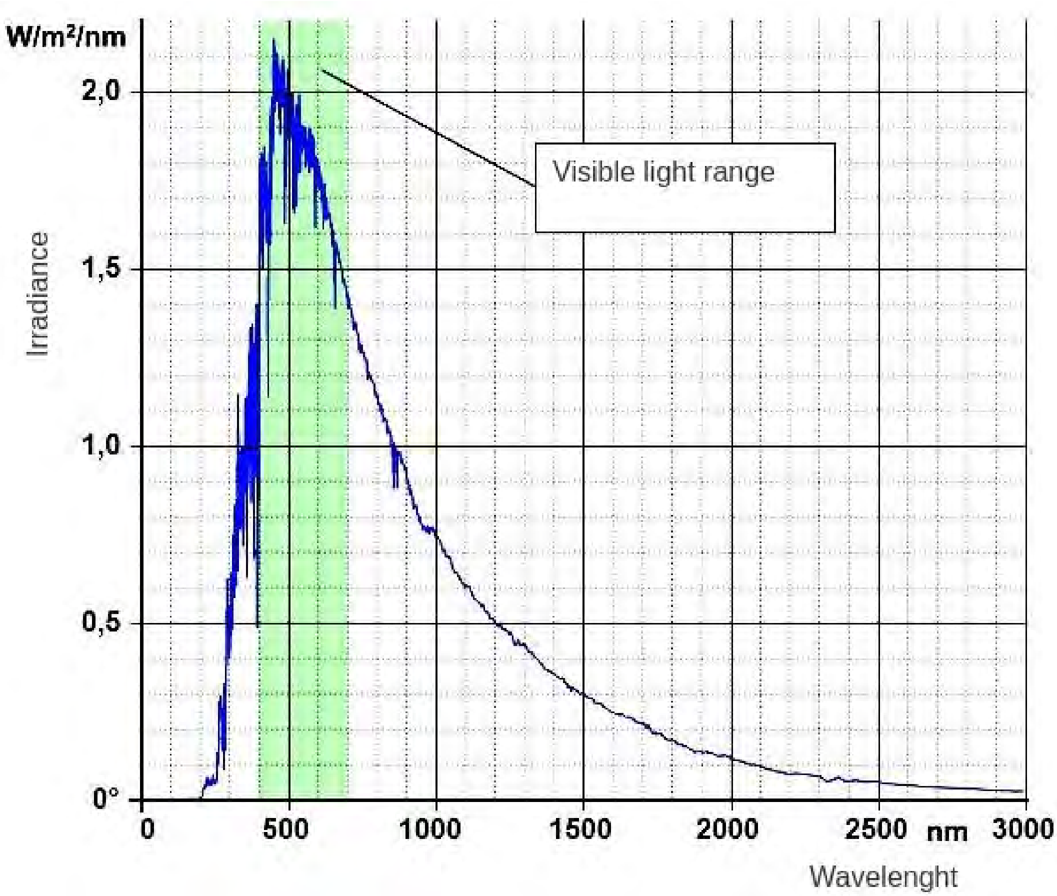
Light consists of photons exhibiting the nature of particles as well as waves. Depending on the experiment being conducted, light can be interpreted as consisting of either particles or waves. When considering its propagation, for instance, light is assumed to consist of waves. When considering its interaction with other objects such as a solar cell, light i.e. photons are assumed to consist of particles.

Every photon is characterized by a wavelength (λ) and energy level (E). The wavelength and energy are inversely proportional to each other as indicated by the equation below.

$$E = \frac{1.24}{\lambda}$$

Photons of a short wavelength (e.g. blue light) therefore possess more energy than photons of a long wavelength (e.g. red light). Conversely, more "red photons" than "blue photons" are needed to deliver the same amount of energy.

The energy spectrum radiated by the sun is shown below.



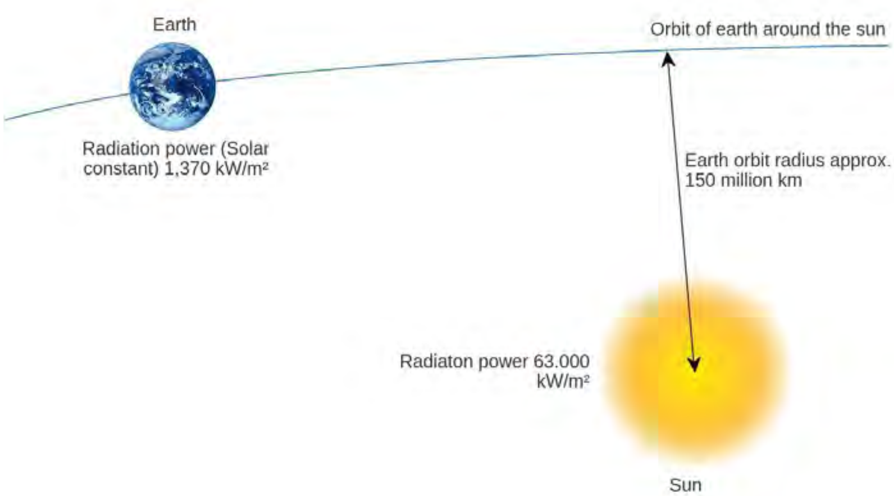
1. The Sun

Mankind's largest inexhaustible source of energy is still the sun, which emits this energy in the form of solar radiation. On reaching earth, the solar radiation is converted almost entirely into heat energy. Photovoltaic systems can be used to directly utilize or store the solar radiation.

The sun has the following composition:

- Approximately 80% hydrogen.
- Approximately 20% helium.
- 0.1% other elements.

Nuclear fusion processes in the sun produce solar radiation with an overall power of about $3.845 \cdot 10^{26}$W. Considered with respect to the sun's surface area, this radiation power results in an emittance of 5,863,110 kW/ft^2.



An area of 0.08 square miles on the sun annually produces enough solar energy to fully cover our primary energy requirements on earth. However, only a small portion of the radiated energy actually reaches the earth.

If we imagine the sun surrounded by a shell with a radius of 93 million mi (the average distance between the sun and the earth's center), the shell's surface emits the same radiant power as the sun's surface. However, the distance between the sun and the earth varies over a year, causing the irradiance on the earth to fluctuate. The average value of the irradiance, also referred to as the solar constant, is E_0= 127 W/ft^2.

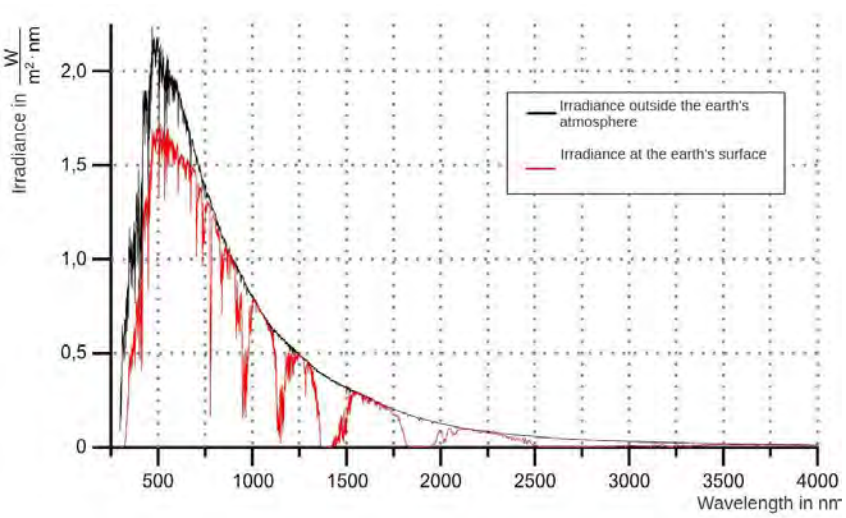
2. Solar Radiation on Earth

The solar constant introduced in the previous chapter indicates the sun's irradiance outside the earth's atmosphere. As the radiation passes through this atmosphere, it is attenuated so that the irradiance at the earth's surface is always less than the value of the solar constant. This attenuation is attributable to

- Reflection by the earth's atmosphere.
- Absorption by the earth's atmosphere.
- Rayleigh scattering.
- Mie scattering.

Reduction Through Absorption

The atmosphere's various constituents (hydrogen, ozone, oxygen, carbon dioxide) reduce irradiance through absorption. However, the absorption varies according to wavelength, as shown in the chart below.



Evidently, the absorption is greatest in the range of visible light.

Rayleigh Scattering

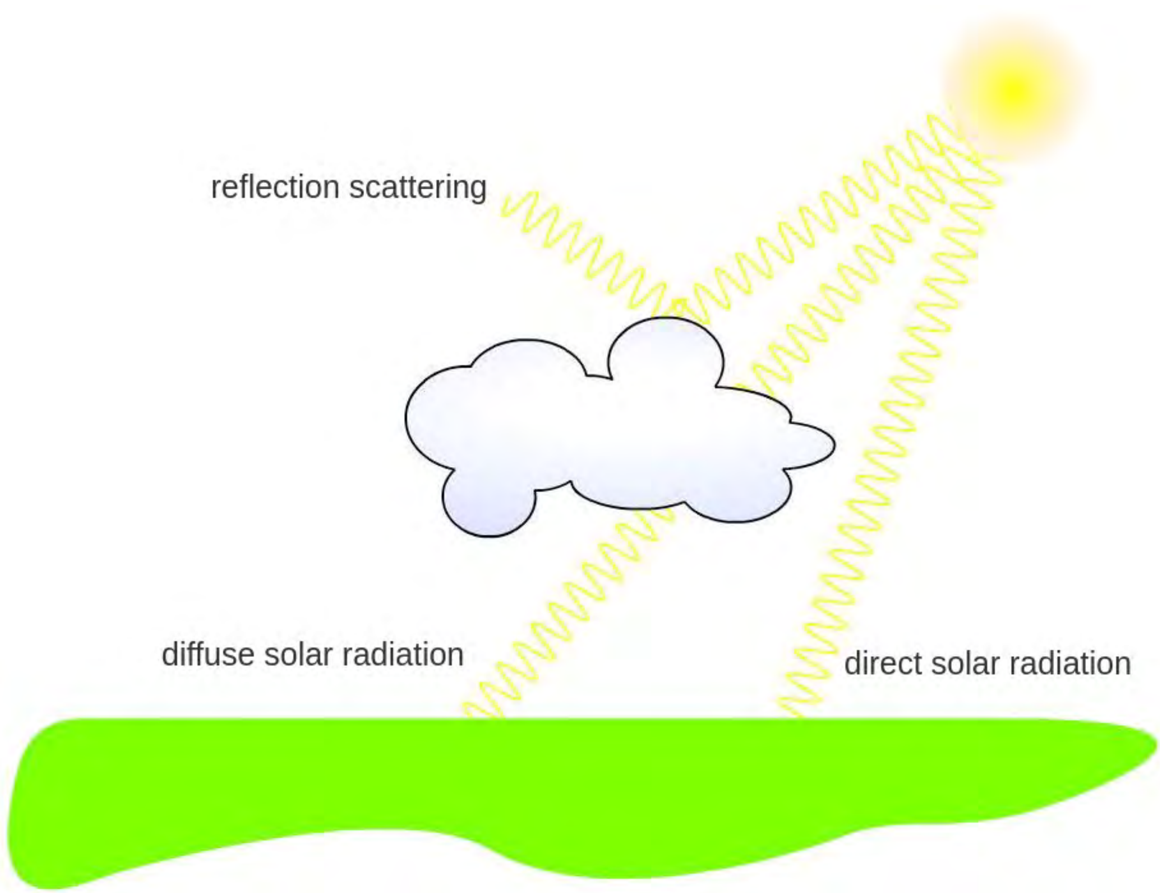
This scattering is caused by atmospheric molecules whose diameter is much smaller than the solar radiation's wavelength, the effect becoming stronger as the solar radiation's wavelength decreases.

Mie Scattering

Impurities and dust particles in the atmosphere cause Mie scattering of solar radiation whose wavelength is smaller than the diameters of the impurities and particles. This effect is stronger at locations where atmospheric pollution is high (e.g. industrial regions) than where atmospheric pollution is low (e.g. high mountain ranges).

Solar Radiation on Earth

Due to scattering, absorption and reflection, the solar radiation at the earth's surface comprises not only the direct component originating from outer space, but also a diffuse component. The composition of solar radiation on earth is illustrated below.



The total solar radiation is defined as:

$$E_{G\,hor} = E_{dir\,hor} + E_{diff\,hor}$$

3. Sun's Position

Motion of the Sun

Though the sun has a fixed position in space, it appears to move across the sky when observed from the earth. This apparent motion by the sun is due to the earth's rotation. As a consequence of the apparent motion, the angle at which sunlight falls directly on to the observer's coordinates changes continuously. The sun's exact position in the sky depends on a number of factors such as the time, date and season of observation.

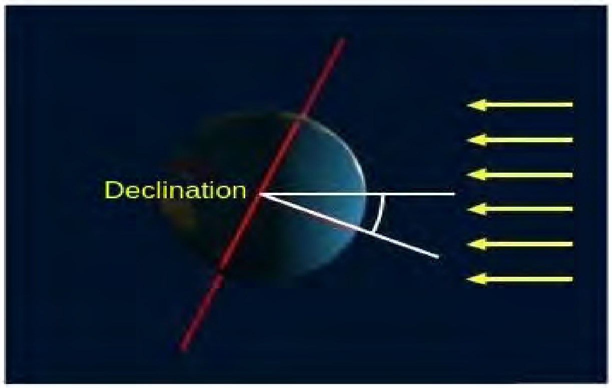
The irradiance, i.e. the quantity of solar energy impinging on a specific area, depends on the sun's position. Only when the sun's rays fall perpendicularly on a surface is the received energy equal to the transmitted energy. At other angles of incidence, the irradiance at the surface is lower.

A precise determination of the sun's position requires a knowledge of the observer's latitude and longitude, as well as the time and date of observation. The relationships involved here are examined in more detail on the next pages.

Declination

Declination is the angle between the equator and the line between the earth's and sun's centers. Because the earth's axis is tiled at an angle of 23.45° with respect to its orbital plane, the declination varies between ±23.45° in the course of a year. The declination reaches its maximum value in summer and winter, and decreases to 0° in spring and autumn.

The variations in declination during a year are demonstrated in the next figure.



Declination is calculated with the following equation:

$$\delta = 23.45° \cdot \sin\left(\frac{360}{365} \cdot (d - 81)\right)$$

δ	Declination
d	Day of the year (on 1st January: d = 1)

4. Solar Time

Local Solar Time (LST)

This is the time determined on the basis of the earth's orbit and the sun's position. The local solar time at two neighbouring spots is never identical unless the spots are on the same line of longitude. A simple sundial, for instance, indicates the local solar time.

$$LST = LT + \frac{TC}{60}$$

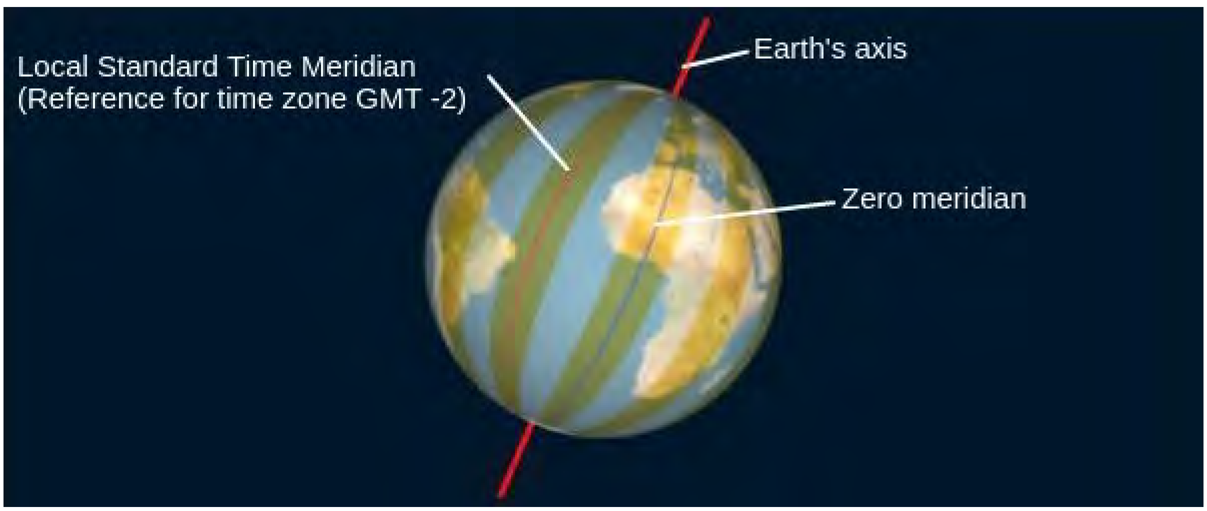
Local Time (LT)

This is the time in a particular time zone.

Local Standard Time Meridian (LSTM)

Serving as a reference for a particular time zone, this meridian always passes through the middle of the zone. Because every time zone spans 15 degrees of longitude, the LSTM can be calculated as follows:

$$\mathrm{LSTM} = 15^{\circ} \cdot \Delta t_{GMT}$$



Equation of Time (EoT)

This equation is used to calculate the difference in minutes between local solar time and current local time. The difference is due to the earth's elliptical orbit about the sun and the tilt in the earth's axis. The equation is:

$$\mathrm{EoT} = 9.87 \cdot \sin(2B) - 7.53 \cdot \cos(B) - 1.5 \cdot \sin(B)$$

where:

$$B = \frac{360}{365} \cdot (d - 81)$$

Time Correction Factor (TC)

This factor accounts for variations in longitude within a time zone as well as the difference resulting from the equation of time. The time correction factor can be used to determine the local solar time from the current local time with the help of the following equation:

$$TC = 4 \cdot (LSTM - \phi) + EoT$$

Hour Angle (HRA)

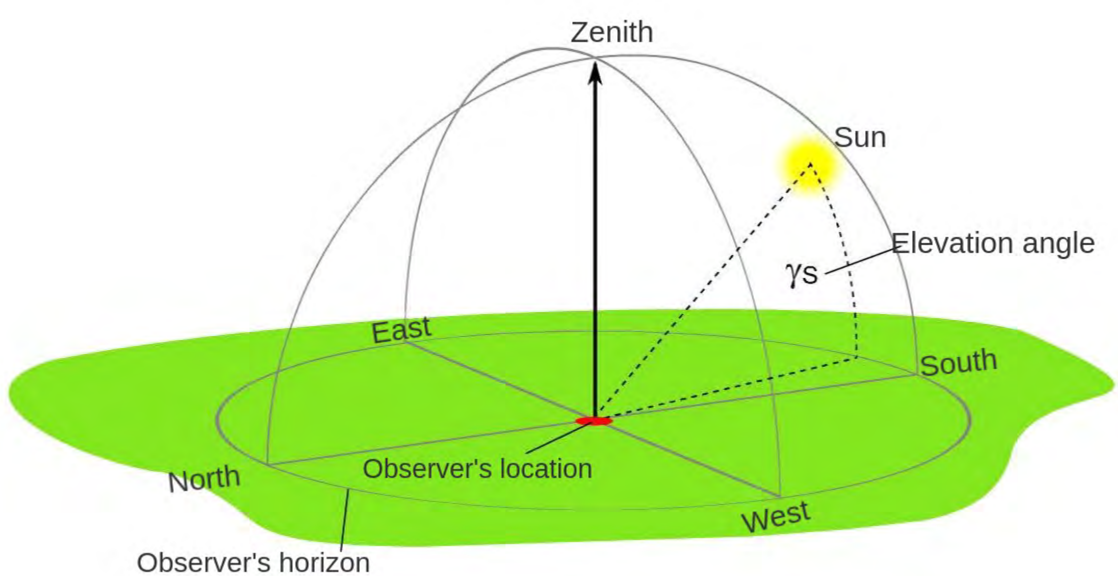
The hour angle converts local time into the number of degrees the sun moves across the sky. By definition, the sun's highest position is at 0°. The earth turns at an angular speed of 15° per hour. The hour angle is negative in the morning, and positive in the afternoon / evening.

$$HRA = 15° \cdot (LST - 12)$$

5. Solar Altitude (Elevation)

Solar Altitude

The solar altitude (elevation) γ_S describes the angle between the horizon (always as seen by the observer) and the sun's centre. The solar altitude is 0° at sunrise and sunset, and 90° when the sun is at its zenith, i.e. directly above the observer.



Always attained at 12.00 hours local solar time, the maximum solar altitude depends on the observer's latitude and the earth's declination. The maximum solar altitude can be calculated with the following equation:

$$\gamma_{max} = 90° - \phi + \delta$$

δ	Declination
Φ	Latitude

Latitude has a positive sign in the northern hemisphere, and a negative sign in the southern hemisphere.

For certain times of the year, the equation above can result in solar altitudes of more than 90° at certain latitudes. In such cases, sunlight otherwise striking on the observer's location from the south now strikes from the north.

Because the sun appears to move across the sky during the day, the solar altitude changes constantly. Consequently, the solar altitude must be tracked in order to prepare accurate simulations and forecasts for photovoltaic systems. The solar altitude at any time can be calculated using the following equation:

$$\gamma = \arcsin\left(\sin(\delta) \cdot \sin(\phi) + \cos(\delta) \cdot \cos(\phi) \cdot \cos(HRA)\right)$$

γ	Elevation
δ	Declination
Φ	Latitude
HRA	Hour angle

Sunrise and Sunset

The equation above can be used to calculate sunrise and sunset times as follows:

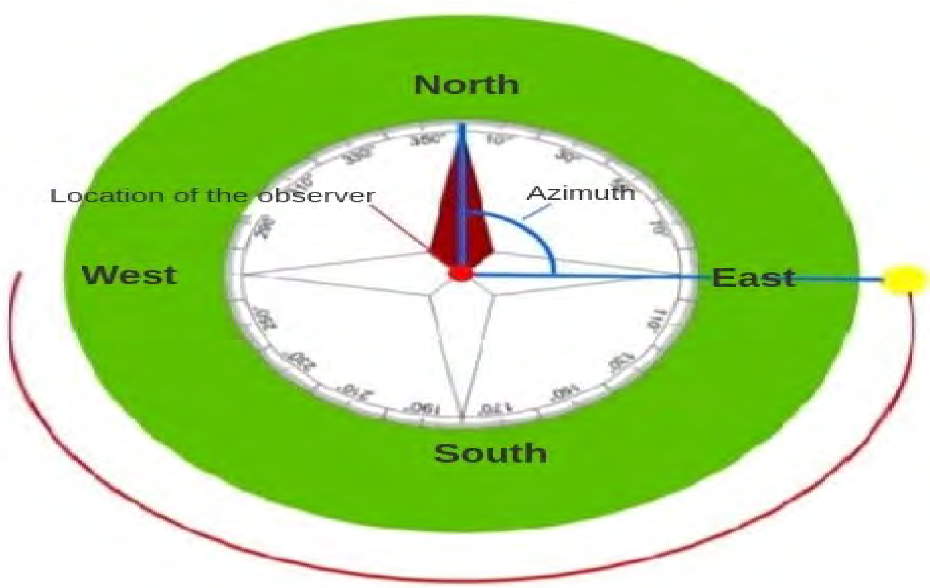
$$t = 12 - \frac{1}{15^\circ} \cdot \cos^{-1}\left(\frac{\sin(\delta)\cdot\sin(\phi)}{\cos(\delta)\cdot\cos(\phi)}\right) - \frac{TC}{60}$$

$$t = 12 + \frac{1}{15^\circ} \cdot \cos^{-1}\left(\frac{\sin(\delta)\cdot\sin(\phi)}{\cos(\delta)\cdot\cos(\phi)}\right) - \frac{TC}{60}$$

δ	Declination
Φ	Latitude
TC	Time correction factor

6. Azimuth

The azimuth angle is the one between geographic north and the sun's compass point. The azimuth angle changes constantly as the sun appears to move across the sky. This is demonstrated in the figure below.



The following equation is used to calculate the azimuth angle:

$$\alpha = \arccos\left(\frac{\sin(\delta)\cdot\cos(\phi) - \cos(\delta)\cdot\sin(\phi)\cdot\cos(HRA)}{\cos(\gamma)}\right)$$

α	Azimuth
δ	Declination
Φ	Latitude
HRA	Hour angle
γ	Elevation

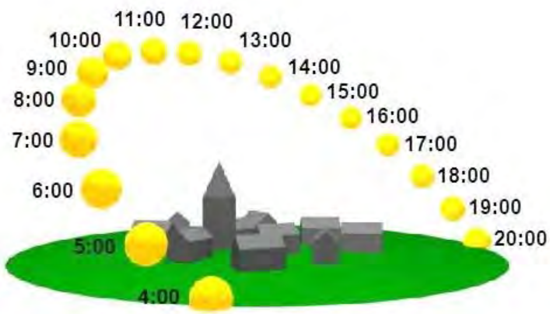
7. Sun's Position as a Function of Latitude

The equations for elevation and azimuth indicate that both these values are independent of longitude. Because declination is considered to remain constant during the day and latitude remains constant too, the sun's position depends solely on the hour angle (HRA).

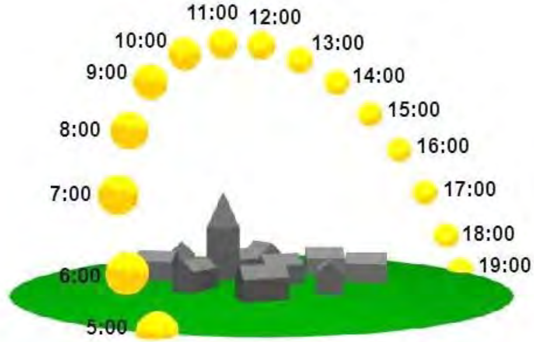
$$\gamma = \arcsin\left(\sin(\delta)\cdot\sin(\phi) + \cos(\delta)\cdot\cos(\phi)\cdot\cos(HRA)\right)$$
$$\alpha = \arccos\left(\frac{\sin(\delta)\cdot\cos(\phi) - \cos(\delta)\cdot\sin(\phi)\cdot\cos(HRA)}{\cos(\gamma)}\right)$$

γ	Elevation
δ	Declination
Φ	Latitude
HRA	Hour angle
α	Azimuth

The chart below shows the sun's path in the course of a day as observed from two separate locations located on the same longitude but different latitudes. Differences are evident particularly in the sun's zenith as well as the sunset and sunrise times.



Sun's path as observed from latitude 50° on 22.06.2018



Sun's path observed from latitude 23,45° on 22.06.2018

Because the equations above only permit a complex representation of the sun's path in the course of a day, sun path diagrams are used instead for easier visualization. These diagrams show elevation as well as azimuth. Sun path diagrams are usually prepared by means of special software for planning and simulating photovoltaic systems. Existent software programs make use of various algorithms (DIN, SUNAE, SOLPOS) developed over the years and differing in terms of accuracy as well as complexity.

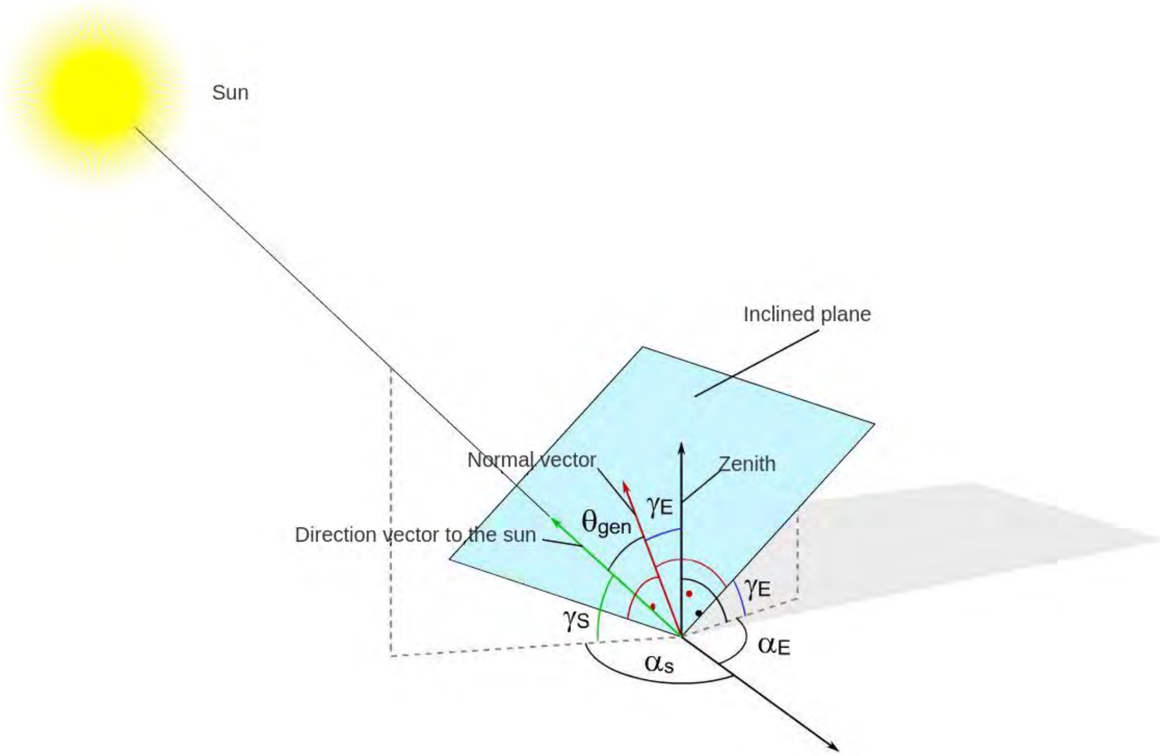
8. Solar Radiation's Angle of Incidence

When solar radiation impinges on a horizontal surface, the angle of incidence θ_{hor} can be determined directly from the solar elevation using the following equation:

$$\theta_{hor} = 90° - \gamma_S$$

This horizontal angle of incidence is also termed zenith angle θ_Z.

However, not all surfaces are horizontal, but inclined instead and possessing an azimuth angle α_E different to that of the sun. To determine the angle of incidence θ_{gen}, you first have to define a vector s aligned toward the sun. The angle between the vector s and the normal (perpendicular to the inclined surface) is then the angle of incidence θ_{gen} and calculated as follows:



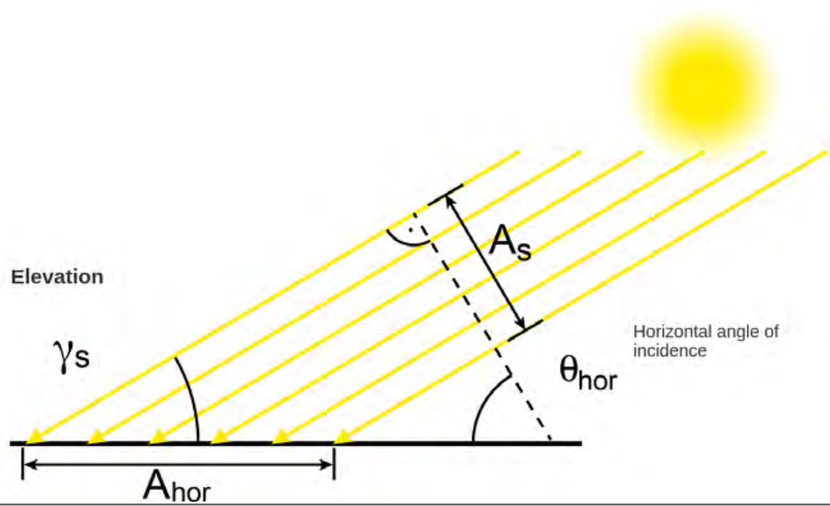
$$\theta_{gen} = \arccos(-\cos \gamma_S \bullet \sin \gamma_E \bullet \cos(\alpha_S - \alpha_E) + \sin \gamma_S \bullet \cos \gamma_E)$$

Irradiance on the Inclined Plane

The global radiation $E_{G\ gen}$ striking on the inclined plane is composed of the following components:

- Direct sky radiation $E_{dir\ gen}$
- Diffuse sky radiation $E_{diff\ gen}$
- Sky radiation reflected by the ground $E_{ref\ gen}$

Direct Sky Radiation

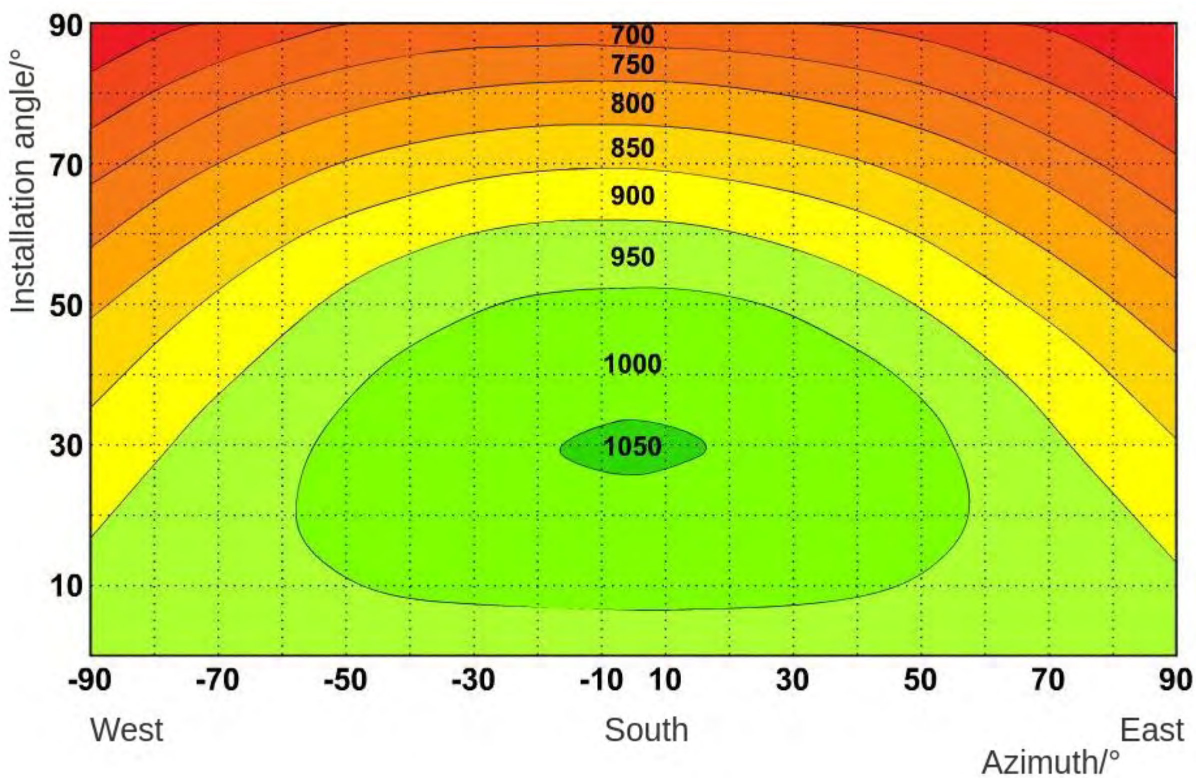


If we compare a horizontal area with an area needing to absorb the same amount of radiation power but inclined vertically with respect to the sun, the latter area turns out to be smaller. Accordingly, solar modules are installed at an angle in order to increase their energy efficiency. If the irradiance on a horizontal surface is known, the irradiance on an inclined plane can be determined as follows:

$$E_{dir\ gen} = E_{dir\ hor} \cdot \cos \theta_{gen} / \sin \gamma_S$$

Increasing Energy Efficiency through Inclination

A southerly inclination of 30° is ideal for facilities located at central European latitudes. Because many photovoltaic facilities are mounted on sloping roofs, however, this optimal inclination cannot always be achieved. A solar generator's alignment does not influence energy yield as much as generally assumed. The illustration below clearly demonstrates the negligible drop in a solar generator's energy output despite large easterly / westerly deviations and notable variations in inclination.



The closer a photovoltaic facility is located to the equator, the smaller the solar modules' ideal angle of inclination.

Basically, the three statements below hold true for a solar generator's alignment.

- Solar generators with small angles of inclination are permitted greater deviations from south.
- Solar generators with large angles of inclination should point as close to south as possible.
- The surface of a solar generator connected to an inverter should remain constantly aligned, unless multiple or multi-string inverters have been employed.

Solar Modules

Implying a **direct** conversion of (sun)light into electrical energy by means of solar cells, the term *photovoltaics* is composed of the Greek word *photon (*light) and *Volta,* the name of an Italian physicist.

A solar cell operates on the principle of the photovoltaic effect (more precisely, the *inner photoelectric effect*), whereby exposure to light causes charge separation. This effect was first observed in 1839 by Alexandre Edmond Becquerel. During an experiment, he discovered that two metal plates in diluted acid generated more energy when irradiated directly by sunlight.

In 1958, the first satellite to obtain its entire electrical energy from solar cells was launched into orbit around the earth.

Photovoltaic technology has now established itself as a viable source of power ranging from a rating of a few milliwatts to several kilowatts.

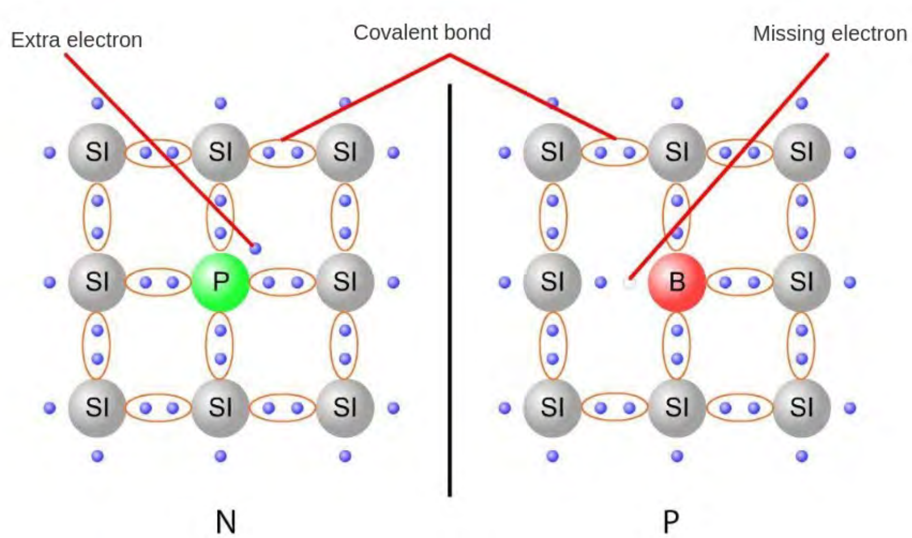
1. Principle of Photovoltaics Solar Cells

Solar cells are usually made of silicon which is the second most frequently found element in the earth's crust. A silicon atom has four valence electrons. In a silicon crystal, two electrons of neighbouring atoms form a pair in each case. In this state, the silicon crystal is not conductive, because no free electrons are available for transporting charge.

hen a silicon crystal receives energy in the form of light or heat, for instance, the energy is also absorbed by the electrons. Once an electron pair has absorbed enough energy, it breaks up so that the electrons are free to move inside the silicon crystal. Each electron which has drifted in this manner leaves a "hole" at its original location in the crystal lattice. The silicon becomes conductive, this property being known as the intrinsic conductivity of a semiconductor. When the energy supply is interrupted, each drifting electron releases the energy it previously absorbed and returns to a free electron hole.

An electrical field can be used to separate the electrons from the electron holes. Impurity atoms permit an electrical field to be generated inside a semiconductor. For this purpose, atoms with five electrons each are integrated into one section, known as n-semiconductor or n-doped. This section bears a slight negative charge with respect to the pure silicon crystal lattice.

Atoms with three electrons each are integrated into another section, known as p-semiconductor or p-doped. This section bears a slight positive charge with respect to the pure silicon crystal lattice. If the n- and p-semiconductors are brought right next to each other, a electric field forms in the p-n junction arising between the two semiconductors.



P-N Junction

A p-n junction is formed by joining p- and n-semiconductor layers. Electrons from the n-layer drift across this junction to the p-layer, where they combine with the holes. When electrons leave the n-layer, the atoms remaining there result in a slightly positive charge in that region. Conversely, the p-layer where the incoming electrons combine with the holes accumulates a slight negative charge as a result. This charge separation creates an electric field across the semiconductor junction, also termed space-charge region.

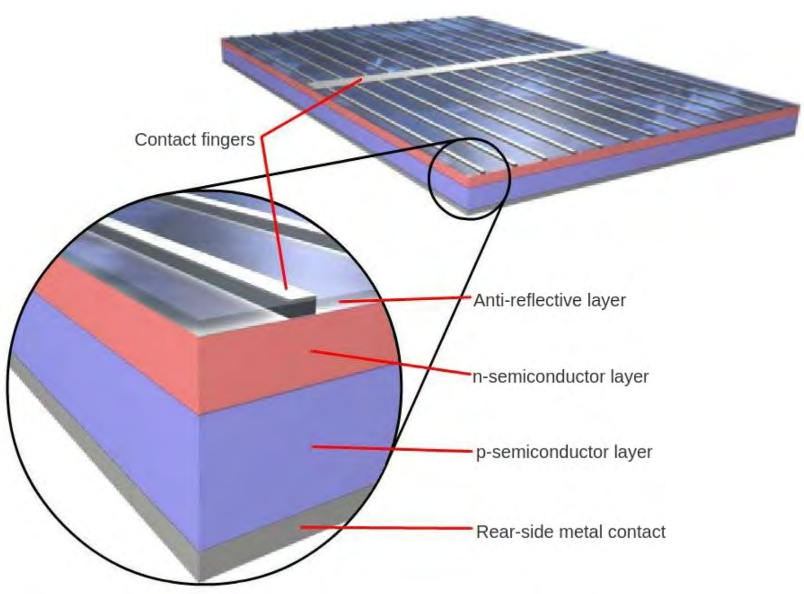
Photovoltaic Effect

When light strikes on the PV cell's crystal lattice, the light energy is transferred to the lattice, where the atoms are excited to form electron-hole pairs. If this happens outside the p-n junction, the electron-hole pairs re-combine very quickly. Electron-hole pairs inside the p-n junction are separated by the local electric field. The resultant electrons drift to the n-layer while the holes drift to the p-layer, causing the PV cell's voltage to build up. If a consumer is then connected to the cell, a current begins to flow.

2. Structure of a Photovoltaic Solar Cell

Photovoltaic cells are semiconductors which become electrically conductive on exposure to light or heat.

The following figure shows the schematic layout of a PV cell:



- **Rear-side metal contact:**

  The PV cell's voltage can be tapped via this contact.

- **p-semiconductor layer:**

  Added to this semiconductor material are foreign atoms possessing fewer free electrons. This results in a surplus of positive charge (electron holes) in the semiconductor. This is a p-type semiconductor layer.

- **n-semiconductor layer:**

  Added to this semiconductor material are foreign atoms possessing more free electrons. This results in a surplus of negative charge (electrons) in the semiconductor. This is a n-type semiconductor layer.

- **Contact fingers:**

  Together with the rear-side metal contact, the contact fingers make up the terminals to which a consumer can be connected, for instance.

- **Anti-reflective layer:**

The anti-reflective layer is meant to protect the PV cell and reduce reflection losses at the cell's surface.

3. Types of Photovoltaic Solar Cell

Solar cells can be divided into three groups based on raw material:

- Monocrystalline.
- Polycrystalline.
- Thin-film.

Thin-film cells include those made of amorphous silicon and other materials like cadmium-telluride (CdTe), copper-indium-diselenide (CIS) and gallium-arsenide (GaAs). Silicon solar cells have prevailed so far in practice.

Monocrystalline Solar Cells

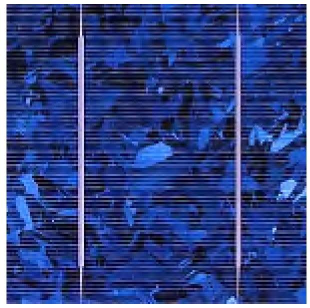
Highly pure silicon melt is used to grow mono-crystals in the form of round silicon blocks. A mono-crystal's lattice has an entirely homogeneous structure. The silicon block is sawed into wafers each 200 to 300 µm thick. To optimize utilization of the solar module's surface, the round cells are cut into square ones. A cell's side usually has a length of 152 mm. The final phase of manufacture involves doping followed by installation of contact surfaces and an anti-reflective layer.

Mono-crystalline solar cells manufactured on an industrial scale have an efficiency of 15 - 18%, the highest among the variety of solar cells presently available. However, monocrystalline solar cells require more energy and time to manufacture compared with polycrystalline solar cells.

(Photo source: www.sunways.de)

Polycrystalline Solar Cells

Highly pure silicon melt also serves as the initial material for polycrystalline cells. However, these cells are manufactured not by growing mono-crystals, but through controlled cooling of the silicon melt in square-shaped moulds. During cooling, the crystals arrange themselves in an irregular pattern resulting in an iridescent surface typical of polycrystalline solar cells. The square silicon blocks are then sawed into wafers with a thickness of 200 to 300 µm. The final phase of manufacture involves doping followed by installation of contact surfaces and an anti-reflective layer. This layer gives the solar cell its characteristic blue sheen, blue being least reflective and most absorptive to light. Polycrystalline solar cells have an efficiency of 13 to 16%.



(Photo source: www.buch-der-synergien.de)

Thin-film cells

Amorphous silicon cell

The expression amorphous is derived from Greek (**a**: without; **morphé**: form). In physics, substances whose atoms form irregular patterns are termed amorphous. Atoms arranged in ordered patterns are said to be crystalline.

(Photo source: www.w-quadrat.de)

To manufacture amorphous solar cells, silicon is vapour-deposited on a carrier, e.g. glass. The vapour-deposited silicon layer has a thickness of 0.5 to 2 µm. Besides lowering silicon consumption, this also dispenses with elaborate sawing of silicon blocks. However, amorphous solar cells only have an efficiency of 6 to 8%.

Copper-indium-diselenide cell (CIS)

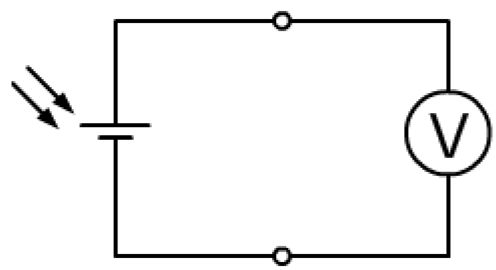
Instead of silicon, this type of cell employs thin films comprising copper, indium and selenium. The cell has a black surface allowing it to absorb nearly 99% of the incident light. Manufacture takes place in a vacuum chamber where the materials are applied to a carrier at a temperature of 500°C.

The table below provides an overview of the various modules' efficiencies and surface areas required to generate a power of 1 kWp.

Raw material	Module efficiency in %	Area in ft^2
Monocrystalline	15-18	75-97
Polycrystalline	13-16	86-97
Amorphous	6-8	140-215
Copper-indium-diselenide	10-12	97-118

4. Open-circuit Voltage of a Photovoltaic Solar Cell

As the largest voltage occurring across the terminals of a PV cell, the open-circuit voltage V_{OC} is important in dimensioning subsequent circuits (e.g. inverters). This voltage is measured without any load being connected to the PV cell.



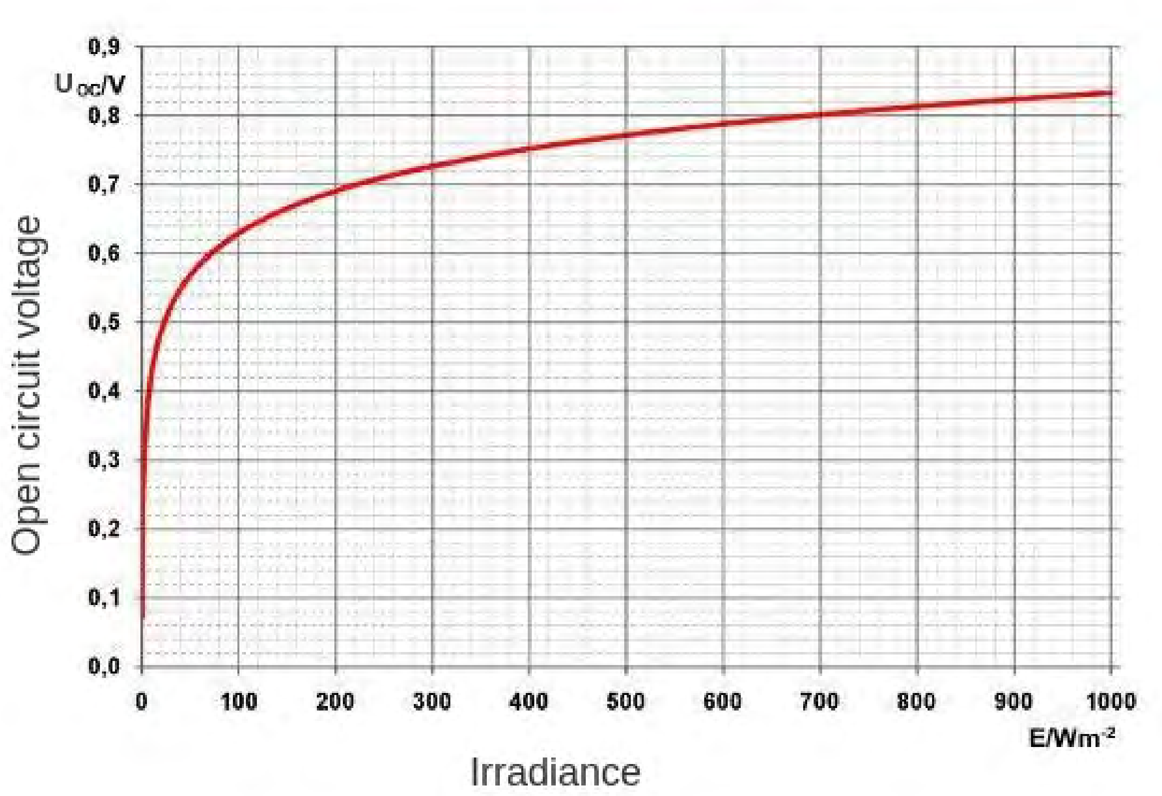
The semiconductor material making up the PV cell decisively determines the voltage produced by the cell.

The factors mentioned next influence the open-circuit voltage:

- Irradiance.
- Angle of incidence.
- Temperature.

Irradiance

The next diagram illustrates the dependency of open-circuit voltage on irradiance.



Obviously, the open-circuit voltage is not a linear function of the irradiance. The voltage approaches its maximum level already at low irradiances. When installing PV cells on roofs, you should therefore bear in mind the cells' ability to produce substantial voltages even under overcast skies.

Angle of Incidence

Measurements of the dependency of open-circuit voltage on angle of light incidence show that this voltage is maximized when the light strikes perpendicularly.

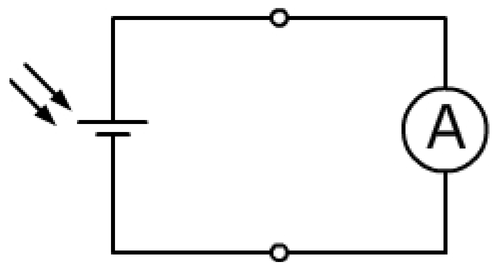
Temperature

A PV cell's open-circuit voltage has a negative temperature coefficient, i.e. as a PV cell or module warms up (e.g. on exposure to light), its open-circuit voltage drops. As an outcome of this temperature dependency, the PV cell's open-circuit voltage is at its highest at low (winter) temperatures.

Accordingly, PV modules destined for use in warm regions require a higher number of cells than usual (e.g. 40 instead of 36).

5. Short-circuit Current of a Photovoltaic Solar Cell

The short-circuit current Isc is the largest possible current a PV cell can supply. This current is measured using an ammeter with a very low internal resistance connected directly to the PV cell's terminals.



PV cells are short circuit proof, i.e. they do not get damaged if their terminals are short circuited.

Because the short-circuit current is only slightly higher than the rated current, the module lines need not be protected by fuses against short circuit. However, the lines must be dimensioned to handle short-circuit current.

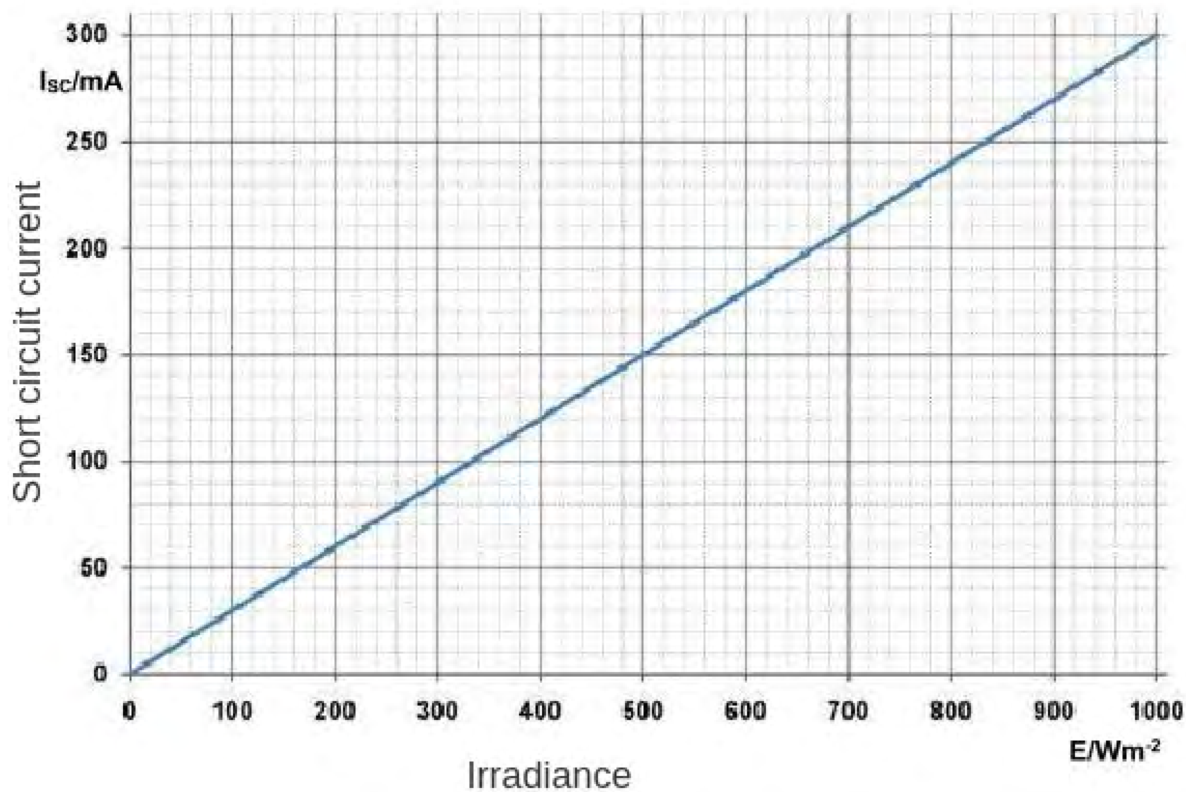
A short circuit resulting from a fault (e.g. defective insulation) can result in hazardous arcs.

The short-circuit current depends on:

- Irradiance.
- Angle of Light Incidence.
- Temperature.

Irradiance

Precise measurements of short-circuit current as a function of irradiance yield the following typical characteristic:



A short-circuited PV cell serves as a sensor for an irradiance meter.

Angle of Light Incidence

Measurements of short-circuit current as a function of the angle of light incidence show that the short-circuit current attains its maximum value when the light strikes perpendicularly on the PV cell.

Temperature

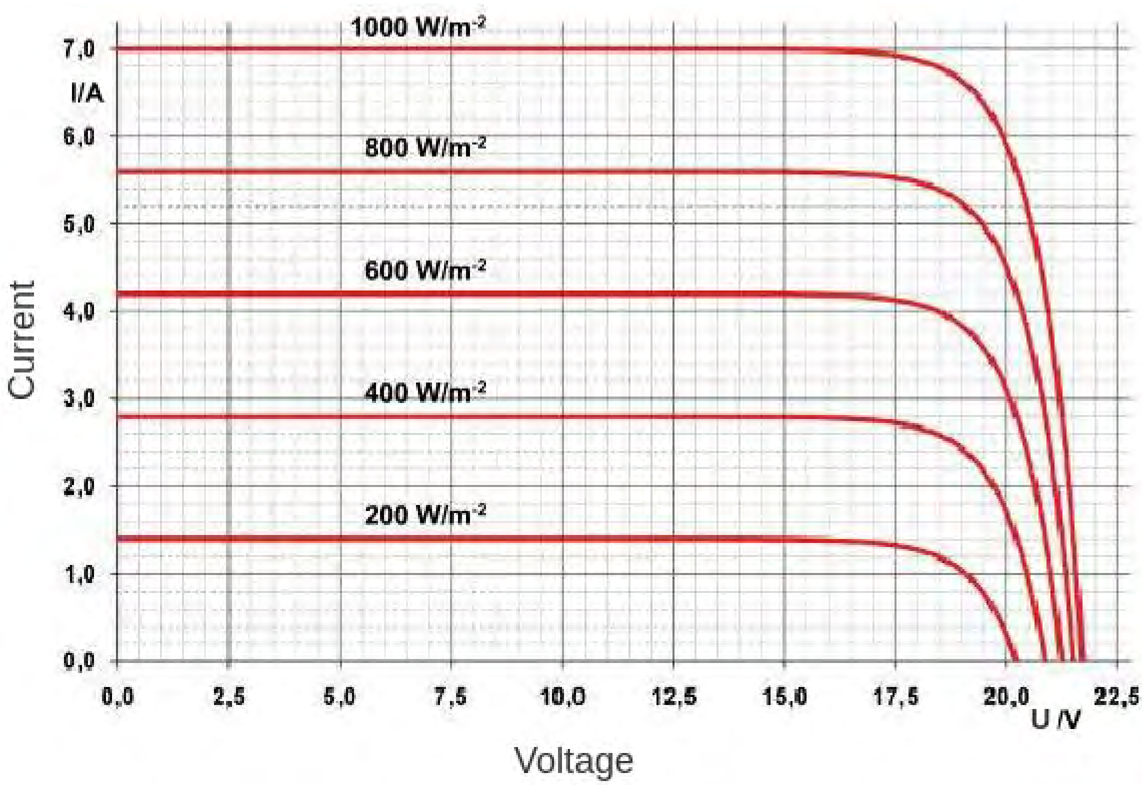
Precise measurements of the temperature-dependency of short-circuit current reveal a positive temperature coefficient, i.e. as the PV cell warms up, its short-circuit current rises.

6. V/I Characteristic of a Photovoltaic Solar Cell

Between the two operating points representing no-load and short-circuit respectively, it is possible to measure further operating points at different currents. All measurement points together result in the cell's characteristic. This characteristic is determined by the various currents and their corresponding voltages.

The characteristic of a cell / module serves as an important assessment criterion in solar technology.

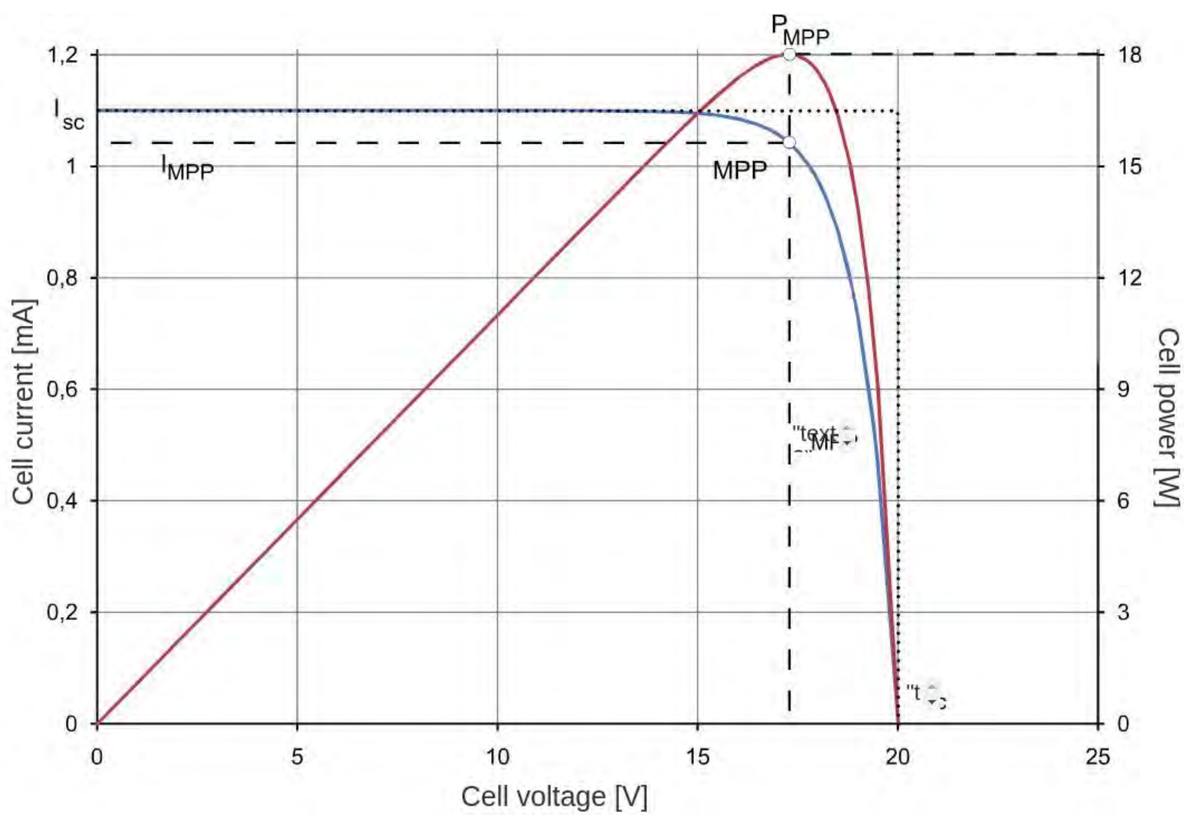
The diagram below shows the typical V/I characteristic of a PV cell at various irradiance levels.



7. Efficiency of a Photovoltaic Solar Cell

The power which can be supplied by a PV cell or module depends not only on the irradiance, but also how well the consumers are matched. The no-load operating point with I = 0 mA and the short-circuit operating point with V = 0 V, yield the output power P = 0 W in accordance with the formula P = V • I. Between these two operating points, the product P = V • I must therefore attain a maximum value. This operating point is termed the **Maximum Power Point (MPP).**

The maximum power P_{Max} a PV cell can deliver to a connected consumer is always smaller than the product of the short-circuit current and open-circuit voltage.



The fill factor

The fill factor is a quality criterion of a solar cell and states to what extent the I/U characteristic approaches the rectangle made up of the no-load voltage (V_{OC}) and short-circuit current (I_{SC}) shown below. The fill factor is calculated using the following equation:

$$FF = \frac{P_{MPP}}{V_{OC} \cdot I_{SC}} = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}}$$

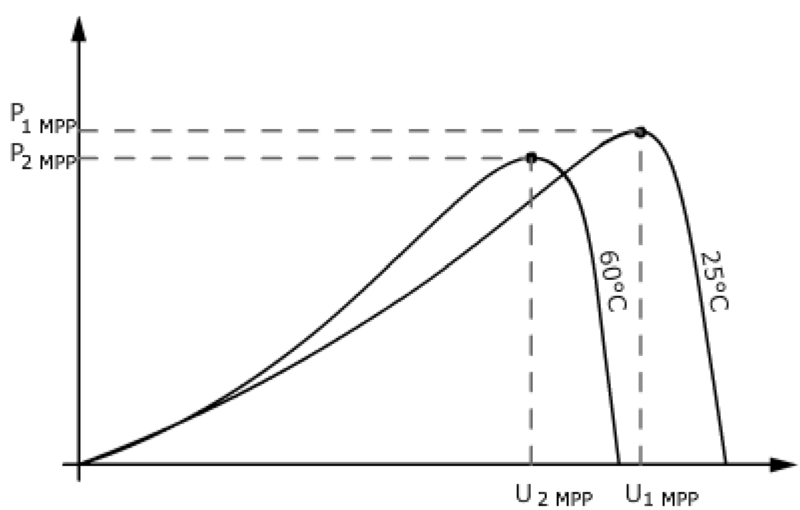
The Efficiency

To determine the efficiency η of a solar cell you need to know the maximum power point (MPP), the irradiance E and the surface area A of the solar cell. The efficiency is then computed from the following expression:

$$\eta = \frac{P_{MPP}}{E \cdot A} = \frac{FF \cdot V_{OC} \cdot I_{SC}}{E \cdot A}$$

Temperature Dependency of the Maximum Power Point

If a cell or module is operated under exposure to strong irradiance, the temperature of the cell/module rises beyond the value of 25°C corresponding to standard test conditions. More precise measurement results regarding the temperature dependency of the MPP are shown in the next diagram.



These measurement results indicate that PV modules should always be well ventilated to maximize their cooling.

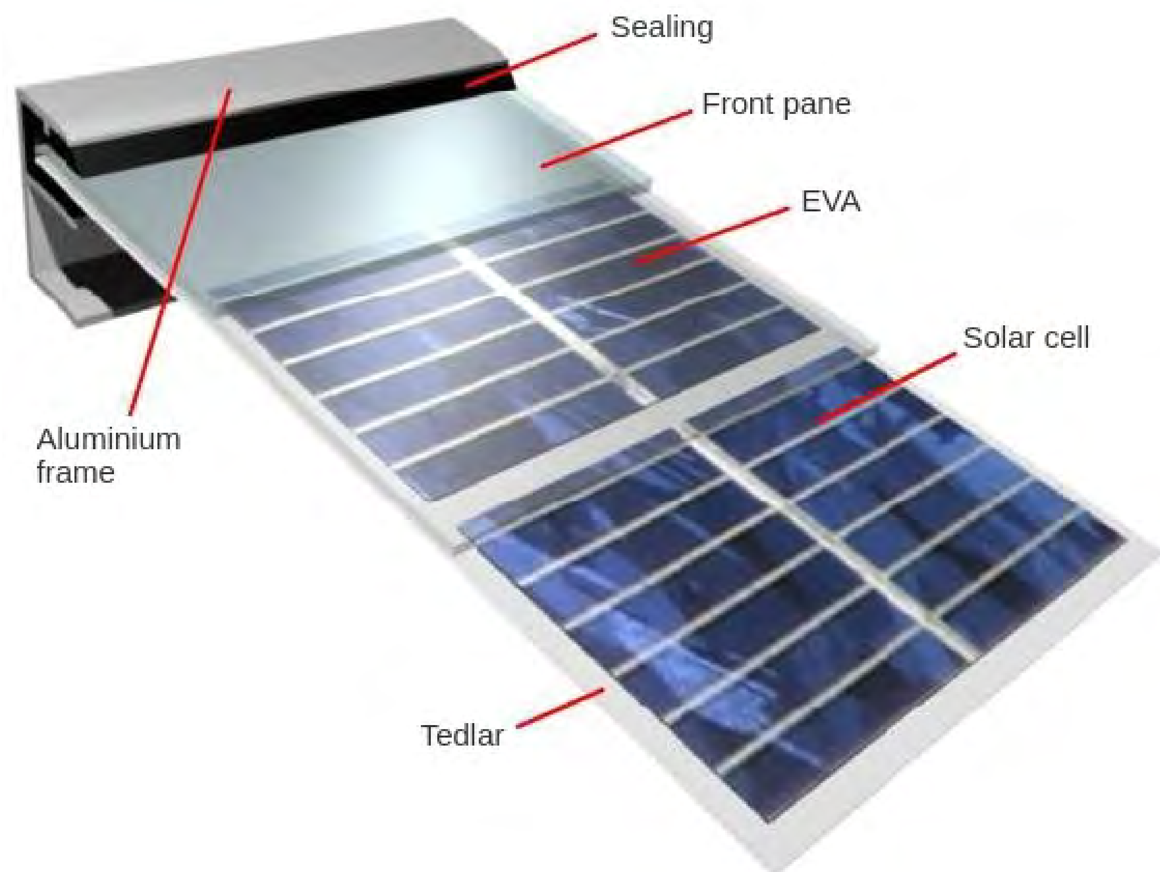
8. Design of a Photovoltaic Solar Module

By combining several individual solar cells into a single unit, a solar module has the following benefits:

- Easier handling.
- Lower mechanical stress on the solar cells.
- Protected terminals for the solar cells.
- Higher rated power and voltage.

A solar module's electrical layout comprises several solar cells connected in series. This is achieved by connecting one solar cell's front contact with the next cell's rear contact. The connections are established by means of solder links consisting of highly flexible, tin-coated copper strips.

Modern solar modules usually comprise 36, 48 or 72 inter-connected solar cells.



Front Pane

The solar module's front pane usually comprises a glass that complies to special standards. The glass must be highly transparent to sunlight and reflect just a minimal proportion of it. For these attributes to be retained over the solar module's entire life cycle, the glass must also be resistant to ultraviolet light. Moreover, the front pane must prevent an ingress of water and water vapor which would notably shorten the solar module's service life.

Encapsulation

Encapsulation serves, firstly, as a mechanical link between the individual solar cells and, secondly, as an optical bridge between the front pane and the solar cells in order to prevent unnecessary losses in solar radiation. The encapsulation must possess the same optical attributes as the front glass pane. Ethylene vinyl acetate (EVA) is normally used for encapsulation.

Rear Surface

Like the front pane, the rear surface must also prevent an ingress of water and water vapor. This surface usually consists of Tedlar or glass.

Socket

The socket is used to connect the solar modules' freewheeling or bypass diodes as well as the connection lines.

Frame

Usually made of aluminum, the solar module's frame is used, for instance, to protect the glass during transport and assembly. The frame also makes the composite structure more rigid and provides mounting points.

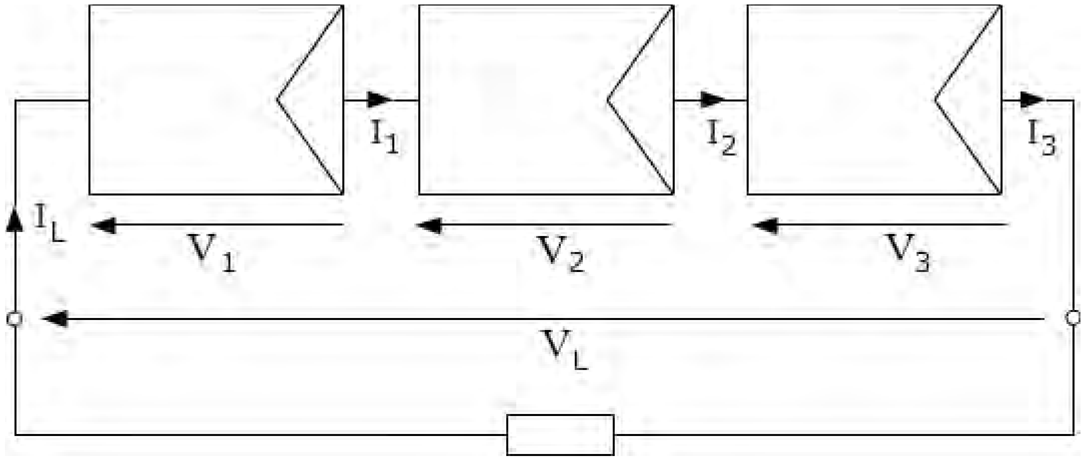
Connecting Solar Modules

Different voltages and amperages can be achieved by wiring PV cells in correspondingly different ways, e.g.

- Series connections.
- Parallel connections.
- Hybrid connections.

1. Series Connection

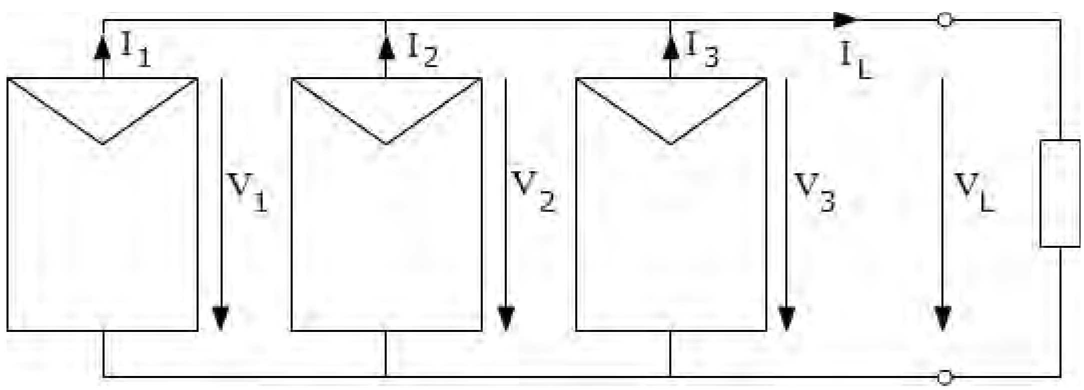
Because individual cells fail to produce a sufficiently high voltage for most applications, several cells can be connected in series so that their individual voltages are added to form the required voltage.



Series-connected modules are often termed **string**. Because cells / modules are not perfectly identical, the total current flowing through a string depends on the lowest-quality cell / module. This effect is known as **mismatching**.

2. Parallel Connection

Connecting cells / modules in parallel adds their individual currents to result in a higher total current.



Only cells / modules of the same type must be connected in parallel, as differences in type would cause compensation currents to flow, thus invalidating the addition of the individual currents.

The described connections of solar cells also apply to solar modules.

3. How Hot-spots Arise

Because it reduces a photovoltaic facility's output, shading should be avoided wherever possible. If shading cannot be avoided, its effects should be minimized by planning the photovoltaic facility expediently. Of considerable help here is the fact that a shadow's movements can be calculated just like those of the sun.

Temporary Shading

Temporary shading is caused by snow, leaves, bird droppings and soiling in general. Rain falling on the solar modules usually results in a self-cleaning effect which gets rid of the soiling again. To achieve self-cleaning, the solar modules must be inclined at an angle of at least 15°, larger angles enhancing the effect further.

Ensure that the rain water can drain off again properly without being hindered by edges on the frame or assembly elements, as this might lead to soiled borders resulting in permanent shading.

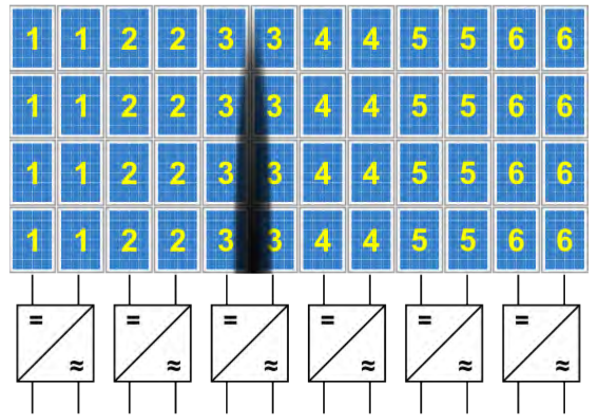
Permanent Shading

Permanent shading can be caused by objects located in the photovoltaic facility's vicinity. Large objects such as neighbouring buildings and trees can cast shadows on the solar generator, as can chimneys, projections and fittings on the roof where the solar generator is mounted.

Some sources of permanent shading can be eliminated (e.g. through relocation or felling of trees). Permanent shading from the remaining sources should be minimized by planning the solar facility appropriately.

Example of Optimal Module Arrangement

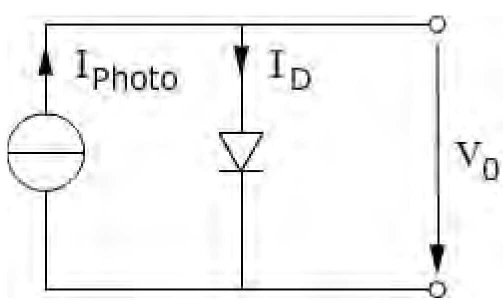
The shadow travels over the whole solar generator in the course of a day.

Wrong	Right
	
In this arrangement, the number of strings affected by shading increases progressively. In the worst circumstance, i.e. when the shadow falls on the middle of the solar generator, all strings are affected.	This arrangement not only requires less inverters, but also prevents more than two strings at a time from being shaded.

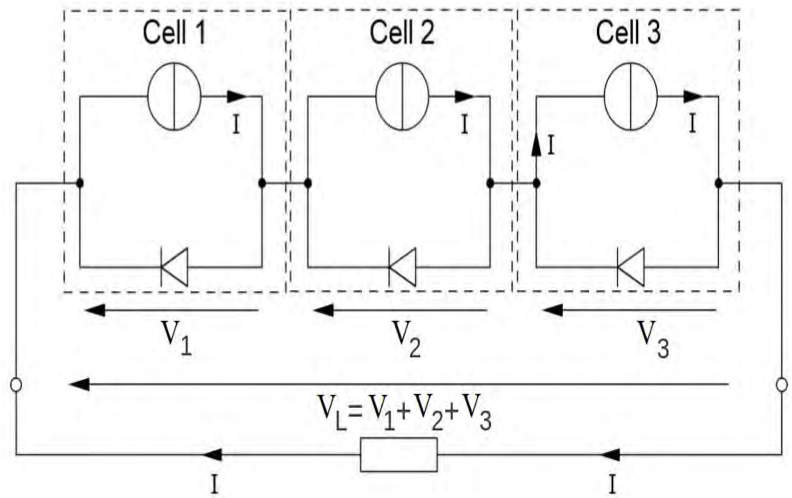
Hot-Spot

If a PV module's entire surface is shaded evenly, the module's output power naturally decreases, but the module suffers no damage. However, problems arise if the module is shaded unevenly, e.g. if just one PV cell is covered.

This can easily be demonstrated by a simplified, equivalent circuit diagram of a PV cell. This diagram represents a current source and diode connected in parallel.

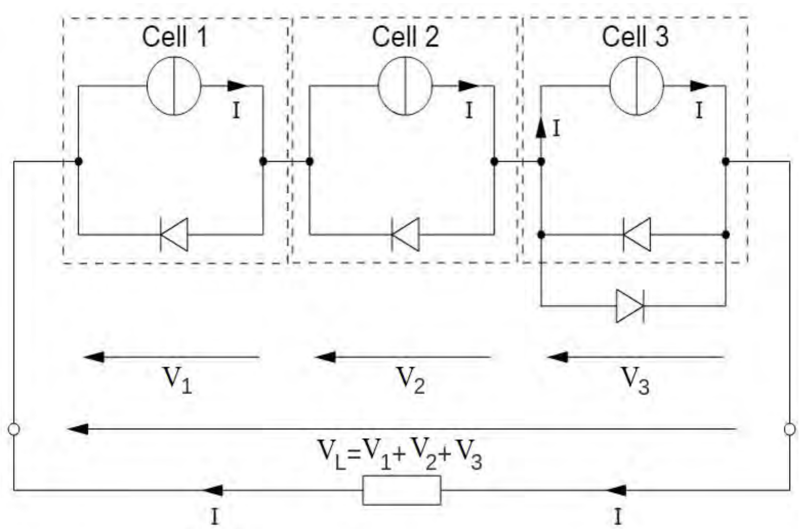


Because a covered PV cell theoretically produces no current, the current source in the equivalent circuit diagram vanishes, leaving just the diode. If connected in series with several PV cells making up a module, the covered cell's diode is switched to the reverse direction, so that the module's overall voltage can drop across this cell. If this overall voltage exceeds the diode's reverse voltage, the diode gets damaged. While this overall voltage remains below the diode's reverse voltage, the diode experiences a power loss causing the cell to heat up and potentially damage the module. This effect is termed *hot-spot*.



By-pass Diodes

Protection against hot-spots is afforded by a *bypass diode* connected anti-parallel to the PV cell. If a PV cell in a string is shaded, the cell stops supplying a voltage and the string's total voltage drops, but the flow of current is nevertheless maintained via the bypass diode.



Because the shaded PV cell no longer develops any power, it does not heat up and get damaged as a result.

Correct Handling of Photovoltaic Generators

1. Hazards

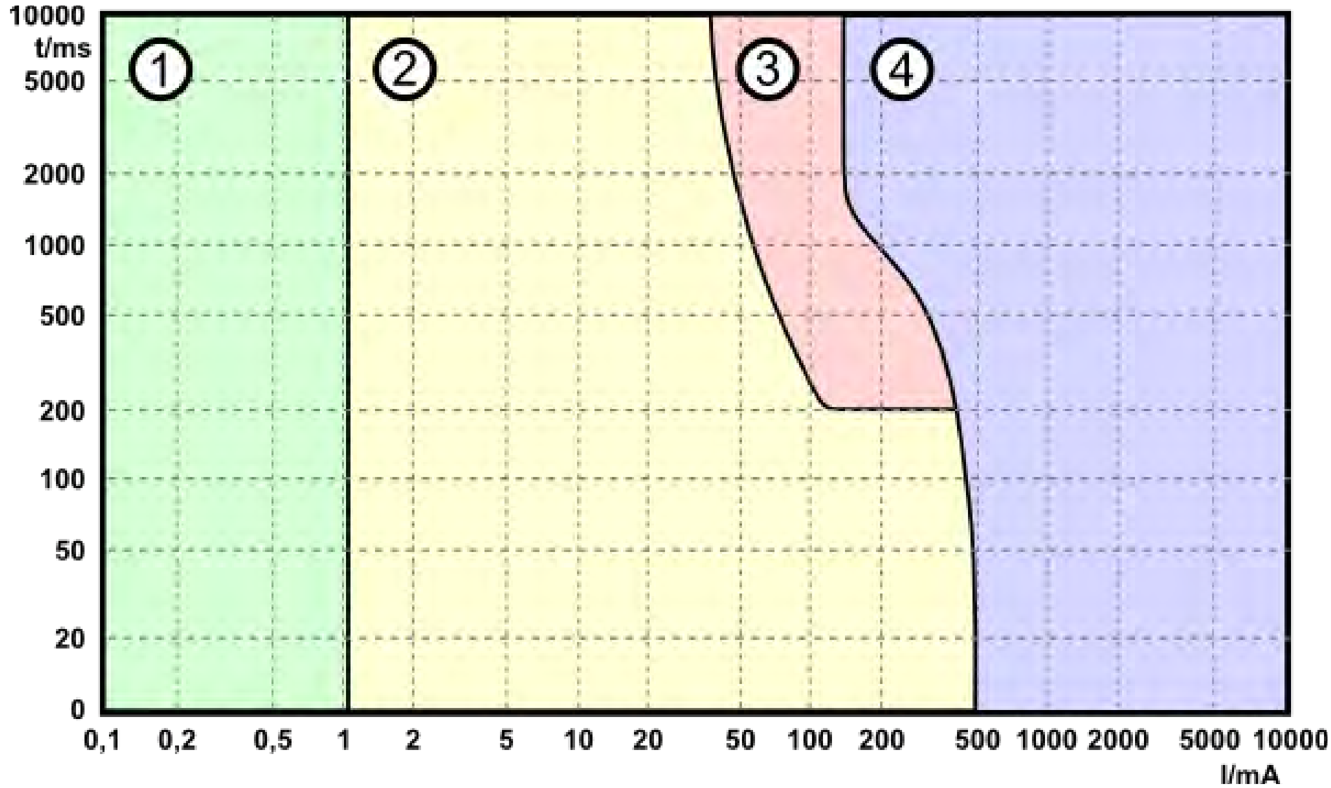
It is necessary to bear in mind a few special aspects when handling photovoltaic systems because their behaviour differs from that of other electrical facilities. The most important difference is that solar generators cannot be turned off in the presence of light. As long as a solar generator remains irradiated, it continues to produce a voltage. Under these circumstances, the only way of deactivating the solar generator is to shade it completely.

Because its short-circuit current is only slightly higher than its rated current, a photovoltaic system should not be furnished with residual-current circuit breakers or automatic/safety fuses. In the event of a short circuit, the solar generator does not shut off but instead continues to operate normally.

High voltage is another hazard posed by solar generators. When contacts or switches are opened, or while measurements are being conducted, there is a possibility of an occurrence of electric arcs which do not disappear again on their own. This exposes the installer to a risk of burns, optical glare and even electric shock.

Electric arcs can even occur on shock-proof plug-and-socket connections and consequently pose a risk

Life-threatening electric shock might be delivered by voltages as low as 120 V_{DC}. The effects of electric shock depend on amperage and the time over which the current flows through the victim's body. The effects of electric shock on the human body are illustrated in the chart below.



Range 1: No perception in general.
Range 2: No health hazards in general.
Range 3: No damage to organs in general. As it rises further in terms of amperage and exposure time, however, electric shock can cause reversible disorders in impulse generation and conduction.
Range 4: Ventricular fibrillation can occur besides the effects mentioned for range 3. Further increases in shock amperage and duration can have additional patho-physiological effects such as severe burns.
At durations of less than 100 ms, range 2 and 3 are no longer differentiable.
With regard to ventricular fibrillation, the curve is based on rising currents and current paths from the left-hand to the feet.

Protective Measures:

Since the DC output of a photovoltaic system cannot be protected by active circuit breakers, passive protection becomes all the more important.

Passive protection is improved by the following means:

- Make sure when installing a photovoltaic system that the all the wiring on the generator side has been installed in such a way that it is secure against short circuits and faults to ground. This is achieved by laying wires in such a way that they cannot touch one another and are physically protected from any damage resulting from external factors.
- For the wiring you should use single-core, double-insulated cables.
- The equipment used should conform to protection category II or have quality assurance in compliance with DIN EN 61730.

Class II equipment has enhanced or double insulation between the electricity supply and its own output voltage. It may have a metal housing and is not connected to the protective earth. Such a protective measure is called protective insulation. Even if there are live surfaces present, the enhanced insulation affords protection from any contact with components carrying a dangerous potential. Portable equipment in protection class II uses plugs with no earth contact (there may still be an earth pin but it will not be connected to anything and may actually be made of insulating plastic).

- Inside the generator's terminal cabinet, there must be strict isolation between the positive and negative sides.

2. Lightning Protection of Photovoltaic Systems

A solar module's frame and mounting structures are usually made of metal and therefore good lightning conductors. Wiring with metallic, electrical conductors is also essential. As a result, lightning bolts are capable of damaging not only the solar module, but also the solar facility's electronics.

Though installation of a photovoltaic facility generally does not increase the risk of lightning strike, suitable lightning protection is recommended due to the high investment costs of such facilities.

According to lightning protection for photovoltaic systems, lightning strikes can be divided into 3 threat categories:

- **Remote strikes (> 3000ft):** capacitive effects, usually not dangerous.
- **Near strikes (< 1600ft):** In this case, large magnetic fields induce voltage surges in the electrical installation loops, thereby potentially resulting in damage.
- **Indirect strikes:** In this case, partial lightning currents potentially causing major damage flow via the electrical installations and supply lines.
- **Direct strikes:** If no lightning protection system is present in this case, the lightning current flows via the in-house installations, which are usually damaged as a result; severe mechanical damage and fire are not ruled out either.

Effects of Lightning

- Fire.
- Significant increase in the affected object's potential compared with the surroundings.
- High induced voltages in neighbouring conductor loops.
- Heating of conductors through which lightning current flows.
- Melting at impact points.
- Explosive action of electric arcs.

Types of Lightning Protection

Internal lightning protection:
Measures against the effects of lightning current, as well as its electric and magnetic fields on metal installations and electrical equipment in the vicinity of the built facility.

External lightning protection:
Measures to prevent direct strikes on the photovoltaic facility. Current from a lightning strike is diverted to earth via long, metallic, conductive rods.

Measures to Protect Electrical Installations Against Lightning

- Prevention of direct strikes by conductive rods.
- Sufficient dimensioning of conductors for lightning current.
- The walls of housings and containers should be sufficiently thick.
- Installation of surge protection devices (SPD) on the AC, DC and data sides. Distribution of lightning current into several partial lightning currents diverted in parallel to earth.
- Realization of potential equalization for all lines leading to the facility from outside.
- Sufficient clearances between lines for conducting lightning current and neighbouring conductor loops.
- In the case of shielded cables, the shield should be earthed at both ends.
- Use of surge diverters at both ends of the line.

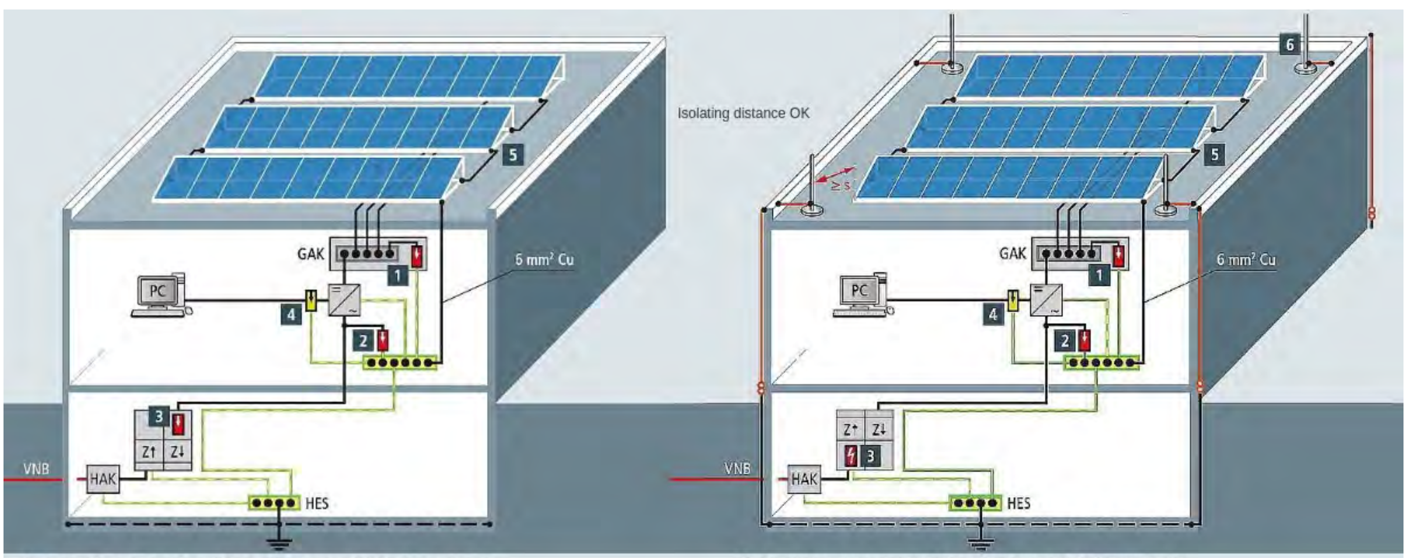
3. Roof Installed Facility

Buildings **without external lightning protection** are vulnerable to direct, near lightning strikes potentially causing dangerous overvoltages in the photovoltaic facility. In this case, a surge protection device (SPD) is needed at every relevant point.

The main objective of **external lightning protection** concepts is to avoid personal harm and material damage due to lightning strikes. One form of protection comprises arrester mechanisms (e.g. arrester rods). This is meant to prevent direct lightning strikes on photovoltaic modules and wiring. A clearance ***s*** must be maintained between all electrically conductive parts of the photovoltaic facility and the lightning protection components in order to avoid shading of the modules.

Equipotential bonding for lightning protection must also be established. This is achieved through direct connection of all metallic systems and indirect connection of all energized systems to the earthing facility via lightning current conductors.

Illustrated next are overvoltage protection concepts for photovoltaic facilities, with and without external lightning protection:



Photovoltaic system on a building with no external lightning protection

Photovoltaic system on a building with external lightning protection

GAK: Generator terminal cabinet

HAK: Building connection box

HES: Main earthing electrode

VNB: Distribution grid operator

Z: Counter

s: Isolating distance

1: DC input to power inverter

2: AC output from power inverter

3: Low-voltage input

4: Data interface

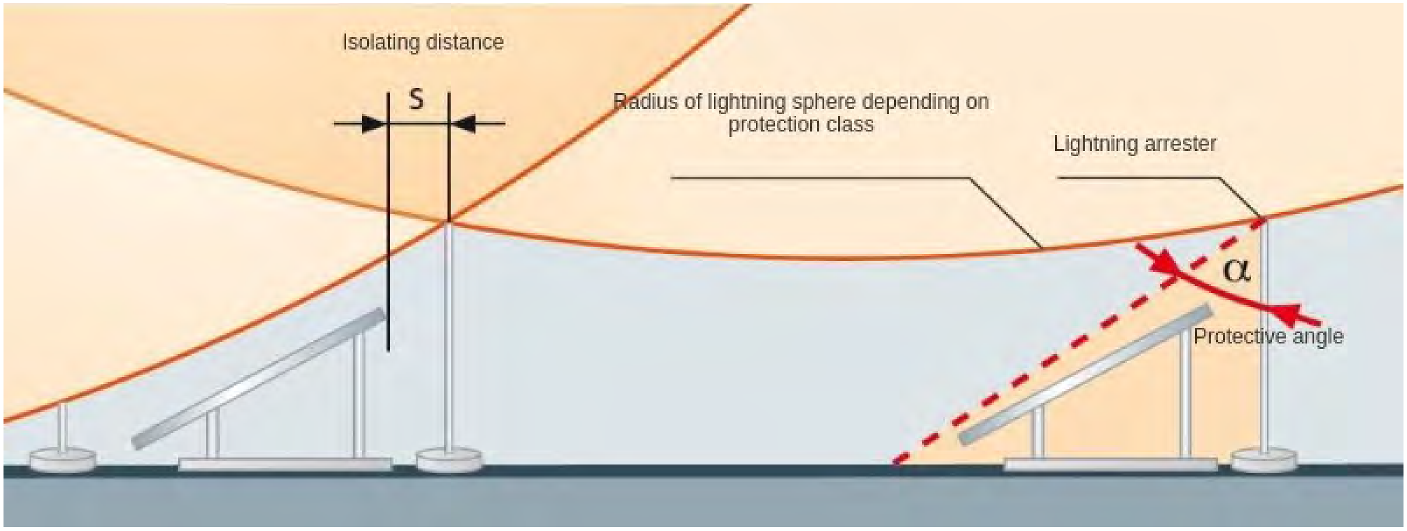
5: Functional earth - Functional potential

6: Functional earth - photovoltaic module (lightning conductor)

Source: Dehn & Söhne - Lightning protection planner

The clearance according to DIN EN 62305-3 (VDE 0185-305-3) is determined by means of two different methods:

- Protective Angle method.
- Rolling Sphere method.



Rolling Sphere method vs. Protective Angle method for determining protection zones

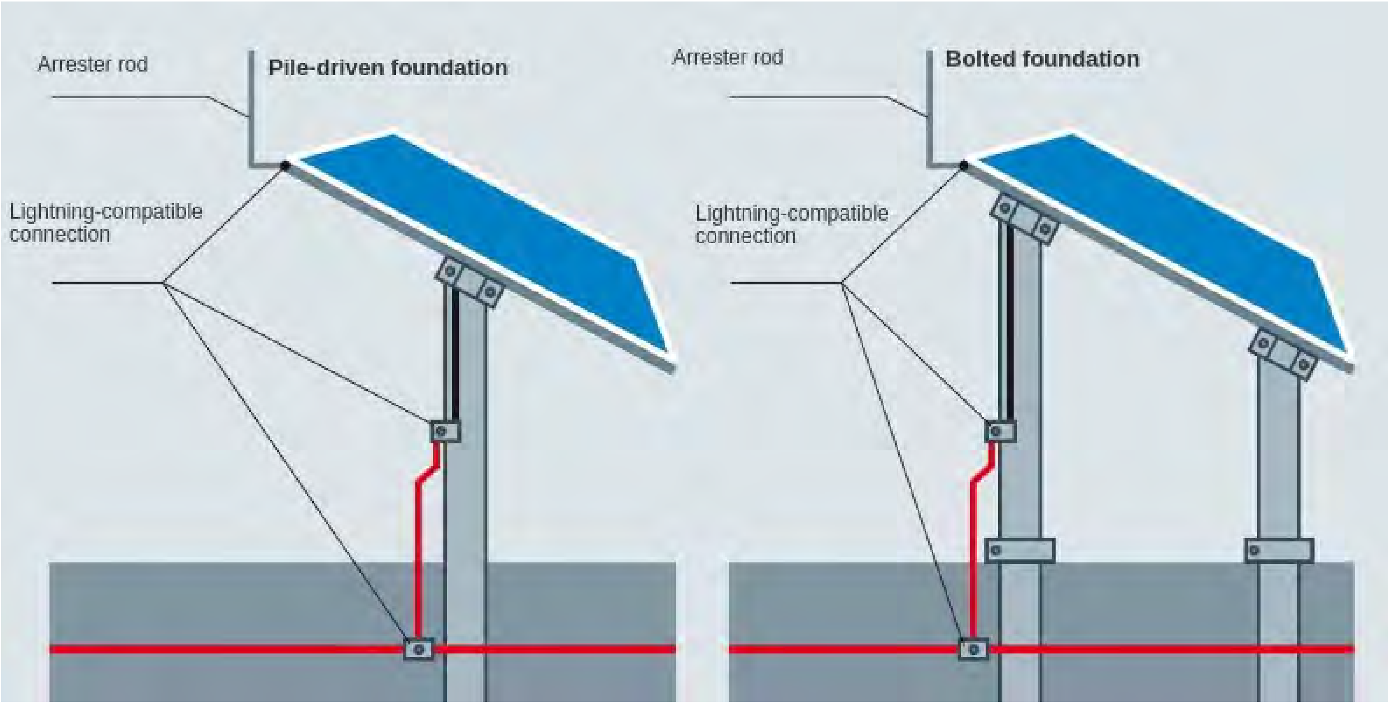
Source: Dehn & Söhne - Lightning Protection Planner

The clearance ***s*** between the photovoltaic and lightning protection facilities is usually 0.5 m to 1.0 m. Precise calculations are possible according to VDE 0185-350 (IEC 62305).

4. Solar Farms

Arrester (Protection Against Direct Lightning Strikes)

One protective zone is created by means of arrester rods. Without this protection, lightning currents would flow into the electrical system and cause severe damage there. The arrester rods should be set up so as to avoid shading of the solar modules. Pile-driven or bolted foundations can be used as earthing structures provided that their material and wall thickness meet the specifications of DIN EN 62305-3.



Pile-driven and bolted foundation with arrester and earthing facilities linked so as to allow conduction of lightning currents

Source: Dehn & Söhne - Lightning Protection Planner

Earthing Facility

This is the main constituent of lightning and voltage protection for outdoor power plants. According to DIN EN 62305-3 (VDE 0185-305-3), a mesh made of 10mm special-steel wire should be installed below frost depth. The earthing resistance should be 10 Ω (recommended value). An equipotential surface is created to reduce the voltage load on electrical cables resulting from the effects of lightning between the photovoltaic modules and the plant building.

Earthing System according to DIN EN 62305-3

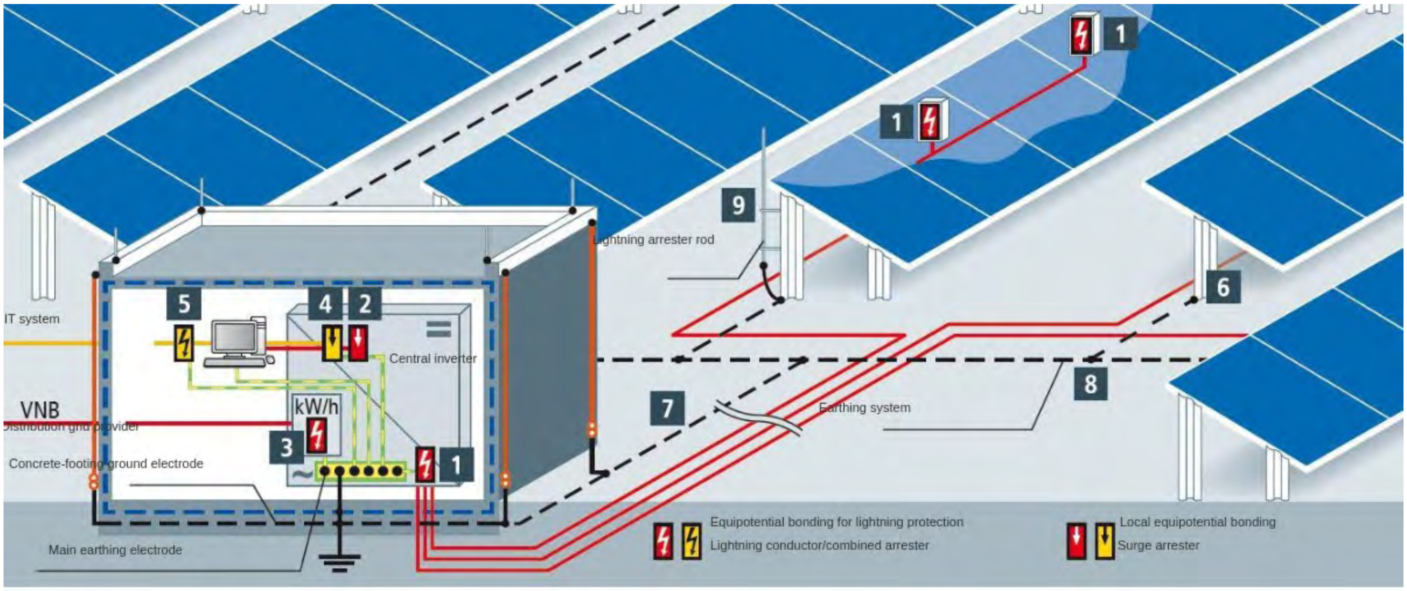
Source: Dehn & Söhne - Lightning Protection Planner

Equipotential Bonding

Direct connection of all metallic systems such as modules, wiring, and plant building, to avoid direct lightning currents through the lines inside the protected zone.

Overvoltage Protection

Surge protection devices (SPD) protect the photovoltaic power plants' internal electrical systems against mains voltage spikes due to lightning strikes.



1: DC input to inverter

2: AC supply to central inverter

3: AC power output from central inverter

4: Data interface

5: Remote maintenance

6: Equipotential bonding

7: Earthiing conductor

8: Linking element

9: Arrester system

Lightning Protection Concept of a Photovoltaic Power Plant

Source: Dehn & Söhne - Lightning Protection Planner

Photovoltaic Solar Cell Installations

1. Types of Solar Facilities

- **Non-concentrating solar heat:** Thermal solar power plants (solar collectors)
  - Heating of drinking water.
  - Room heating

- **Concentrating solar heat:** Thermal solar power plants
  - Parabolic-trough power plants: Parabolic-trough collectors focus sunlight onto an absorber pipe.
  - Solar-tower power plants: Concentration of solar radiation (megawatt range) on a single point.
  - Dish/Stirling facilities: Small units for supplying remote locations (kilowatt range).
  - Solar furnaces and solar chemistry.

- **Photovoltaics**
  - Outdoor plants: Solar farms in the megawatt range.
  - Flat-roof facilities: Kilowatt range.
  - Sloping-roof facilities: The most commonly found type of solar plant (kilowatt range).
  - Facade systems (high-rise office buildings, commercial buildings)

2. Differences Between Small and Big Facilities

Whereas small facilities (such as those on sloping roofs or facades) generating a few kilowatts are suitable for use by private households and companies, large outdoor installations (such as photovoltaic solar farms or solar-tower power plants) are intended for supplying multiple consumers (e.g. in a village or small town). These facilities are able to supply power in the megawatt range.

Solar farms require huge spaces. For example, California's Topaz solar power plant, one of the most powerful solar farms in the world, occupies an area of about 25 km^2 (9.65 mi^2).

Solar Power Plant	Type	Power/MW	Area	Location	Supplied Households
Topaz Solar Farm	Photovoltaic	550	9.65 mi^2	San Luis Obispo County, California	160,000
Sunlight Solar Farm	Photovoltaic	550	6.2 mi^2	Riverside County, California	160,000
Ivanpah	Solar tower	396	9.65 mi^2	San Bernandino County, California	140,000
Cestas (under construction)	Photovoltaic	300	0.97 mi^2	Bordeaux, France	-
Agua Caliente	Photovoltaic	290	3.75 mi^2	Arizona	100,000
Mojave	Parabolic trough collectors	280	9.3 mi^2	Los Angeles, California	88,000
Andasol	Parabolic trough collectors	150	2.3 mi^2	Granada, Spain	33,000

3. Installation of Photovoltaic Solar Cell Facilities

Installation on Inclined Roofs

Solar modules for inclined roofs are mounted at a height of 5-10 cm over the roof's surface. First, hooks are installed in the roof to serve as anchorage points for solar module frames. The illustrations below show how the hooks and framework are installed.

The advantage of roof installation is that it is fast, easy, and therefore inexpensive. Furthermore, the entire roof remains sealed. A disadvantage of roof installation is the additional load exerted on the roof.

Installation on Flat Roofs and Outdoor Surfaces

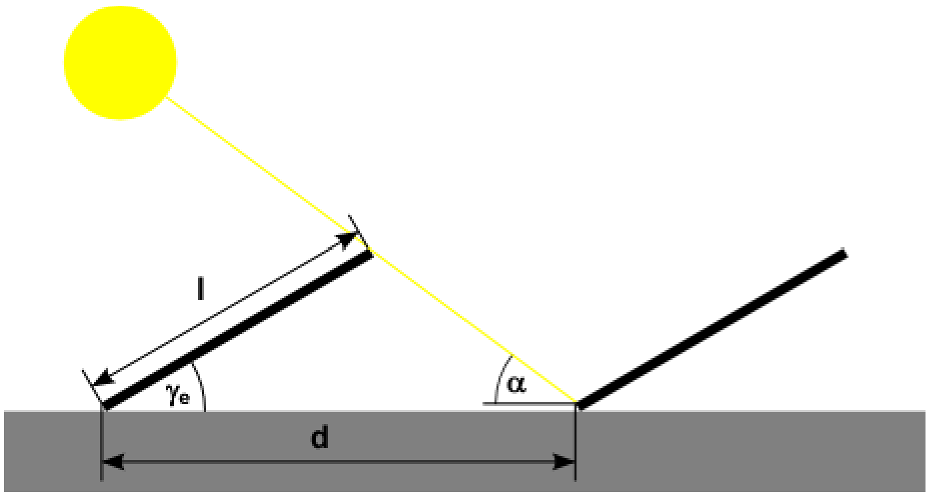
In this case, the solar generators are not mounted horizontally on the base, but at an angle on stands. Besides increasing energy yield compared with horizontal installation, the inclined stands also provide for automatic cleaning of the modules by rain and melted snow/ice. A disadvantage of inclined stands is a mutual shading of solar modules resulting in power losses. During planning of such installations, the row spacing should be optimized in order to minimized shading losses.

Because a solar module's lowermost points are affected most by shading, row spacing is optimized by considering these points in addition to the following criteria:

- Module length.
- Module inclination.
- Shading angle*.

*The shading angle corresponds to the height of the sun at which the installed rows of solar modules stop shading each other.

The shading angle is calculated on the basis of the sun's highest point on the shortest day of the year (21st December in the northern hemisphere, 21st June in the southern hemisphere).

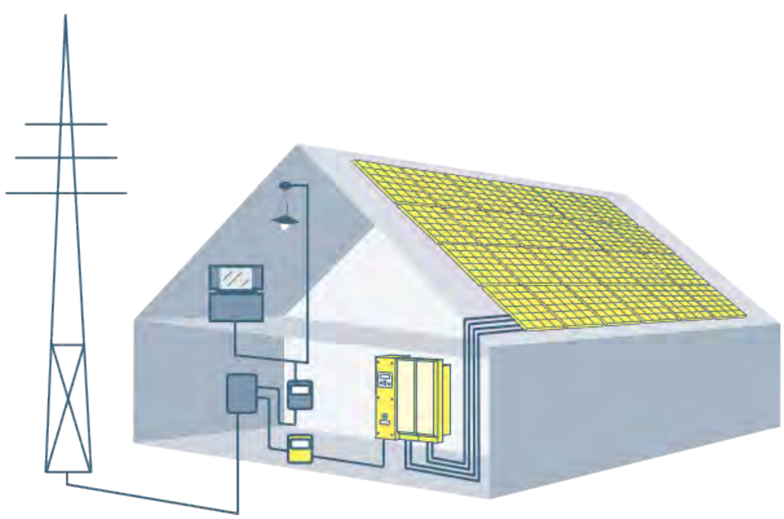


Optimal row spacing is calculated with the following equation:

$$d = \frac{\sin \gamma_e + \cos \gamma_e \cdot \tan \alpha}{\tan \alpha} * I$$

Experiments

Grid-connected Photovoltaic Systems

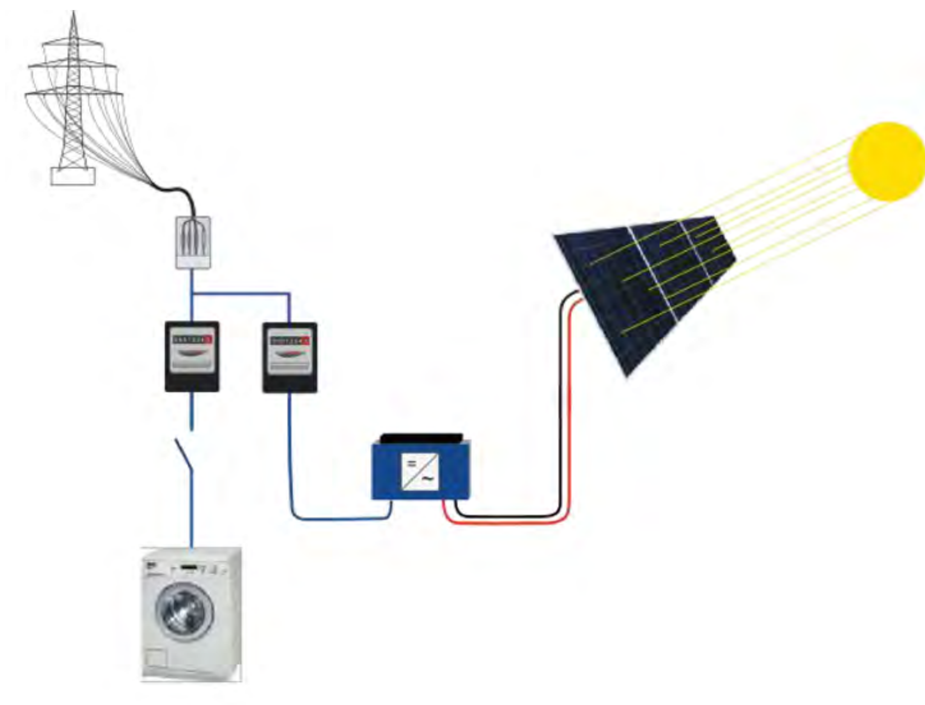


Source: www.steca.de

Layout of a Grid-connected System

While performing the usual function of directly supplying local consumers with energy, a photovoltaic facility operating in parallel with the electrical grid feeds surplus energy into the grid instead of storing it. The energy fed into the grid is recompensed by the responsible electricity supply company. Varying from one region to another, the compensation rate cannot be generalized.

Illustrated below are all the components needed to set up and operate a photovoltaic facility connected to the electrical grid.



Source: www.sunenergy.eu

Grid Connected Inverter

Forming a photovoltaic system's core, the inverter converts the solar generator's direct current into alternating current with a frequency of 50/60 Hz to feed the generated energy into the grid.

Photovoltaic mains inverters additionally perform the task of tracking the maximum power point (MPP). They ensure that the photovoltaic generator operates at the optimal point in order to deliver maximum power.

Due to changing solar irradiance, the inverter operates in the partial load range over long periods. Its efficiency should therefore have a high value even at low powers.

Line-commutated as well as self-commutated inverters are used for photovoltaic systems. Their design can include or exclude a transformer. Transformerless inverters have a higher efficiency because no transformer losses occur here.

Photovoltaic inverters rarely operate at the rated power P_N. The inverter power should normally be less than the rated power. However, it should be at least **85%** of the rated power under standard test conditions (STC*) for the solar generator. As a result, the inverter attains medium partial load ranges and, consequently, higher efficiency levels already at moderate irradiation.

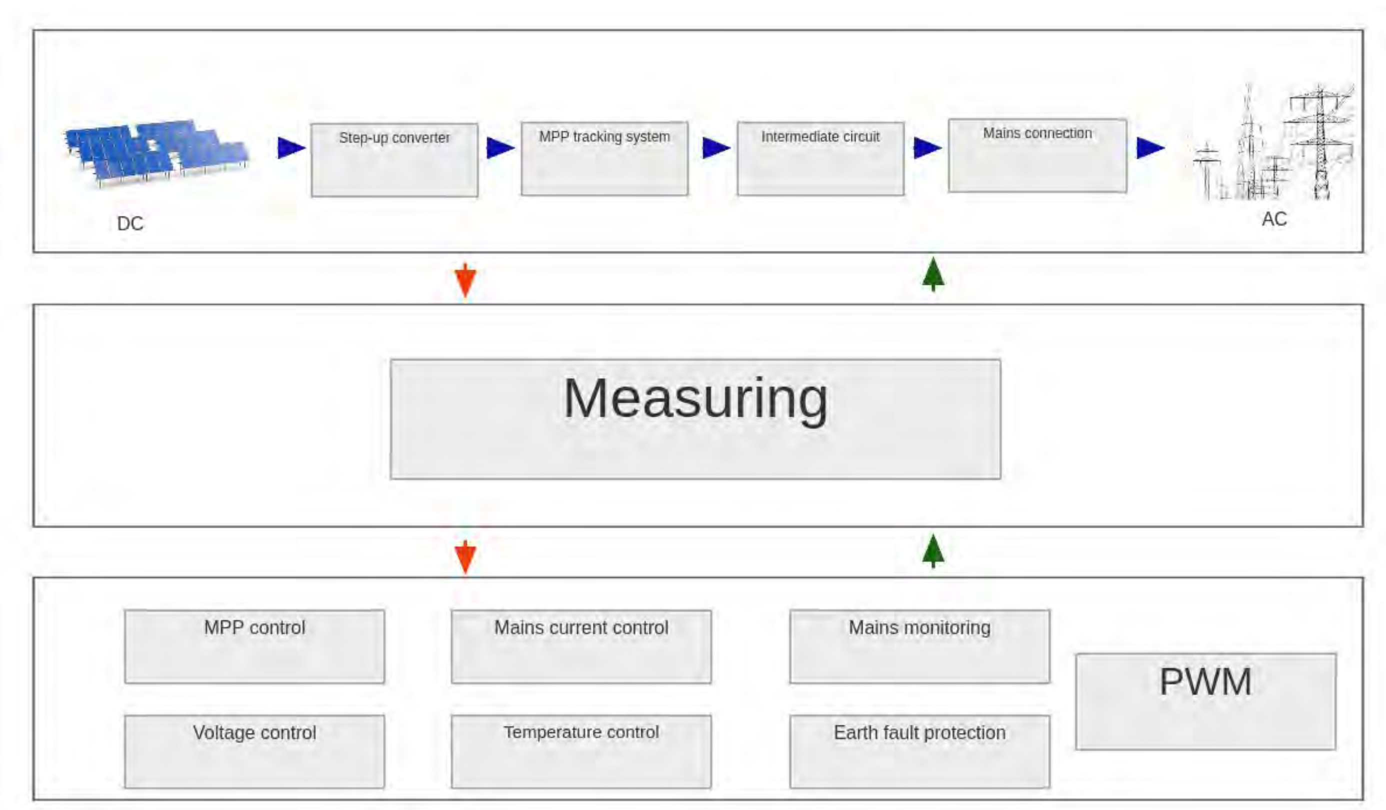
*STC (Standard Test Conditions):

- Solar radiation: 1000 W/m^2.
- Module temperature: 25°C.
- Radiation spectrum according to air mass: 1.5.
- Wind speed: 2.24 mph

Construction of a Transformerless Grid Connected Inverter

PV inverters usually consist of three blocks in the functional diagram:

- Power level: PV generator, step-up converter, MPP tracking system, intermediate circuit and mains connection.
- Signal level: Data logging and signal conversion.
- Computation level: MPP control, voltage control, temperature control, earth fault protection, monitoring, etc.



Inverter Concepts

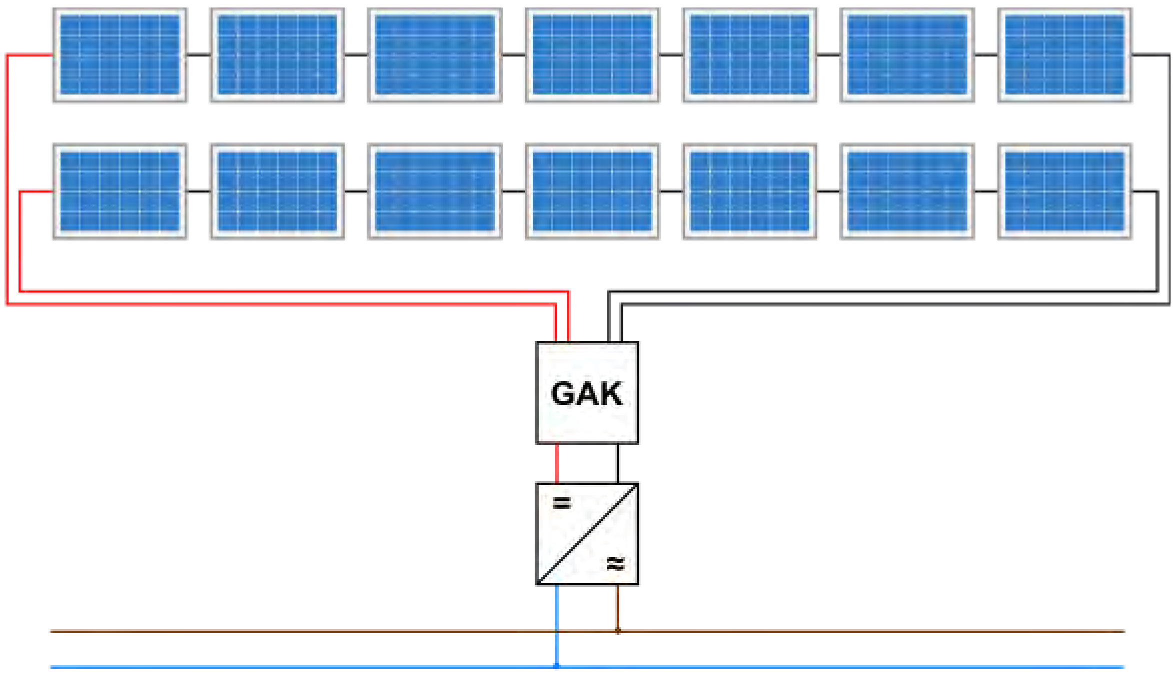
Three inverter concepts for grid-coupled photovoltaic systems have established themselves in practice:

- Central Inverter
- String Inverters
- Module Inverters

The inverter concept most suitable for a photovoltaic system depends on local circumstances and employed components.

Central Inverter

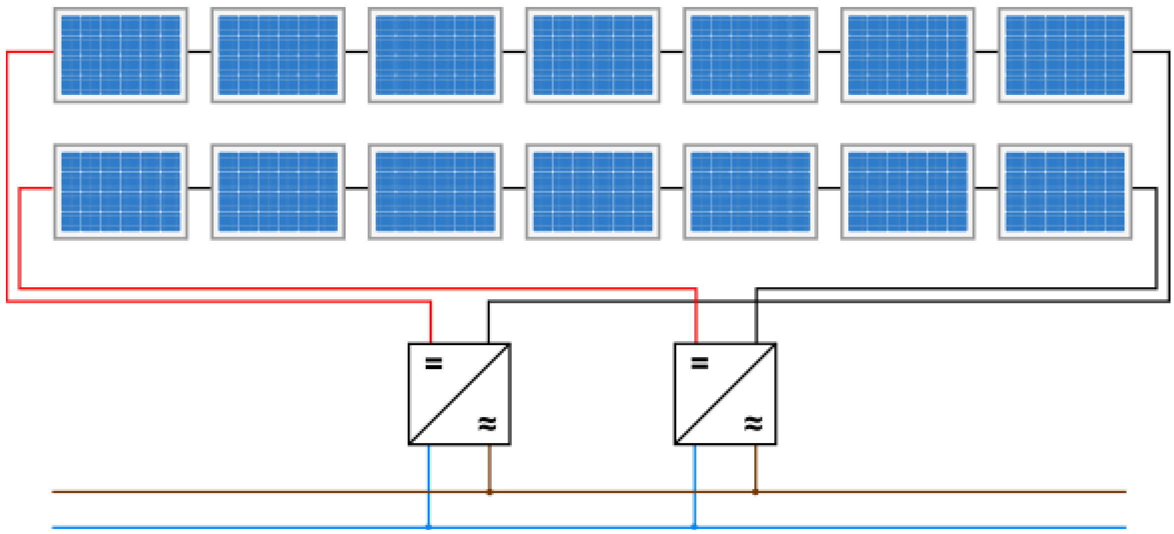
As the name suggests, all solar modules are connected to a single inverter. Even if the solar generator consists of several strings, they all converge in the generator's terminal box before connection to the inverter.



The efficiency of a photovoltaic facility with a central inverter is generally lower than that of a facility with several string inverters.

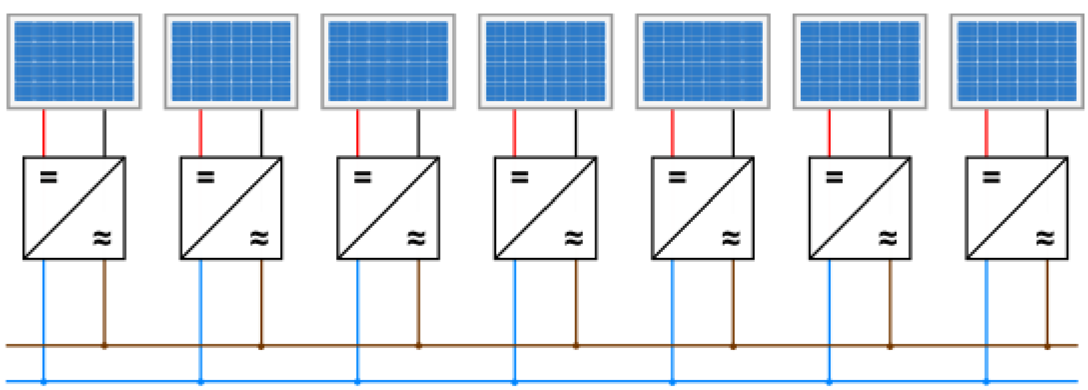
String Inverters

In this concept, the solar generator is divided into strings, each of which is connected to a separate inverter. This enables flexible matching to power requirements.



Module Inverters

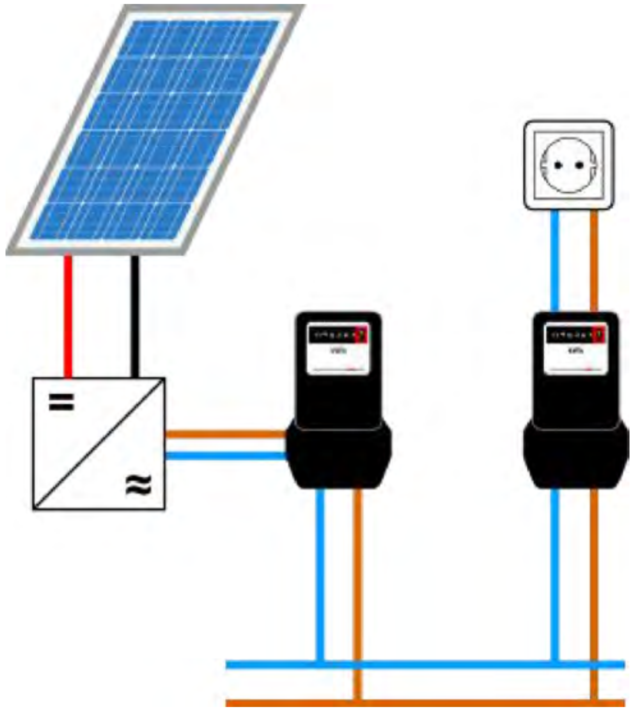
Connected directly to solar modules, module inverters can be thought of as forming photovoltaic sub-systems. For this very reason, module inverters are used preferably for low-power photovoltaic facilities.



Measurement Concepts for Photovoltaic Systems

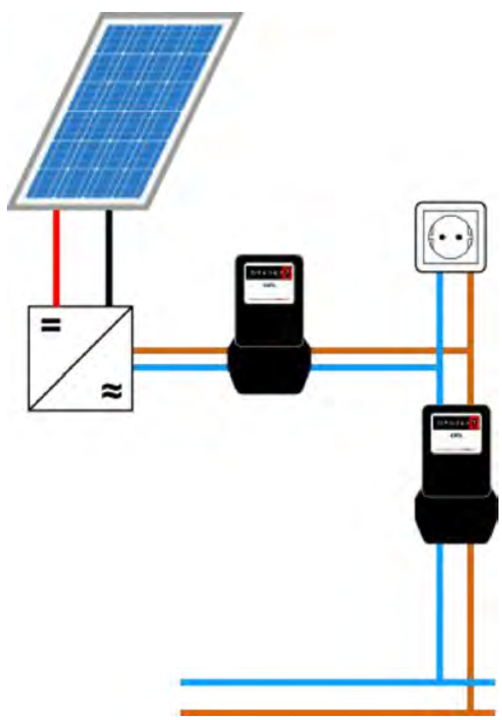
Full Feed-in

All the locally generated energy is fed into the electrical grid. For this purpose, two separate meters are installed in the house connection box. A consumption meter measures the energy obtained from the electrical grid to power local consumers. An export meter measures the energy fed into the grid. This measurement concept is illustrated below.



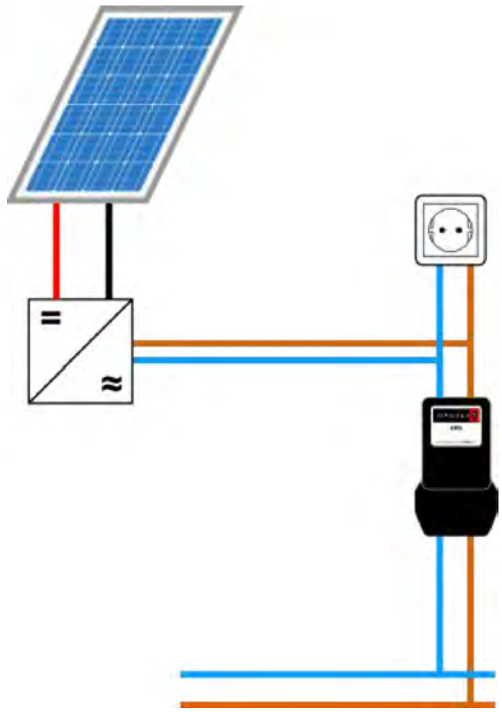
Surplus Feed-in

The local power generation facility feeds energy into the electrical grid only if local consumers are already receiving their required energy. A bi-directional meter measures the energy quantities supplied to, and received from, the electrical grid. This measurement concept is illustrated below.



Zero Feed-in

All the energy generated by the solar facility is consumed locally.

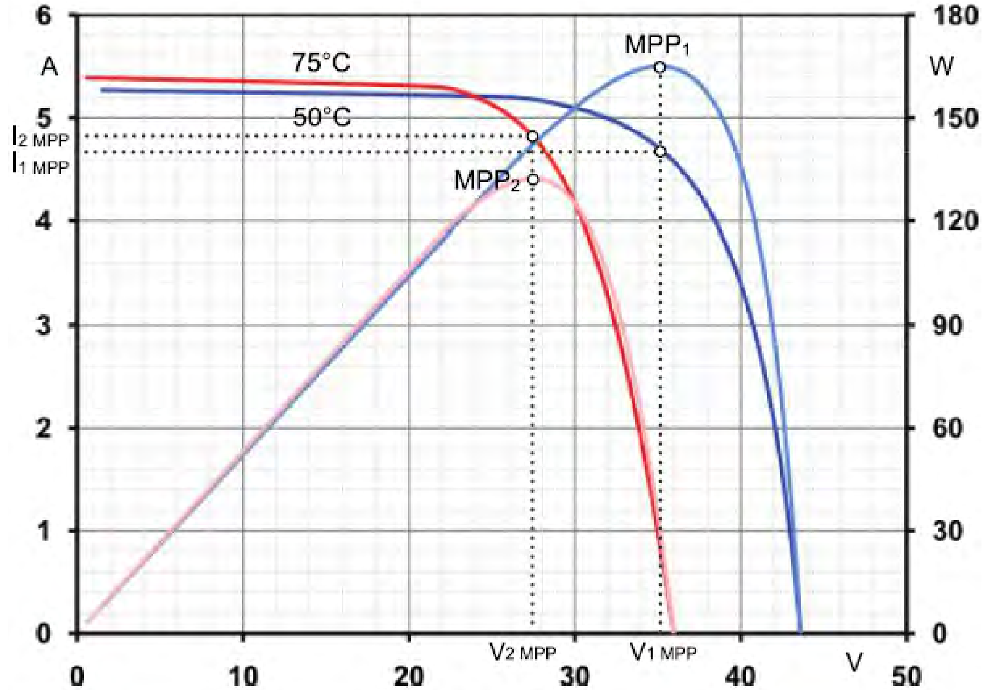


Procedure

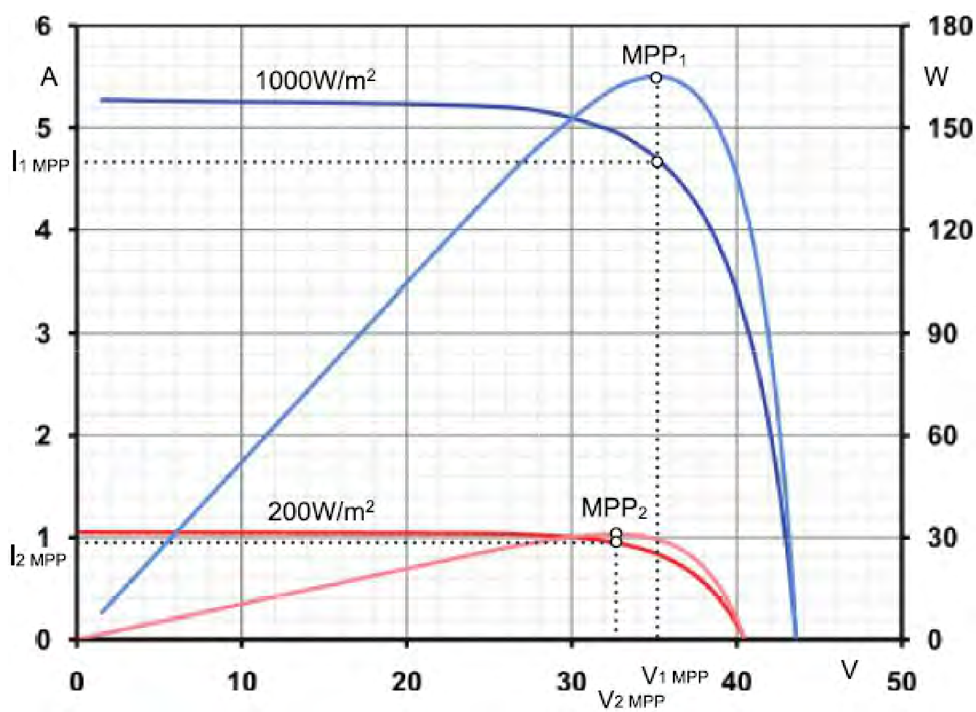
Case 1: MPP Tracking

Maximum power point (MPP) tracking is an electronic system which continually adjusts a solar module's or generator's operating point so that it coincides with the maximum power point. The irradiance and temperature on a solar generator change constantly in the course of a day, causing corresponding shifts in the MPP and consequential losses in system power. This situation can be remedied by means of an MPP tracker comprising, in principle, a transformer which sets the solar module's voltage to a value different to that on the consumer (in this case, for instance, the network inverter).

If the solar generator's operating temperature rises, the solar modules' negative temperature coefficient causes a drop in voltage. As a result, the solar generator's power drops and the maximum power point shifts as illustrated below.



Because a solar generator's current is proportional to the irradiance, a drop in irradiance causes a corresponding drop in the solar generator's current. The resultant change in the solar generator's voltage is very slight. The maximum power point shifts toward the current's axis.



A: MPP Tracking Without Shading

> **Important note:** The System operates on a **400 V$_{L-L}$** grid. The transformation station CO3208-1N7A will couple the system with the 208 V$_{L-L}$ / 60 Hz local grid.

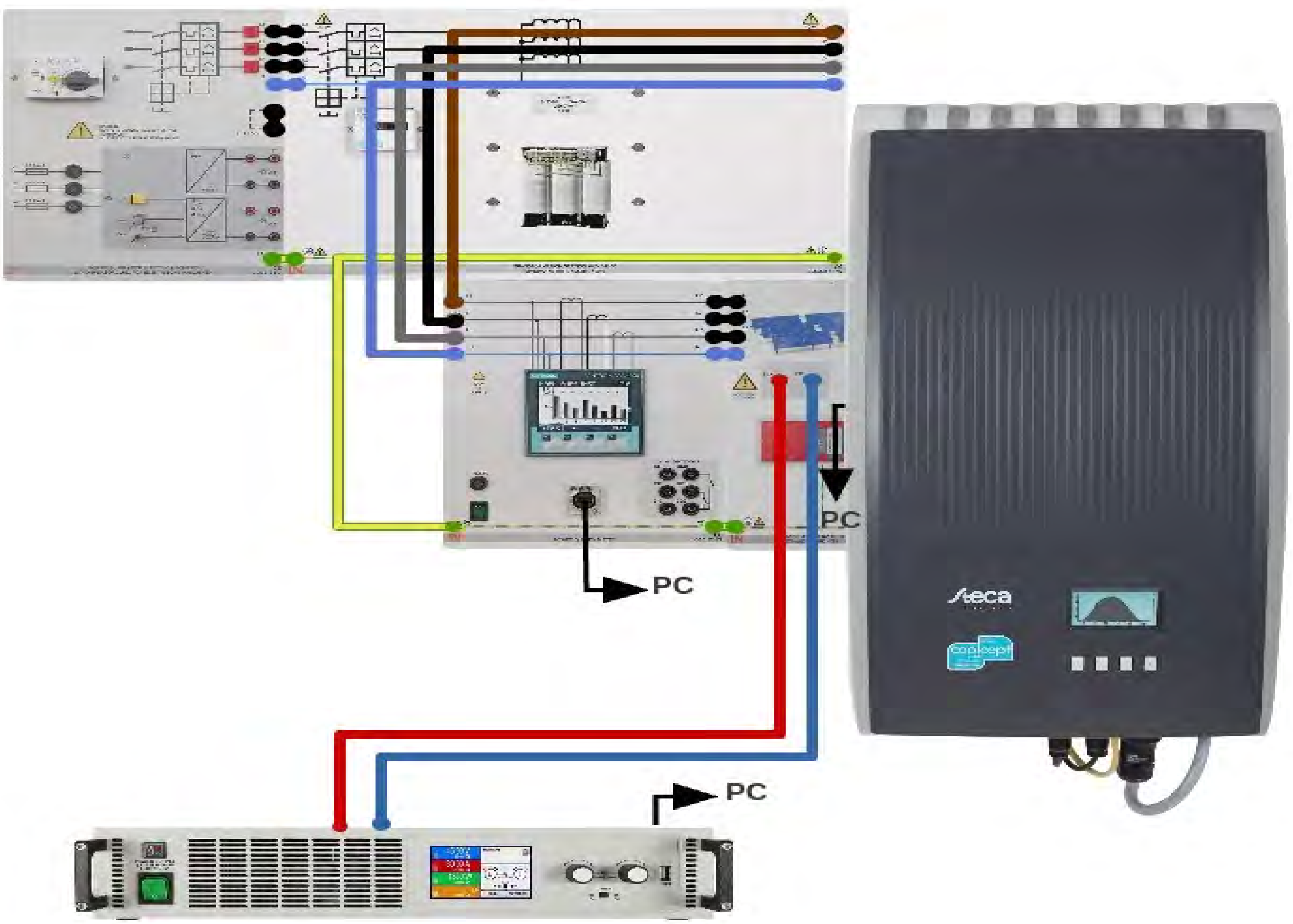


Figure 1

1. Assemble the circuit in accordance with the layout and wiring diagram of Figure 1.
2. Turn on the mains voltage via power supply CO3212-5U7 for electrical machines.
3. Turn on the "Solar panel emulator" CO3208-1P7.
4. Open the *"Solar Panel"* virtual instrument .
5. Perform the settings shown next:

SHADOW [%]	0%
SHADED MODULES	0
IRRADIANCE [%]	100%

6. Activate the "Solar Panel " virtual instrument via the POWER button.
7. Wait until the PV inverter has synchronized itself with the grid and is supplying the maximum power. This can take up to 5 minutes.
8. Copy/save the graphic's characteristic.
9. Record the variables indicated in Table 1 from "Solar panel emulator".
10. Repeat steps 8 and 9 for reduced IRRADIANCES of 80% and 50%.
11. Turn off the solar panel emulator via the POWER button of the "Solar Panel" virtual instrument.

	% Irradiance		
	100	80	50
P_DC (W)			

Table 1

B: MPP Tracking With Shading

Important note: The System operates on a **400 V_{L-L}** grid. The transformation station CO3208-1N7A will couple the system with the 208 V_{L-L} / 60 Hz local grid.

1. Keep the circuit in accordance with the layout and wiring diagram of Figure 1.
2. Turn on the mains voltage via power supply CO3212-5U7 for electrical machines.
3. Turn on the "Solar panel emulator" CO3208-1P7.
4. Open the "Solar Panel" virtual instrument 
5. Perform the settings shown next:

SHADOW [%]	20%
SHADED MODULES	**2**
IRRADIANCE [%]	100%

6. Activate the "Solar Panel" virtual instrument via the POWER button.
7. Wait until the PV inverter has synchronized itself with the grid and is supplying the maximum power. This can take up to 5 minutes.
8. Copy/save the graphic's characteristic.
9. Repeat step 8 for increased SHADOWS of 50% and 80%.

Note: The "Solar Panel" virtual instrument must be switched off for every adjustment.

10. Perform the settings shown next:

SHADOW [%]	20%
SHADED MODULES	**5**
IRRADIANCE [%]	100%

11. Repeat steps 6 to 8.
12. Repeat step 8 for increased SHADOWS of 50%, 80%, and 100%. The "Solar Panel" virtual instrument must be switched off for every adjustment.
13. Turn off the "solar panel emulator (CO3208-1P7) via the POWER button of the "Solar Panel" virtual instrument.

Case 2: Inverter´s Efficiency Factor

Inverter efficiency can be specified in terms of several parameters. These are explained briefly next.

Conversion efficiency:

Conversion efficiency indicates how efficiently the DC power (P_{DC}) supplied by the solar generator is converted into AC power (P_{AC}). The value depends on the employed components, switching frequency and magnitude of the conducted current and, thus, the device's operation under partial load.

The efficiency is then calculated from the following relationship:

$$\eta_P = \frac{P_{AC}}{P_{DC}}$$

MPP tracking efficiency:

MPP tracking efficiency indicates how effective tracking of the operating point (MPP) can be under variable conditions (radiation, cell temperature). The value depends on the control caliber.

$$\eta = \frac{1}{T_M \cdot P_{MPP}} \cdot \int_0^{T_M} v_{DC}(t) \cdot i_{DC}(t) \cdot dt$$

Total efficiency:

The total efficiency is calculated as the product of the conversion efficiency η_P and η_{MPP} efficiency:

$$\eta_{Tot} = \eta_P \cdot \eta_{MPP}$$

European efficiency:

The DIN EN 50524 standard defines European efficiency η_{EU} to permit comparisons between different types of inverter efficiency. This efficiency is specified for typical irradiation conditions in central Europe. Its value should lie between 92% - 95%. Values for transformer-less equipment are 1 to 2% higher.

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

$\eta_{x\%}$ = percentage of the rated DC power

California Energy Commission (CEC) efficiency:

$$\eta_{CEC} = 0.04 . \eta_{10\%} + 0.05 . \eta_{20\%} + 0.12 . \eta_{30\%} + 0.21 \cdot \eta_{50\%} + 0.53 \cdot \eta_{75\%} + 0.05 \cdot \eta_{100\%}$$

Determination of the Inverter´s Efficiency Factor

> **Important note:** The System operates on a **400 V_{L-L}** grid. The transformation station CO3208-1N7A will couple the system with the 208 V_{L-L} / 60 Hz local grid.

1. Keep the circuit in accordance with the layout and wiring diagram of Figure 1.
2. Turn on the mains voltage via power supply CO3212-5U7 for electrical machines.
3. Turn on the "Solar panel emulator" CO3208-1P7.
4. Open the "Solar Panel" virtual instrument .
5. Perform the settings shown next:

SHADOW [%]	0%
SHADED MODULES	0
IRRADIANCE [%]	approx. 5%

6. Activate the "Solar Panel" virtual instrument via the POWER button.
7. Wait until the PV inverter has synchronized itself with the grid and is supplying the maximum power. This can take up to 5 minutes.
8. Vary the IRRADIANCE of the Solar Panel from 5% to 100% as indicated by the Table 2, and enter the values of the active power at the inverter output (P_{AC}), as well as the DC active power at the input (P_{DC}). The AC active power can be read directly via the power quality meter (CO5127-1S). For this, set the total power display mode.

> **The device indicates negative AC active powers. Enter the absolute amounts into the Table 2. Before reading the values, wait until a "stable" operating point has formed.**

9. Then calculate and record the conversion efficiency from the given equation in Table 2.
10. After you have carried out all measurements and calculations, turn off the "solar panel emulator (CO3208-1P7) via the POWER button of the "Solar Panel" virtual instrument.

	CO5127-1S	Solar Panel Emulator	Efficiency
IRRADIANCE in %	**$\lvert P_{AC} \rvert$ in W**	**$\lvert P_{DC} \rvert$ in W**	**$\eta = P_{AC} / P_{DC}$**
5			
10			
20			
30			
50			
75			
100			

Table 2

Case 3: Requirements for Changing Mains Connections

The share of renewables in energy production is raising requirements concerning mains connection conditions:

Requirements for Grid Operators

The grid operator is entitled to demand a reduction of the feed-in power or perform a system shutdown in the following cases:

- Potential threat to safe operation of the system.
- Bottlenecks or risk of overload in the operator's grid.
- Risk of formation of isolated grids.
- Hazard to static or dynamic grid stability.
- Increases in frequency posing a hazard to the system.
- Repairs and construction measures.
- As part of generation management / network security management / feed-in management.

Requirements for Generation Units

The grid connection conditions specify, among other things, technical rules for trouble-free operation of distribution and transmission grids as well as fault management. This leads to minimum technical requirements concerning mains connections for generation facilities reliant on renewable energy sources.

Special requirements for photovoltaic inverters for grid-connected systems:

- Absolutely synchronous operation with the interconnected grid.
- Automatic activation and synchronization given sufficient irradiation, and deactivation given insufficient irradiation.
- No feed of DC power into the grid.
- Immediate switch-off in the event of a grid failure (avoidance of off-grid operation). Capacity reduction (de-rating) should be available for the purpose of reducing active power. This is typically achieved through gradual power reduction in stages comprising 100%, 60%, 30%, 0%.
- Service life of 15 to 20 years.
- Error-free tracking of the maximum power point.
- High efficiency.
- Minimal consumption of reactive power from the mains. During a feed of active power of less than 13.8 kVA by the generator units, a supply of reactive power should possible at every operating point. The displacement factor at the mains connection point should lie in the range from $\cos \varphi = 0.95_{\text{under-excited}}$ to $\cos \varphi = 0.95_{\text{over-excited}}$.
- Protection against overvoltage.
- Minimal generation of high-frequency interference voltages (EMC standards EN6100-6-3). Sinusoidal current waveform (EN6100-3-2).
- DC-side filtration.
- Energy supply facilities are to be built and operated in a manner guaranteeing technical safety.

Requirements for Grids

- Expansion of transmission networks (for example, to distribute large amounts of energy from offshore wind power plants).
- Establishment of smart grids to adapt load profiles to energy supply, and reduce the size of the required energy storage elements.

Active Power Derating

> **Important note:** The System operates on a **400 V_{L-L}** grid. The transformation station CO3208-1N7A will couple the system with the 208 V_{L-L} / 60 Hz local grid.

1. Keep the circuit in accordance with the layout and wiring diagram of Figure 1.
2. Turn on the mains voltage via power supply CO3212-5U7 for electrical machines.
3. Turn on the "Solar panel emulator" CO3208-1P7.
4. Open the "Solar Panel" virtual instrument .
5. Perform the settings shown next:

SHADOW [%]	0%
SHADED MODULES	0
IRRADIANCE [%]	100%

6. Activate the "Solar Panel" virtual instrument via the POWER button.
7. Wait until the PV inverter has synchronized itself with the grid and is supplying the maximum power. This can take up to 5 minutes.
8. Save the file from the link "EPH3_Derating_Manual_us.pvc“ to a working directory on your PC.
9. Open the SCADA viewer and select the file named "EPH3_Derating_Manual_us.pvc".
10. Perform the communication settings such that communication can be established with all devices. For related instructions, refer to the chapter titled "Configuring SCADA for PowerLab".
11. Activate SCADA via the start-stop symbol or F5.

12. Use the de-rating slider to perform a power reduction from 0% to 100% according to the Table 3 and enter the values of the active power P_{Grid} at the inverter output.
13. After you have carried out all measurements, set the de-rating slider back to 50%.

The device indicates negative AC active powers. Enter the absolute amounts into the Table 3. Before reading the values, wait until a "stable" operating point has formed.

Active Power Derating in %	|P| in W (Grid)
0	
50	
60	
70	
80	
90	
100	

Table 3

14. Determine the MPP operating point at a derating of 50%.
15. Copy/save the graphic's characteristic from the *Solar Panel* virtual instrument.
16. Repeat steps 14 and 15 for derating settings of 60% and 80%.
17. Set the de-rating to 70%.
18. Use the IRRADIANCE slider to reduce the irradiance from 100% to 0% in accordance with the Table 4, and enter the values of the resultant active power P_{Grid} at the inverter output.
19. Repeat step 18 at a de-rating of 80%.
20. Reset the derating to 0%.
21. Deactivate SCADA via the start-stop symbol or F5.

The device indicates negative AC active powers. Enter the absolute amounts into the Table 4. Before reading the values, wait until a "stable" operating point has formed.

	70%	80%
IRRADIANCE in %	**|P| in W (Grid)**	**|P| in W (Grid)**
100		
80		
60		
40		
20		
0		

Table 4

Case 4: Provision of Reactive Power

In addition to purely active power supply, modern inverters can also feed inductive or capacitive power into the grid.

Directives concerning generation facilities connected to medium-voltage grids stipulates that a feed of active power by generator units demands an ability to supply, at every operating point, a reactive power corresponding to at least the following power factor at the mains connection point:

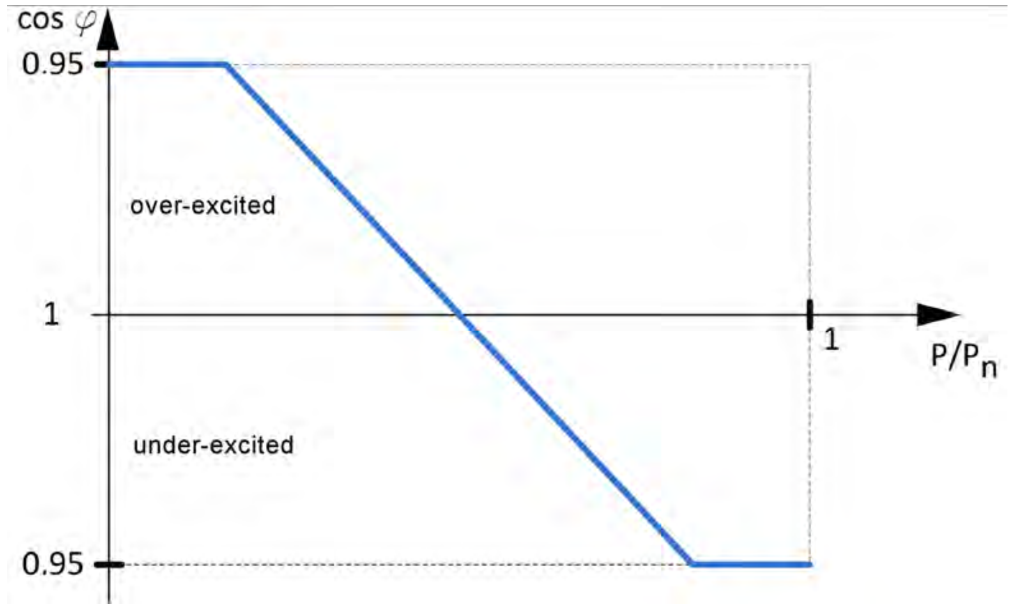
$$\cos \varphi = 0.95_{\text{under-excited}} \text{ to } \cos \varphi = 0.95_{\text{over-excited}}.$$

The grid operator can define any one of the following alternatives:

- A fixed setpoint value for the power factor cos φ.
- A fixed reactive power in MVar.
- A characteristic for cos φ (P) or Q (V).

The last one should be achieved automatically. This is to be reached within 10 seconds for the cos φ (P) characteristic. The time for the Q (V) characteristic can be set between 10 seconds and 1 minute.

Example of a cos φ (P) characteristic:



The following table indicates the requirements for reactive power supply in accordance with inverter power.

Inverter power / kVA	**Reactive power supply**
< 3.68	Not necessary
3.68 < P < 13.8	cos φ 0.95 inductive/capacitive
> 13.8	cos φ 0.9 inductive/capacitive

Provision of Reactive Power

Important note: The System operates on a **400 V_{L-L}** grid. The transformation station CO3208-1N7A will couple the system with the 208 V_{L-L} / 60 Hz local grid.

1. Keep the circuit in accordance with the layout and wiring diagram of Figure 1.
2. Turn on the mains voltage via power supply CO3212-5U7 for electrical machines.
3. Turn on the "Solar panel emulator" CO3208-1P7.
4. Open the "Solar Panel" virtual instrument .
5. Perform the settings shown next:

SHADOW [%]	0%
SHADED MODULES	0
IRRADIANCE [%]	40%

6. Activate the "Solar Panel" virtual instrument via the POWER button.
7. Wait until the PV inverter has synchronized itself with the grid and is supplying the maximum power. This can take up to 5 minutes.
8. Save the file from the link "EPH3_Provision_Reactive_Power_us.pvc" to a working directory on your PC.
9. Open the SCADA viewer and select the file named "EPH3_Provision_Reactive_Power_us.pvc".
10. Perform the communication settings such that communication can be established with all devices. For related instructions, refer to the chapter titled "Configuring SCADA for PowerLab".
11. Activate SCADA via the start-stop symbol or F5.
12. Adjust the irradiance of the Solar Panel virtual instrument until the inverter supplies a power of approximately 500 W.
13. Select an inductive displacement factor.
14. Vary the displacement factor cos φ according to Table 5, and enter the inductive reactive power in the same table.
15. Repeat step 14 at a power value of 1000 W.

	500 W	**1000 W**
Cos ϕ	**Q in Var**	**Q in Var**
1.00		
0.95		
0.90		
0.85		
0.80		

Inductive Displacement Factor
Table 5

16. Adjust the irradiance of the Solar Panel virtual instrument until the inverter supplies a power of approximately 500 W.
17. Select an capacitive displacement factor.
18. Vary the displacement factor cos φ according to Table 6, and enter the capacitive reactive power in the same table.
19. Repeat step 18 at a power value of 1000 W.

	500 W	**1000 W**
Cos ϕ	**Q in Var**	**Q in Var**
1.00		
0.95		
0.90		
0.85		
0.80		

Capacitive Displacement Factor
Table 6

20. Do **not** switch off the Solar Panel virtual instrument.
21. Adjust the irradiance to **10%** and the displacement factor to **1 (inductive)**.
22. Vary the irradiance from 10% to 100% according to the Table 7 and enter the values of the active power at the inverter output (P_{AC}) as well as the displacement factor cos φ. The measured values can be read directly via the power quality meter (CO5127-1S), but also more conveniently and at a glance in SCADA.
23. After you have carried out all measurements, deactivate SCADA via the start-stop symbol o  or F5.

The power quality meter indicates negative AC active powers. Enter the absolute amounts into the Table 7.

IRRADIANCE in %	$\lvert P_{AC} \rvert$ in W	Cos ϕ
0	0	0.00
10		
15		
20		
40		
70		
100		

Displacement factor cos φ
Table 7

Case 5: Automatic Release Point

The automatic release point is a safety mechanism which monitors the power supply mains and prevents inadvertent formation of an isolated system should the supply mains fail; for this purpose, the solar generator is disconnected from the power mains to prevent power feedback. Monitored variables include voltage, frequency and impedance of the mains. Formations of isolated systems are indicated by jumps in mains impedance or overshoots of frequency / voltage limits. Prescribed additionally for inverters without a transformer are insulation monitoring and an all-current sensitive circuit breaker.

The automatic release point has a redundant (dual) configuration in order to minimize the risk of failure. For this reason, the presence of an automatic release point in a photovoltaic system eliminates the need for installing and checking a release mechanism accessible by the power mains operator.

In the event of parameters going above or below the following limits, the system must shut down within 200 ms:

➢ Voltage in conductor being fed: $V \leq 80\%\ V_N$ and $V \geq 115\%\ V_N$
➢ $106\%\ V_N \leq V \leq 115\%\ V_N$, measured as an average over a period of 10 minutes according to DIN VDE 0126 -1 -1 (the value is specified by the electricity provider responsible for the interconnection)
➢ Frequency: $f \leq 57.5$ Hz and $f \geq 60.2$ Hz

Study of the Behaviour of a PV System in Case of Power Failure

Important note: The System operates on a **400 V_{L-L}** grid. The transformation station CO3208-1N7A will couple the system with the 208 V_{L-L} / 60 Hz local grid.

1. Keep the circuit in accordance with the layout and wiring diagram of Figure 1.
2. Turn on the mains voltage via power supply CO3212-5U7 for electrical machines.
3. Turn on the "Solar panel emulator" CO3208-1P7.
4. Open the "Solar Panel" virtual instrument .
5. Perform the settings shown next:

SHADOW [%]	0%
SHADED MODULES	0
IRRADIANCE [%]	100%

6. Activate the "Solar Panel" virtual instrument via the POWER button.
7. Wait until the PV inverter has synchronized itself with the grid and is supplying the maximum power. This can take up to 5 minutes.
8. Determine the values of the AC voltage and AC power via the power quality meter (CO5127-1S), and enter them into the fields provided in Table 8.
9. Simulate a failure of the supply network by disconnecting the inverter from the mains via the CO3212-5U7 supply unit (turn off).

10. Determine the values of the AC voltage and AC power via the power quality meter (CO5127-1S), and enter them into the fields provided in Table 8.

	Step 8	Step 10
$V_{L\text{-}N}$ (V)		
$P_{\_AC}$ (W)		

PV System Power Failure

Table 8

Case 6: Monitoring of Photovoltaic Systems

Source: www.steca.com

Monitoring of photovoltaic systems makes it possible to acquire data regarding the systems, which can then be processed via a user interface on a PC.

Features:

- Automatic data acquisition and storage.
- Despatching of fault notifications via e-mail, SMS or fax to operators as long as an internet connection is present.
- Display of electricity consumption.
- Display of yield data. (daily, monthly, yearly).
- Possibility for operators to remotely shut down the system.

Recording of Yield Data

> **Important note:** The System operates on a **400 V_{L-L}** grid. The transformation station CO3208-1N7A will couple the system with the 208 V_{L-L} / 60 Hz local grid.

1. Keep the circuit in accordance with the layout and wiring diagram of Figure 1.
2. Turn on the mains voltage via power supply CO3212-5U7 for electrical machines.
3. Turn on the "Solar panel emulator" CO3208-1P7.
4. Open the "Solar Panel" virtual instrument  .
5. Perform the settings shown next:

SHADOW [%]	0%
SHADED MODULES	0
IRRADIANCE [%]	100%

6. Configure the sun's path following the next settings:

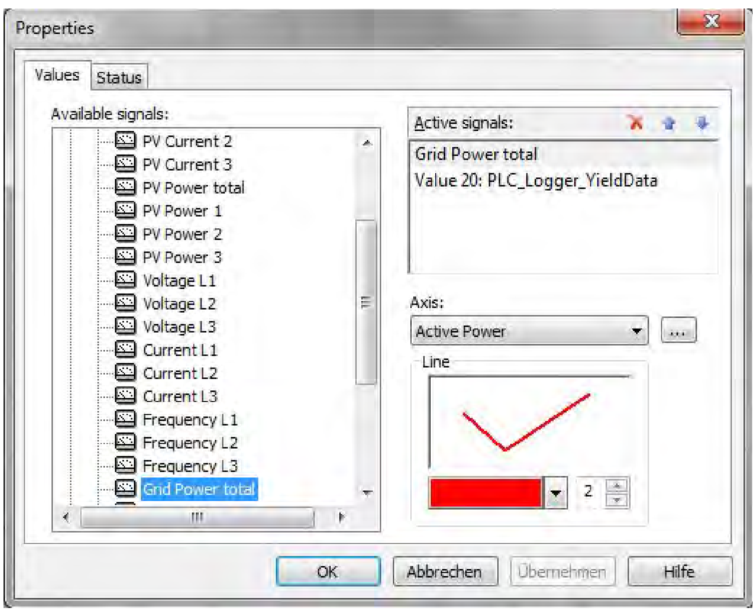
- *First alternative*: Load the file from the link " EPH3_SolarPanel_YieldData_Week.sopan ". All settings necessary for the following measurement have been prepared here. Save the file in a temporary folder. Open the file with the "Solar Panel Emulator" software.

- *Second alternative*: Open the CSV file named " EPH3_SolarPanel_YieldData_Week.csv " and copy the values in column B.In the window for the sun's path, click the right mouse button and select "Import from clipboard".

- Perform the following settings for the axis:

Axis	Title	Minimum	Maximum	Division
Irradiance	E in %	0	100	10
Time	t in minutes	0	14	2

7. Activate the "Solar Panel" virtual instrument via the POWER button.
8. Set the irradiance to 100% and wait until the PV inverter has synchronized itself with the grid and is supplying the maximum power. This can take up to 5 minutes.
9. Save the file from the link " EPH3_Yield_Data.pvc " to a working directory on your PC.
10. Open the SCADA viewer  and select the file named "EPH3_Yield_Data.pvc".
11. Perform the communication settings such that communication can be established with all devices. For related instructions, refer to the chapter titled "Configuring SCADA for PowerLab".
12. Open SCADA's "Logger" virtual instrument via the Instruments |Logger menu path. Click on ↑Y and perform the settings shown next.



Axis	Title	Active signals	Colour	Min	Max	Division
Active Power	P in W	Total grid power (CO3208-1N)	Green	0	1500	100
Daily yield data	Yield Data in kWh	Value20: PLC_Logger_YieldData (LUCAS NÜLLE SCADA SPS)	Red	0	50	5
Time	t in s		Black	0	840	60

Note: In the model, 2 minutes are equivalent to one day. This permits the measurement results to be transferred as quickly as possible.

13. Activate SCADA via the start-stop symbol or F5.
14. Select "Use profile" for the irradiance in the Solar Panel virtual instrument.
15. Now **quickly** activate the solar logger via the Start button on the SCADA user interface.
16. Let the simulation run until the weekly yield data have been fully obtained (takes about 14 minutes).
17. Stop the recording in the logger.
18. Enter the obtained readings in the Table 9 and the value of the total weekly yield into the field provided.
19. After you have carried out all measurements, copy/save the graphic of the SCADA logger's measurement results.
20. Deactivate SCADA via the start-stop symbol or F5.

Day	**kWh**	**Total Weekly Yield**
Monday		**kWh**
Tuesday		
Wednesday		
Thursday		
Friday		
Saturday		
Sunday		

Yield Data

Table 9

Report Questions

1. Display/show the graphic's characteristics of the MPP tracking without shadow with 100%, 80%, and 50% irradiance.
2. What does the maximum power point (MPP) in a PV inverter depend on?
3. What is needed to operate the PV inverter at its maximum power point (MPP)?
4. How does the direct voltage and direct current change with decreasing irradiance in the MPP tracking without shadow?

5. Display/show the graphic's characteristics of the MPP tracking with 100% irradiance and 2 shaded modules with 20%, 50%, and 80% shadow.
6. What did you observe about the search for the maximum power point (MPP) in the case of shaded modules?
7. What happens to the maximum power point (MPP) when two modules are shaded?
8. What effect does having two solar modules in shadow have on the solar generator as a whole and what effect does one solar cell in shadow have on a solar module?
9. Display/show the graphic's characteristics of the MPP tracking with 100% irradiance and 5 shaded modules with 20%, 50%, 80%, and 100% shadow.
10. What effect does 100% shading of 5 solar modules have on the PV inverter?
11. Why is the search algorithm not able to find the maximum power point (MPP) at a shadow of 80% and 100% in the MPP tracking with shadow?
12. Plot $\eta = f(|P_{AC}|)$ from values of Table 2.
13. According to the plot of question, what can be said about the conversion efficiency?
14. Calculate the European efficiency (η_{EU}) and California Energy Commission efficiency (η_{CEC}).
15. The inverter's European efficiency is 98.2% according to the data sheet. How can the difference between the measured and specified values be explained?
16. How does the power fed into the grid respond to changes in irradiance?
17. Calculate the inverter power losses ($Losses_{x\%} = |P_{DC}| - |P_{AC}|$) from the Table 2 above.
18. How is the inverter losses at various photo-voltaic powers?
19. Plot $|P| = f(\%$ Active Power Derating$)$ from values of Table 3.
20. What de-rating to 100% and 0% means?
21. What explanations are correct about active power reduction?
22. Display/show the graphic's characteristics of the MPP tracking with derating settings of 50%, 60%, and 80% in the case of active power derating.
23. What effect does de-rating have on the MPP tracking operating point?
24. Why is the MPP still at the vertex at 50% derating?
25. Calculate the inverter power corresponding to a reduced level of 80%. (The inverter has a rated power of 3200 W.)
26. Plot $|P| = f(\%$ Active Power Derating$)$ from values of Table 4.
27. Why does the active power remain constant in the upper range? (Use data of Table 4 as reference.)

28. Plot Q = f(cos φ) from values of Table 5.
29. Calculate the inductive reactive power that the inverter would need to supply at an active power of 1000 W and cos φ= 0.9. Compare the calculated value with the actual value from Table 5.
30. Plot Q = f(cos φ) from values of Table 6.
31. What can be said about the inverter's supply of reactive power?
32. Why do photo-voltaic inverters need to supply reactive power?
33. Plot cos φ = f(|$P_{\_AC}$|) from values of Table 7. Explain your conclusions from this plot.
34. What can you observe after simulate a failure of the supply network by disconnecting the inverter from the mains via the CO3212-5U7 supply unit? How can the photo-voltaic facility's behavior be explained?
35. Plot kWh = f(Day) from values of Table 9.
36. Using your data of Table 9. On which day was the energy yield at its highest? Why does this day exhibit a higher energy yield than the day with the highest power peak?
37. Display/show the graphic of the SCADA logger's measurement results from recording of yield data. (Step 19).

Local Network Transformer

Source: Siemens - local network transformer

The significant proliferation of photovoltaic electricity in low-voltage grids causes, in some areas, large voltage fluctuations on changes in irradiation and load conditions. For this reason, the industry is developing voltage regulators for the transformers of local grids too. These usually have an electronic design for cost reasons.

According to regulations, these voltage fluctuations should be confined to the range of ± 10% of the supply voltage, in order to guarantee reliable operation of electronic devices.

In large grids, electrical energy can be transmitted economically only if this is done across multiple voltage levels. Depending on generator ratings, power plants have voltages of up to 27 kV, while transmission over long distances, including supply for large cities in Europe, takes place at 220 kV or 380 kV.

Distribution networks in North America for connecting medium-sized cities and industries usually have 230 - 345 kV, while supply for rural areas and business enterprises takes place at 10 kV or 20 kV. Voltages of 120/208V are furthermore available for local grids (households and small consumers).

Transformers are used to interconnect the different voltage levels. They usually have no fixed transformation ratio, but can instead be adapted to the respective load situation by means of coil taps. This ensures a reduction of voltage dips in the grid, and a supply of largely constant power to customers. Variable local network transformers (VLNT) dynamically change the transmission ratio. They influence only the value of the secondary voltage, but not the transformer's phase position. Transformers of this type can therefore only perform longitudinal control or direct voltage adjustment.

Variable local network transformers (VLNT) can be used in any of the following modes:

- Individual
- Per phase
- Area-wide

Procedure

<u>Case 1: Voltage Regulation for Local Network Transformer at Different Load Values</u>

Important note: The System operates on a **400 V_{L-L}** grid. Some experiments are designed to adjust the voltage by means of the 3-phase variable transformer CO3301-3P up to this value. The transformation station CO3208-1N7A will couple the system with the 208 V_{L-L} / 60 Hz local grid.

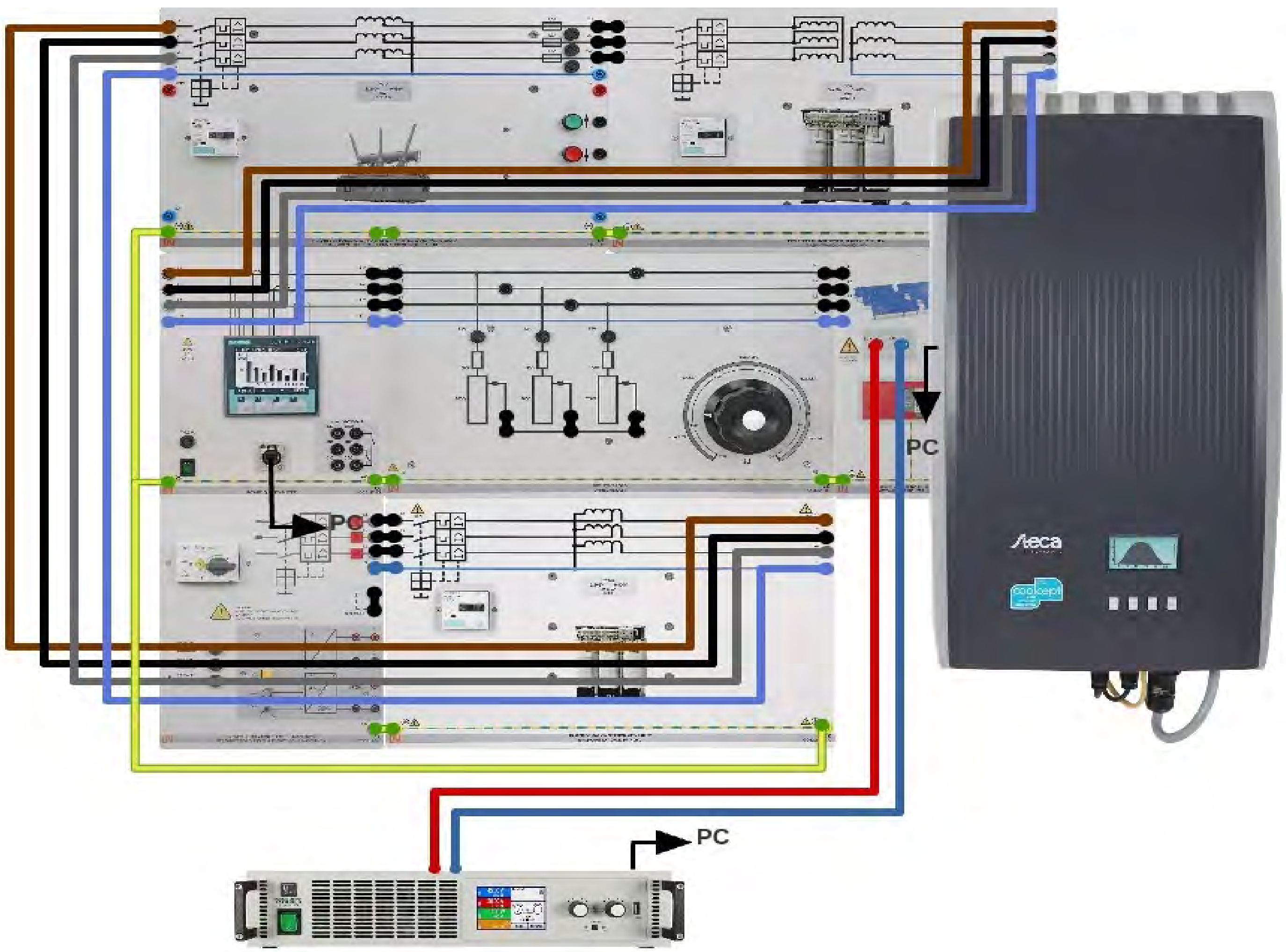


Figure 2

1. Assemble the circuit in accordance with the layout and wiring diagram of Figure 2.
2. Set the load to 750 Ω.
3. Turn on the mains voltage via power supply CO3212-5U7 for electrical machines.
4. Turn on the 3-phase transformation station CO3208-1N7A.
5. Turn on the 3-phase variable transformer CO3301-3P.
6. Turn on the 3-phase isolating transformer CO3301-3N.

7. Adjust the inverter's mains voltage by means of 3-phase variable transformer CO3301-3P to 400 V_{L-L}. Perform manual adjustment via the two pushbuttons. The solar panel emulator must be inactive for these settings to be performed. The voltage can be read directly via the power quality meter (CO5127-1S).
8. Turn on solar panel emulator CO3208-1P7.
9. Open the "Solar Panel" virtual instrument .
10. Perform the settings shown next:

SHADOW [%]	0%
SHADED MODULES	0
IRRADIANCE [%]	50%

11. Activate the "Solar Panel" virtual instrument via the POWER button.
12. Wait until the PV inverter has synchronized itself with the grid and is supplying the maximum power. This can take up to 5 minutes.
13. Save the file from the link " EPH3_Voltage_Regulation_at_different_Loads_us.pvc " to a working directory on your PC.
14. Open the SCADA viewer and select the file named "EPH3_Voltage_Regulation_at_different_Loads_us.pvc".
15. Perform the communication settings such that communication can be established with all devices. For related instructions, refer to the chapter titled "Configuring SCADA for PowerLab".
16. Activate SCADA via the start-stop symbol or F5.
17. Now set the load to 200 Ω.
18. Now, adjust again the inverter's mains voltage by means of 3-phase variable transformer CO3301-3P to **400 V_{L-L}**. Perform manual adjustment via the two pushbuttons.
19. Set the Irradiance to 100%.
20. Measure the AC voltage and active power at the variable local network transformer "P in W (VLNT)", and enter the values, **including their sign**, in the Table 10. The values can be read directly via the SCADA interface.
21. Dectivate SCADA via the start-stop symbol or F5.

Note: VLNT→Variable Local Network Transformer

Irradiance in %	P in W (VLNT)	V in V
100		
90		
80		
70		
60		
50		
40		
30		
20		
10		
0		

Table 10

Case 2: Voltage Regulation in Local Network Transformer via SCADA

Important note: The System operates on a **400 V_{L-L}** grid. Some experiments are designed to adjust the voltage by means of the 3-phase variable transformer CO3301-3P up to this value. The transformation station CO3208-1N7A will couple the system with the 208 V_{L-L} / 60 Hz local grid.

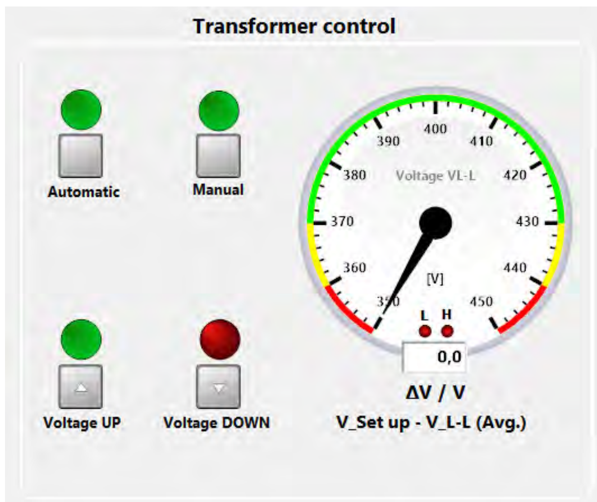
Voltage Control by Means of SCADA

SCADA offers various possibilities of controlling a local network transformer. The transformer can be controlled either manually via pushbutton operation, or via automatic voltage control.

- **Automatic :** Automatic voltage adjustment is activated here. The PLC adjusts the control transformer's output voltage automatically so as to achieve an output voltage V_{L-L} of 400V. When this mode is selected, the green LED above "Automatic" shines permanently.

➢ **Manual:** This control mode is available via the front panel. In this case, up/down buttons are used to control the transformer's output voltage. When this mode is selected, the LED above "Manual" shines permanently. The "Voltage UP" and "Voltage DOWN" buttons can be used to increase and decrease the voltage. The set voltage is influenced by the feed-in voltage and load (as is usually the case), and may therefore change in the course of time.

➢ **ΔV / V:** The difference between the set-point voltage of 400 V and average value of the output alternating voltage is displayed in this field.



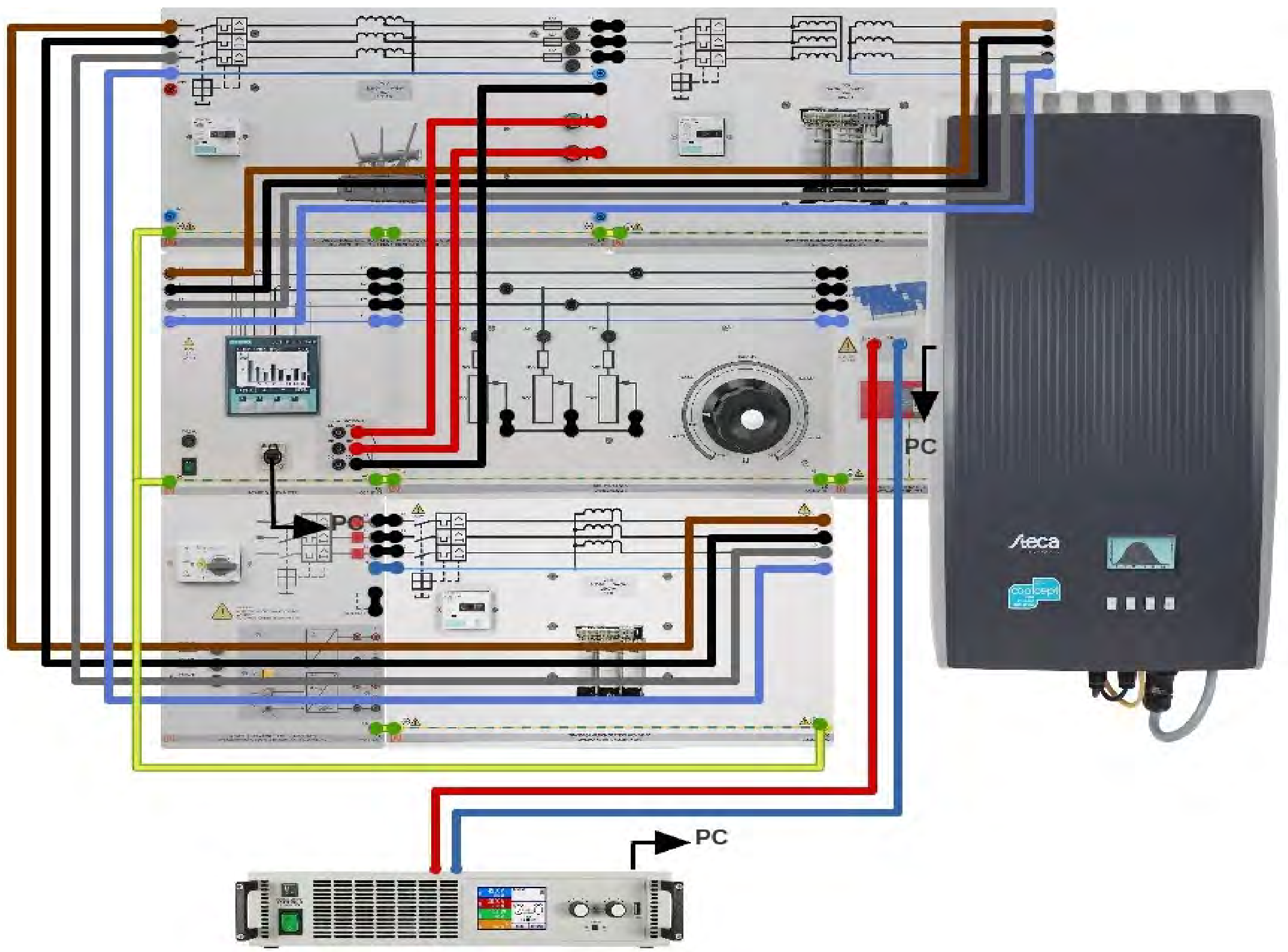
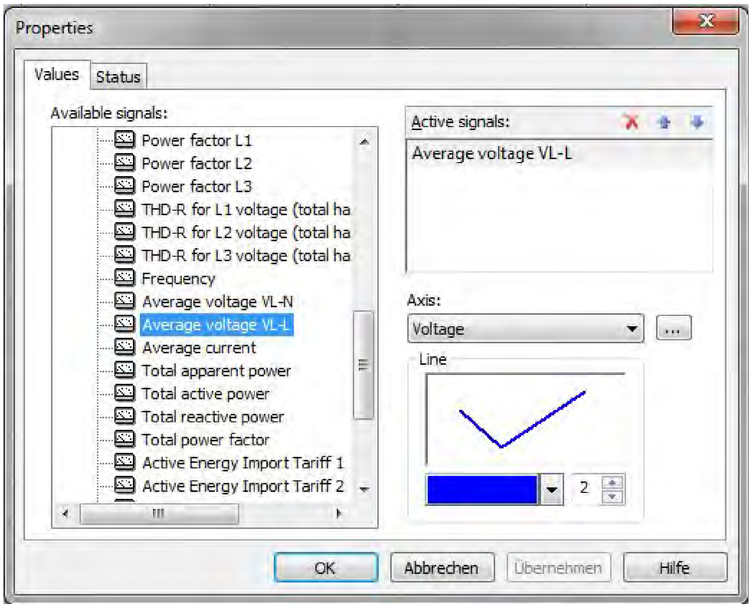


Figure 3

1. Assemble the circuit in accordance with the layout and wiring diagram of Figure 3.
2. Set the load to the maximum resistance value (750 Ω).
3. Turn on the mains voltage via power supply CO3212-5U7 for electrical machines.
4. Turn on the 3-phase transformation station CO3208-1N7A.
5. Turn on the 3-phase variable transformer CO3301-3P.
6. Turn on the 3-phase isolating transformer CO3301-3N.
7. Save the file from the link "EPH3_VoltageRegulation_with_SCADA_us.pvc" to a working directory on your PC.
8. Open the SCADA viewer  and select the file named "EPH3_VoltageRegulation_with_SCADA_us.pvc".
9. Perform the communication settings such that communication can be established with all devices. For related instructions, refer to the chapter titled "Configuring SCADA for PowerLab".

10. Open SCADA's "Logger" virtual instrument via the Instruments|Logger menu path.

11. Click on ↑Y and scale the diagram axes to fit the measurement values (right-click on the diagram | properties) performing the settings shown next.



Axis	Title	Active signals	Color	Minimum	Maximum	Division
Voltage	V in V	Average voltage $V_{L\text{-}L}$ (Available signals from the CO5127-1S)	Blue	350	450	5
Time	t in s		Black	0	60	10

While the variable transformer is performing control, the PLC should not be stopped/deactivated (▶). To end the experiment, activate the manual mode and then stop SCADA, which also stops the PLC; this ensures that there will be no more control requests for the transformer after deactivation of the PLC.

12. Activate SCADA via the start-stop symbol ▶ or F5.

13. Perform the settings shown next in the SCADA user interface:

Transformer control:	*AUTOMATIC*

14. The mains voltage is adjusted automatically to 400 $V_{L\text{-}L}$.

The solar panel emulator remains switched off for this experiment.

15. Start the recording in the logger.
16. Change the load several times (at least five settings) between 750 Ω and 200 Ω, and observe the recording in the logger.
17. Stop the recording in the logger.
18. Copy/save the graphic's characteristic of the logger.
19. Set the load back to 750 Ω.
20. Delete the loggers contents.
21. Turn on the solar panel emulator (CO3208-1P7).
22. Open the "solar panel" virtual instrument .
23. Perform the settings shown next:

SHADOW [%]	0%
SHADED MODULES	0
IRRADIANCE [%]	50%

24. Activate the "Solar Panel" virtual instrument via the POWER button.
25. Wait until the PV inverter has synchronized itself with the grid and is supplying the maximum power. This can take up to 5 minutes.
26. Start the recording in the logger.
27. Change the irradiance several times (at least five settings) between 100% and 0%, and observe the recording in the logger.
28. Stop the recording in the logger.
29. Copy/save the graphic's characteristic of the logger.
30. Deactivate the automatic transformer control performing the settings shown next:

Transformer control:	*MANUAL*

31. Deactivate SCADA via the start-stop symbol or F5.

Case 3: Automatic Active Power Derating

Important note: The System operates on a **400 V_{L-L}** grid. Some experiments are designed to adjust the voltage by means of the 3-phase variable transformer CO3301-3P up to this value. The transformation station CO3208-1N7A will couple the system with the 208 V_{L-L} / 60 Hz local grid.

1. Keep the circuit in accordance with the layout and wiring diagram of Figure 3.
2. Turn on the mains voltage via power supply CO3212-5U7 for electrical machines.
3. Turn on 3-phase transformation station CO3208-1N7A.
4. Turn on the 3-phase variable transformer CO3301-3P.
5. Turn on the 3-phase isolating transformer CO3301-3N.
6. Turn on solar panel emulator CO3208-1P.
7. Open the "S*olar Panel"* virtual instrument  .
8. Perform the settings shown next:

SHADOW [%]	0%
SHADED MODULES	0
IRRADIANCE [%]	50%

9. Activate the "Solar Panel" virtual instrument via the POWER button.
10. Wait until the PV inverter has synchronized itself with the grid and is supplying the maximum power. This can take up to 5 minutes.
11. Save the file from the link "EPH3_Automatic_ActivePower_Derating_us.pvc" to a working directory on your PC.
12. Open the SCADA viewer  and select the file named "EPH3_Automatic_ActivePower_Derating_us.pvc".
13. Perform the communication settings such that communication can be established with all devices. For related instructions, refer to the chapter titled "Configuring SCADA for PowerLab".
14. Activate SCADA via the start-stop symbol  or F5. The de-rating is set automatically to 0%.
15. Set the load to a resistance value of 200 Ω.

16. Set the variable local network transformer voltage with the help of the UP/DOWN buttons on SCADA to **400 V (L-L).**
17. Set the irradiance to 100%
18. Change the load to about 350 Ω.
19. Adjust the values for inverter de-rating with the help of the buttons on SCADA.
20. Measure the AC voltage, active power at the variable local network transformer "P in W (VLNT)", and active power at the PV inverter "P in W (PV-Inverter). Enter the values, **including their sign**, in the Table 11. The values can be read directly via the SCADA interface.
21. Reset the derating to 0%.
22. Repeat steps 18 to 20 with a load of about 750 Ω.
23. Reset the derating to 0%.
24. Deactivate SCADA via the start-stop symbol or F5.

350 Ω.			
Derating in %	P in W (VLNT)	V (LL) in V	P in W (PV - Invt)
0			
10			
20			
30			
40			
50			
750 Ω.			
Derating in %	P in W (VLNT)	V (LL) in V	P in W (PV - Invt)
0			
10			
20			
30			
40			
50			

Table 11

Case 4: Smart Grid Active Power Regulation

Important note: The System operates on a **400 V_{L-L}** grid. Some experiments are designed to adjust the voltage by means of the 3-phase variable transformer CO3301-3P up to this value. The transformation station CO3208-1N7A will couple the system with the 208 V_{L-L} / 60 Hz local grid.

The previous experiment showed that derating of a PV inverter can only be used conditionally for voltage stabilization. Today's networks are usually designed to be able to cope properly with fluctuating loads. The growing number of decentralized feed-in sources is problematic, however. The next example employs a variable local network transformer for voltage regulation. De-rating of the PV inverter is used only if the feed-in power exceeds the power of the grid's consumers by 300 W.

1. Keep the circuit in accordance with the layout and wiring diagram of Figure 3.
2. Set the load to 750 Ω.
3. Turn on the mains voltage via power supply CO3212-5U7 for electrical machines.
4. Turn on the 3-phase variable transformer CO3301-3P.
5. Turn on the 3-phase isolating transformer CO3301-3N.
6. Turn on the 3-phase transformation station CO3208-1N7A.
7. Turn on solar panel emulator CO3208-1P7.
8. Open the "S*olar Panel"* virtual instrument  .
9. Perform the settings shown next:

SHADOW [%]	0%
SHADED MODULES	0
IRRADIANCE [%]	50%

10. Activate the "Solar Panel" virtual instrument via the POWER button.
11. Wait until the PV inverter has synchronized itself with the grid and is supplying the maximum power. This can take up to 5 minutes.
12. Save the file from the link "EPH3_SmartGrid_Active_Power_Regulation_us.pvc" to a working directory on your PC.

13. Open the SCADA viewer and select the file named "EPH3_SmartGrid_Active_Power_Regulation_us.pvc".

14. Perform the communication settings such that communication can be established with all devices. For related instructions, refer to the chapter titled "Configuring SCADA for PowerLab".

15. Activate SCADA via the start-stop symbol or F5.

16. Now, set the Irradiance to 100%

17. Perform the settings shown next in the SCADA user interface:

Transformer control	Automatic
Derating for a 1.5 kW photovoltaic system - Smart Grid	Manual

18. Activate the various de-rating levels according to Table 12 with the help of the buttons on SCADA.

19. Measure the AC voltage, active power at the variable local network transformer "P in W (VLNT)", and active power at the PV inverter "P in W (PV-Inverter). Enter the values, **including their sign**, in the Table 12. The values can be read directly via the SCADA interface.

20. Change the irradiance to 50% and repeat steps 18 and 19.

21. Activate automatic derating in the SCADA user interface.

22. Change the irradiance levels following the settings shown in Table 13 on the *"Solar Panel"* virtual instrument.

Irradiance 100%			
Derating in %	P in W (VLNT)	V (LL) in V	P in W (PV-Invt)
0			
30			
60			
100			
Irradiance 50%			
Derating in %	P in W (VLNT)	V (LL) in V	P in W (PV-Invt)
0			
30			
60			
100			

Table 12

23. Measure the AC voltage, active power at the variable local network transformer "P in W (VLNT)", and active power at the PV inverter "P in W (PV-Inverter). Enter the values, **including their sign**, in the Table 13. The values can be read directly via the SCADA interface.

24. Repeat steps 22 and 23 with a load of about 350 Ω.

750 Ω			
Irradiance in %	P in W (VLNT)	V (LL) in V	P in W (PV-Invt)
100			
80			
60			
40			
20			
350 Ω			
Irradiance in %	P in W (VLNT)	V (LL) in V	P in W (PV-Invt)
100			
80			
60			
40			
20			

Table 13

The inverter now receives data about the corresponding de-rating level from the grid operator. In the SCADA project, this specification is calculated by the PLC. As soon as the "feedback" power exceeds 300 W, switchover to the next de-rating level is performed.

25. Deactivate the automatic derating and the automatic transformer control:

Transformer control	Manual
Derating for a 1.5 kW photovoltaic system - Smart Grid	Manual

26. Deactivate SCADA via the start-stop symbol or F5.

Report Questions

1. Plot V = f(P) from values of Table 10.
2. What does the voltage in a variable local network transformer (VLNT) depend on?
3. How can the behaviour of the power at the variable local network transformer be explained?
4. Display/show the graphic's characteristics of the variable local network transformer (VLNT) with different load settings. Explain the voltage's reaction.
5. Display/show the graphic's characteristics of the variable local network transformer (VLNT) with different irradiance settings.
6. What can be said about voltage control during operation of the photovoltaic inverter?
7. Why is it important to regulate the voltage at the local network transformer?
8. Plot V = f(Derating %) from values of Table 11. Explain your results.
9. Does derating at different loads permit the variable local network transformer's voltage to be stabilized?
10. What are the practical reasons why derating cannot be employed freely for voltage stabilization in local networks? Consider only purely technical aspects.
11. How can derating in spite of that contribute to mains voltage stabilization?
12. Plot V = f(Derating %) from values of Table 12. Explain your results.
13. Plot P(VLNT) = f(Derating %) from values of Table 12. Explain your results.
14. What is the advantage of inverter derating?
15. Plot V = f(Irradiance %) from values of Table 13. Explain your results.
16. Plot P(VLNT) = f(Irradiance %) from values of Table 13. Explain your results.
17. What can be said about the system's behavior at different irradiance and load settings?

Battery Storage Systems with PV Systems

An electrochemical energy storage device with a photovoltaic system or another energy generation system such as a combined heat and power plant is intended as a means of shifting or transferring power generation to periods of consumption or peak consumption periods to power generation periods. For this purpose, existent and available (solar) energy must be generated and subsequently stored so that it can be used in times of energy demand.

The most important objectives of an electrochemical energy storage device are therefore:

- To increase own or private consumption.
- To ensure dependable supply through backup power.

Figure 4 below shows the power levels of a PV system with electrochemical energy storage in the course of a typical day, as well as the load transfer function for increasing self-consumption.

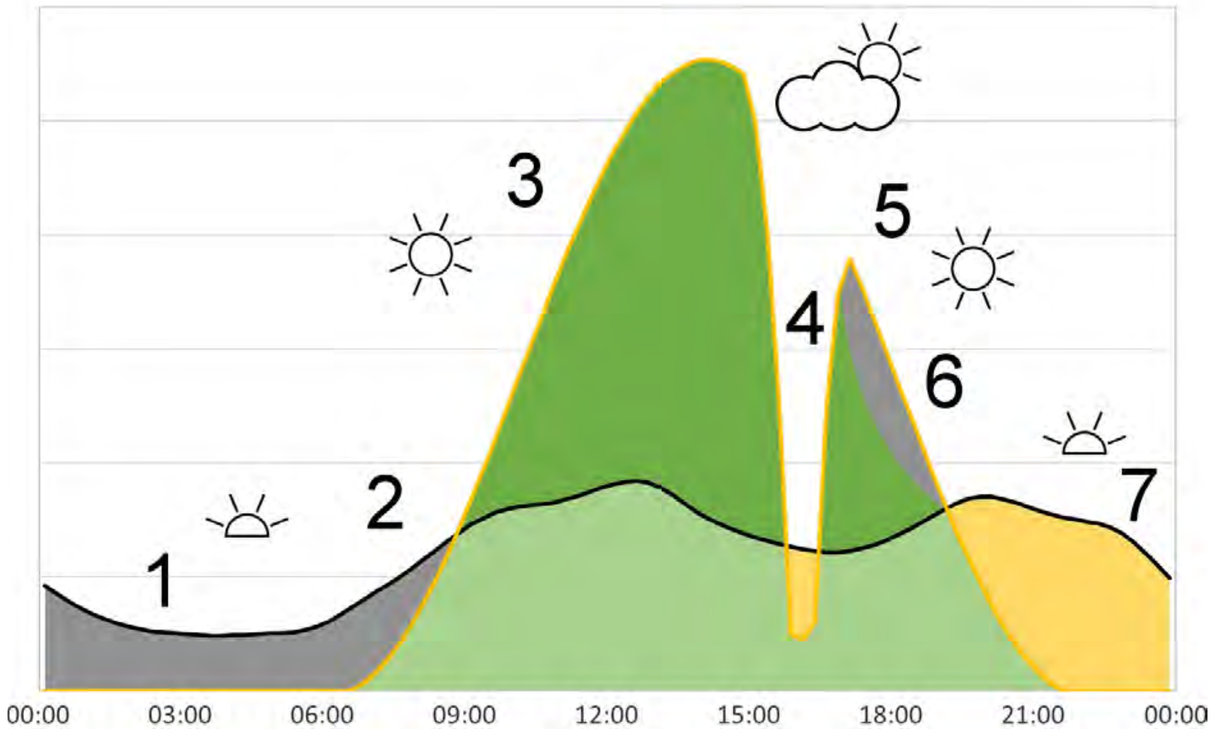


Figure 4

Mode of Operation of an Electrochemical Storage System

1. At sunrise, the battery is empty and the consumers are supplied from the grid.
2. As the PV system's output increases, so does the fulfilment of consumer demand.
3. If the available energy exceeds consumption, the storage system uses the excess energy to charge the battery.
4. If the PV system's output falls short of consumer demand, the storage system takes over.
5. In times of excess energy, the battery is always recharged.
6. If the battery becomes fully charged in the course of the day, the PV system's power generation is reduced and/or the surplus is fed to the grid.
7. At sunset, the storage system assumes the task of supply until the battery is empty.

For grid connections of power generation plants, the grid operator may prescribe a maximum feed-in power as a function of rated power. In such cases, for example, a PV system must not feed in more than 50% of the facility's capacity. If a systemy cannot comply with the feed-in limit, the capacity needs to be restricted. However, such restrictions cause energy to remain unused. Instead, self-consumption can be increased by connecting consumers. With the help of a storage system, though, excess energy can be used more flexibly and compliantly with demand.

Accordingly, an intelligent storage system charges the battery so as to adhere to the feed-in limit. Prepared for this purpose are production and consumption forecasts which may include current and historical weather data as well as different computation models.

Topologies of Battery Storage Devices

An electrochemical storage system consists of numerous different components:

- Battery/batteries
- Battery management system
- Power measurement electronics for:
    - Consumption
    - Generation
- PV battery or battery inverter, sometimes with a two-quadrant controller or transformer
- Control system
- Control and display elements
-

Figure 5

Components

Components from different manufacturers can be put together - batteries from manufacturer A and charge controller from manufacturer B. During installation, these components are combined to form a single storage system.

Offered alternatively are fully integrated storage systems already incorporating all components which are necessary for operation and have been matched together. In this case, the components are grouped to the greatest possible extent in a single housing. One advantage of a fully integrated storage system is that the system's provider is responsible for the functioning and interplay of all components (from different manufacturers). Commissioning is also facilitated due to the large number of components pre-assembled in the housing. A compact housing with a high storage capacity is realized using batteries based on lithium compounds.

Component designs vary significantly due to different philosophies and objectives of a storage system. Based on the type of coupling, however, the employed topologies can be divided into three systems:

- DC systems
- DC generator systems
- AC systems

DC Systems

The PV inverter also couples the storage device to the electricity grid. The batteries are supplied via the link circuit here.

- Higher efficiency compared to AC systems.
- Limited installation space due to DC coupling.
- Oversized inverter.
    - Consideration of storage system and PV system.
- Problematic retrofitting if no provisions have been made.
    - PV inverter replacement.

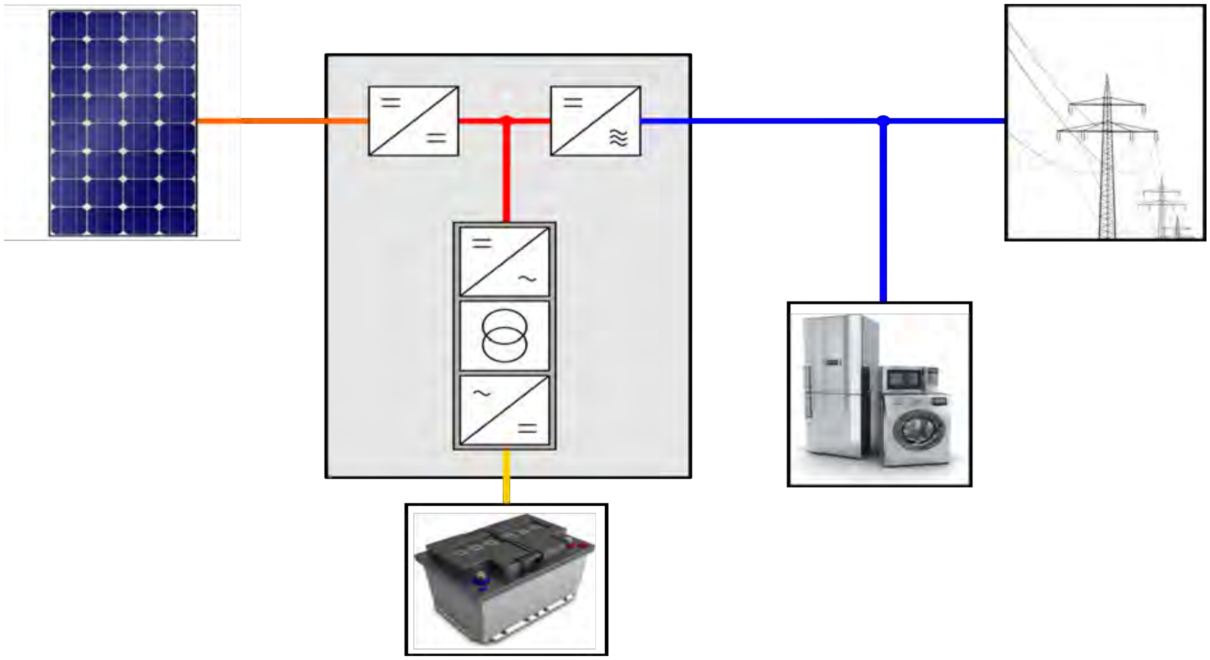


Figure 6:
Inverter with Transformer for Low Battery Voltage

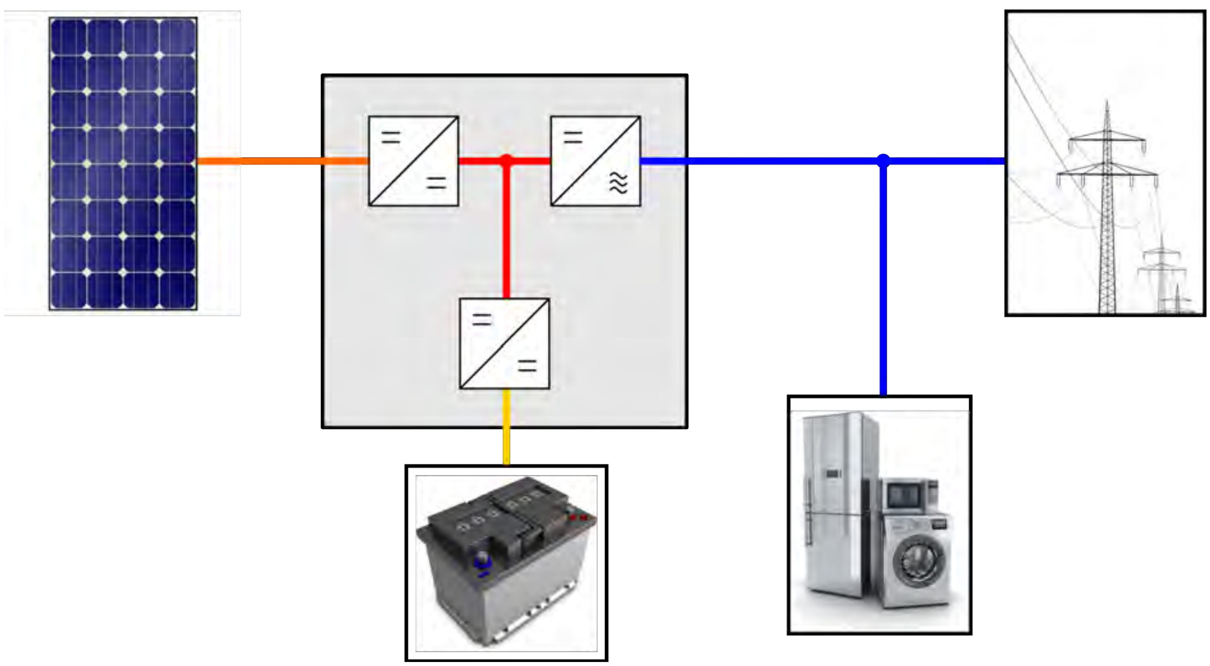


Figure 7:
Transformerless Inverter

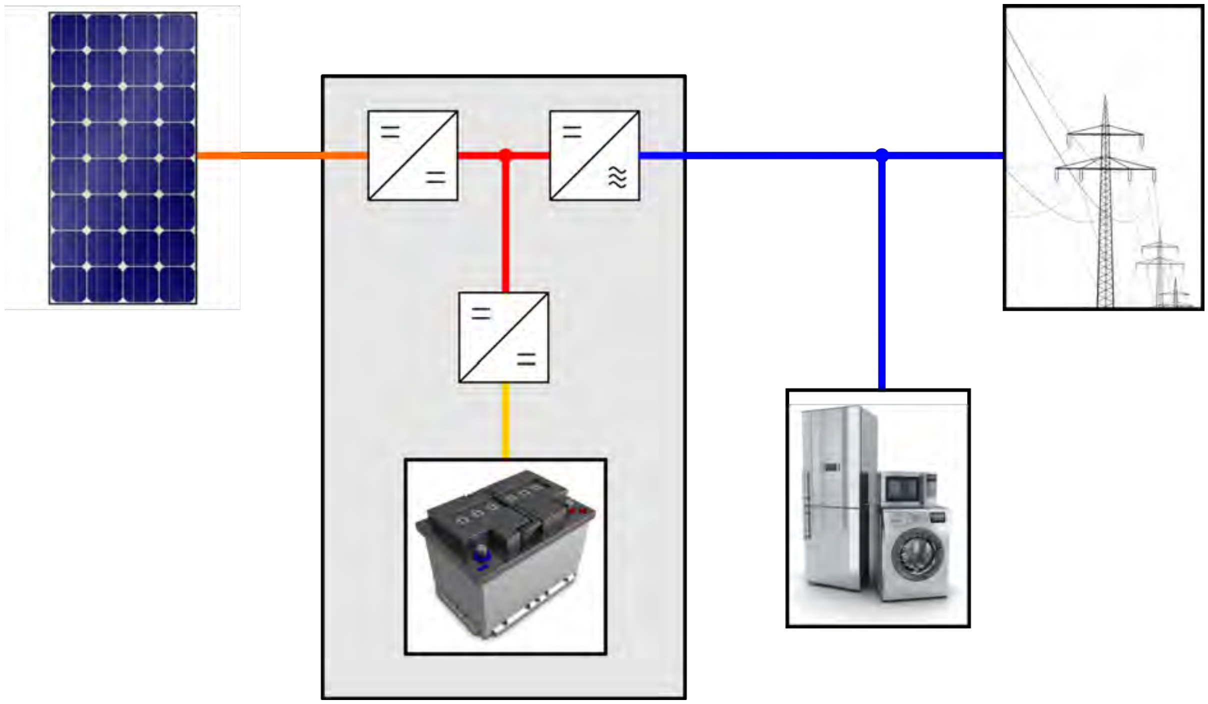


Figure 8:
Fully Integrated Storage System with DC Coupling

DC Generator Systems

These systems are connected between the PV system and PV inverter.

- Easy retrofitting.
    - No absolute necessity for PV inverter replacement.
    - Limitation of discharge power by the PV inverter's maximum power and voltage.
- More elaborate regulation due to PV voltage fluctuations.
    - Higher losses under certain circumstances.
- No possibility of recharging the storage device from an AC grid.
- Lower conversion losses compared with AC systems.

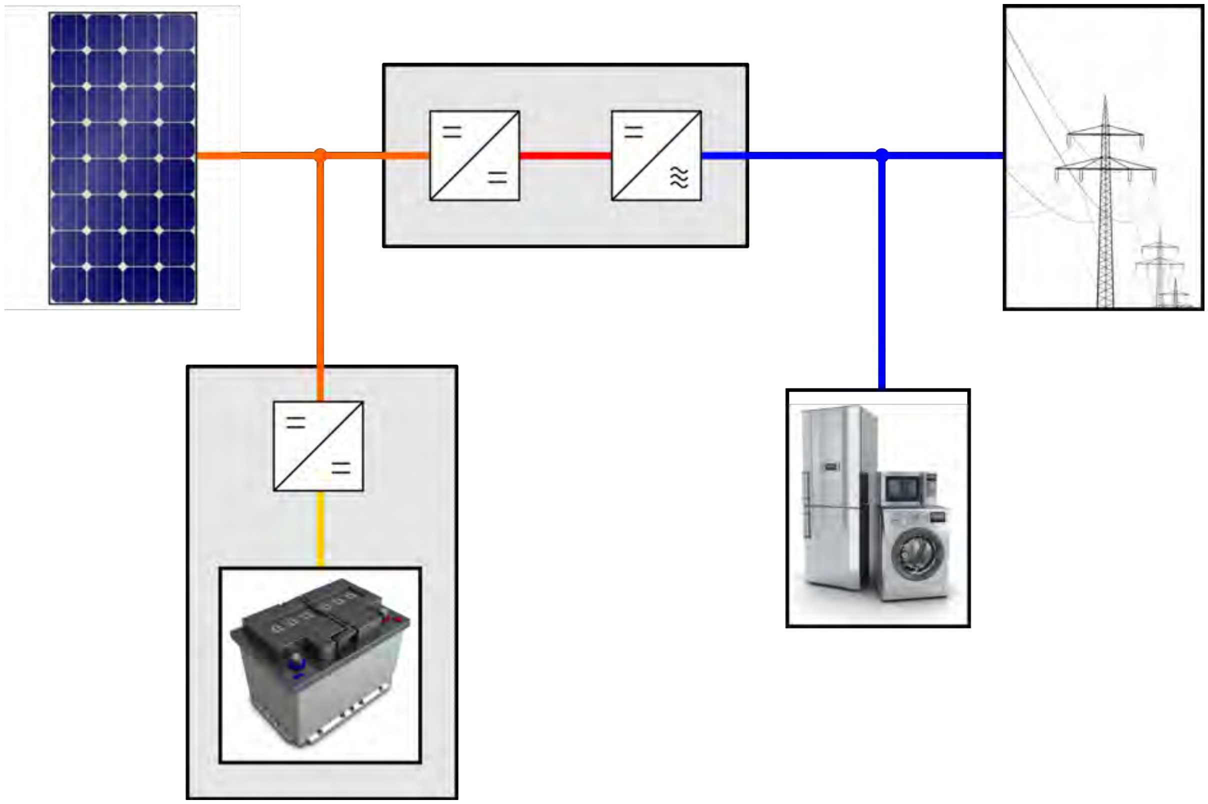


Figure 9:
Storage System with Generator Coupling

AC Systems

A system with AC coupling is independent of the PV system, and connected in single-phase or three-phase mode to an AC grid. Further energy generation systems such as combined heat and power plants as well as (small) wind turbines can also be taken into consideration.

- Very flexible use due to independence from PV facilities:
    - Installation site.
    - Storage system's power.
    - Battery capacity.
    - Number of phases.
- Easy retrofitting.
- Potentially more expensive in the case of a newly built PV facility with a storage system.

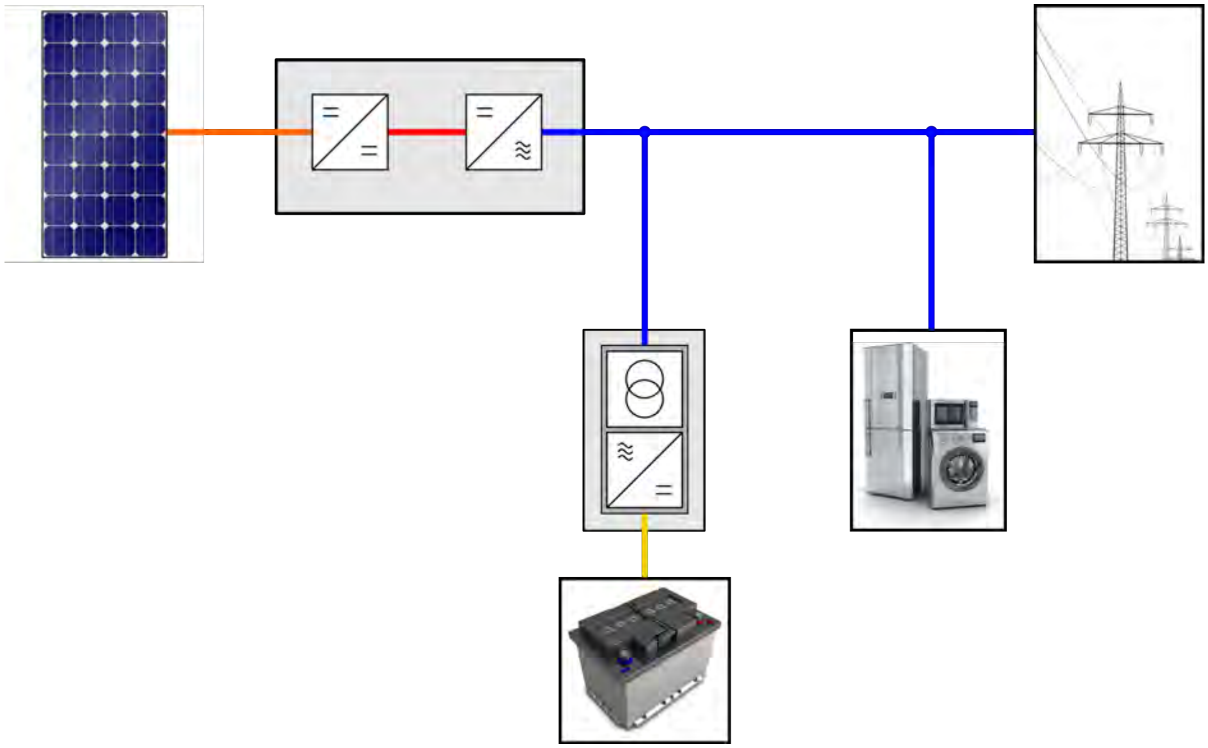


Figure 10:
Storage System with Transformer and AC Coupling

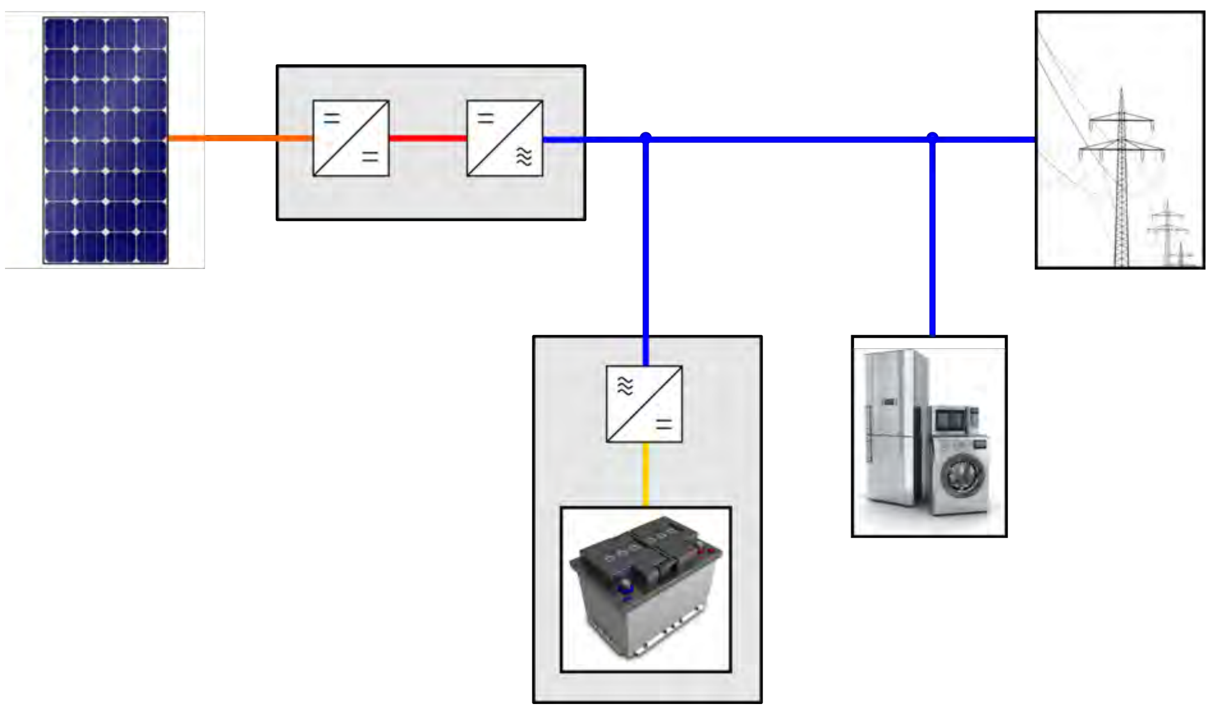


Figure 11:
Fully Integrated, Transformerless Storage System with AC Coupling

Our CO3208-2L storage system belongs to the category of fully integrated, transformerless storage systems with AC coupling.

Installation of the Battery Storage Device with a PV Facility

Our CO3208-2L storage system is integrated into the electrical distribution in parallel with the consumers and the photovoltaic system. This also allows a PV system to be equipped later with a storage device without a need for elaborate modifications to the existent distribution system.

The storage system's power output and power consumption are configured in dependence on the charge level so as to minimize the energy exchange with the electrical grid and increase private or self-consumption. For this purpose, the consumption (Figure 12, (5); Figure 13, (2)) and output (Figure 12, (2); Figure 13, (14)) are measured.

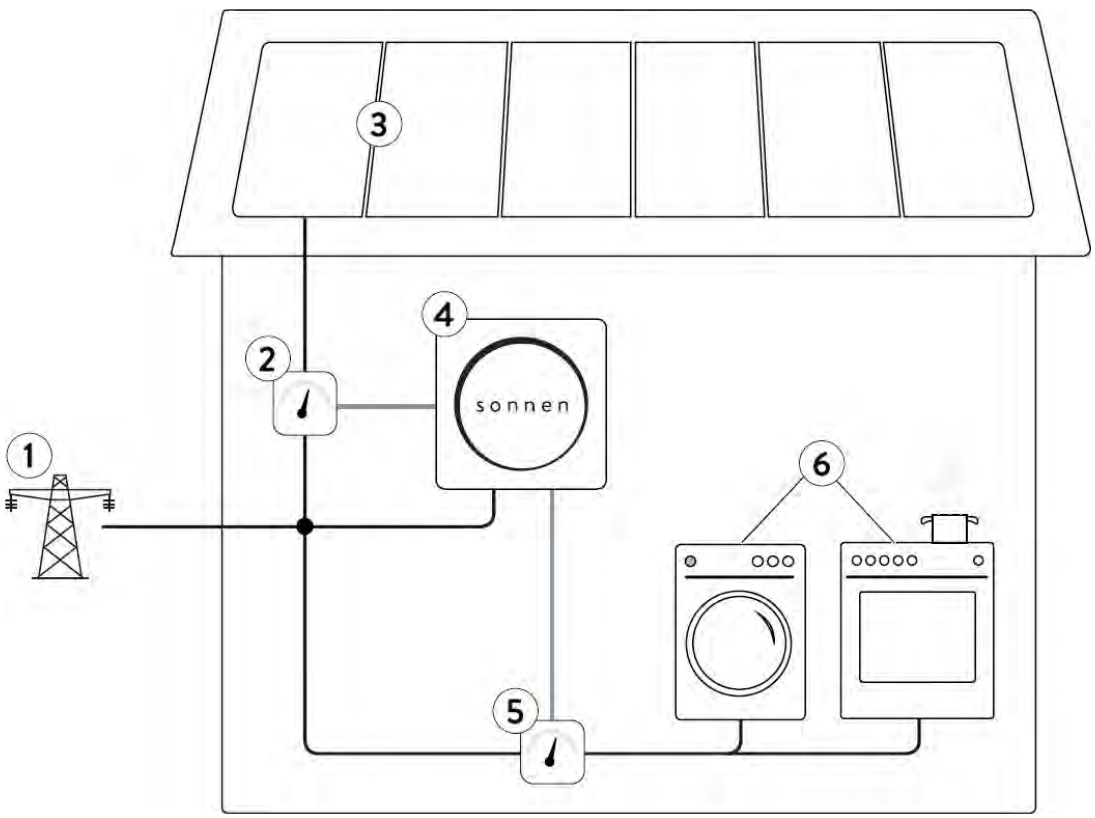


Figure 12:

Schematic Representation of the CO3208-2L Storage System with a PV Facility

- 1: Electrical grid
- 2: Power measurement of the PV system
- 3: PV system with inverter
- 4: Energy storage system
- 5: Power consumption measurement
- 6: Consumer

The wiring shown next corresponds to the connecting board of CO3208-2L.

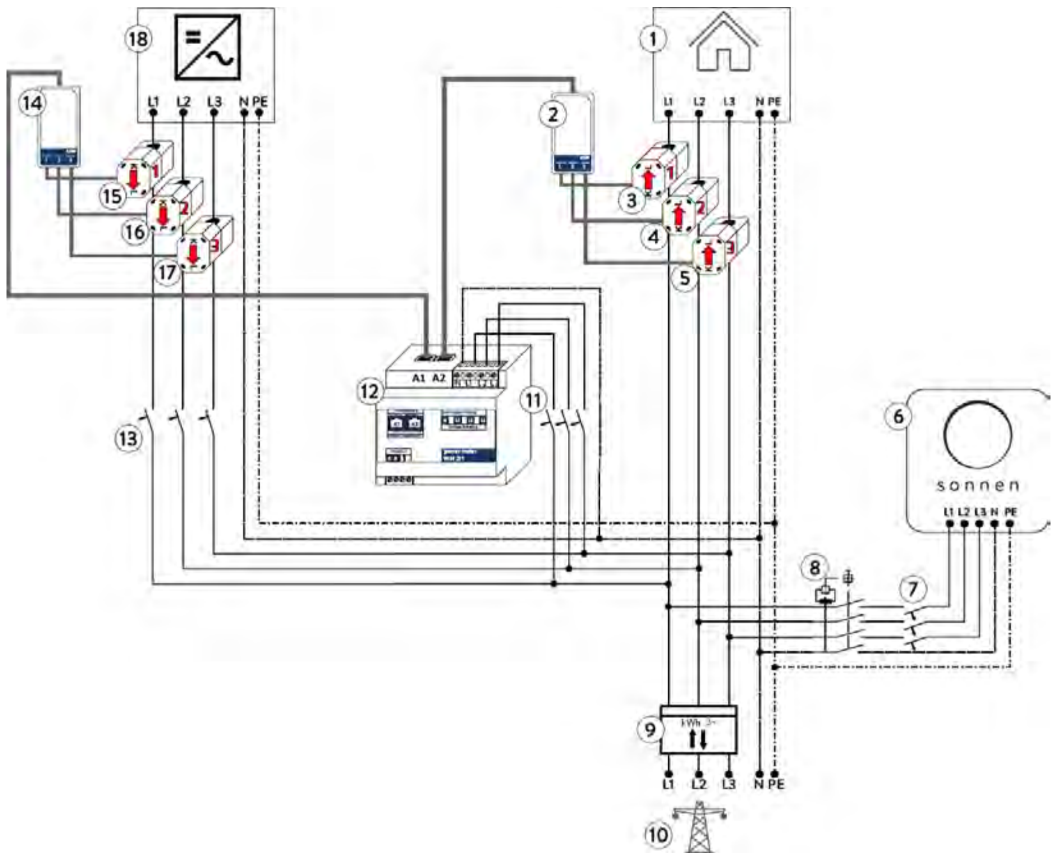


Figure 13:
Overview of Electrical Connections

- 1: Consumer
- 2: Transformer interface - consumption
- 3-5: Snap-on current transformer - consumption L1-L3
- 6: Energy storage system
- 7: Circuit breaker
- 8: FI-protection switch (part of the laboratory)
- 9: Power Quality Meter CO3301-1S
- 10: Electricity grid CO3212-5U7
- 11: Circuit breaker
- 12: Wattmeter
- 13: Circuit breaker (not required / available)
- 14: Transformer interface - generation
- 15-17: Snap-on current transformer - generation L1-L3
- 18: PV Inverter

Assembly Instructions

1. Wire up the circuit in accordance with the set-up and wiring diagram of Figure 14.

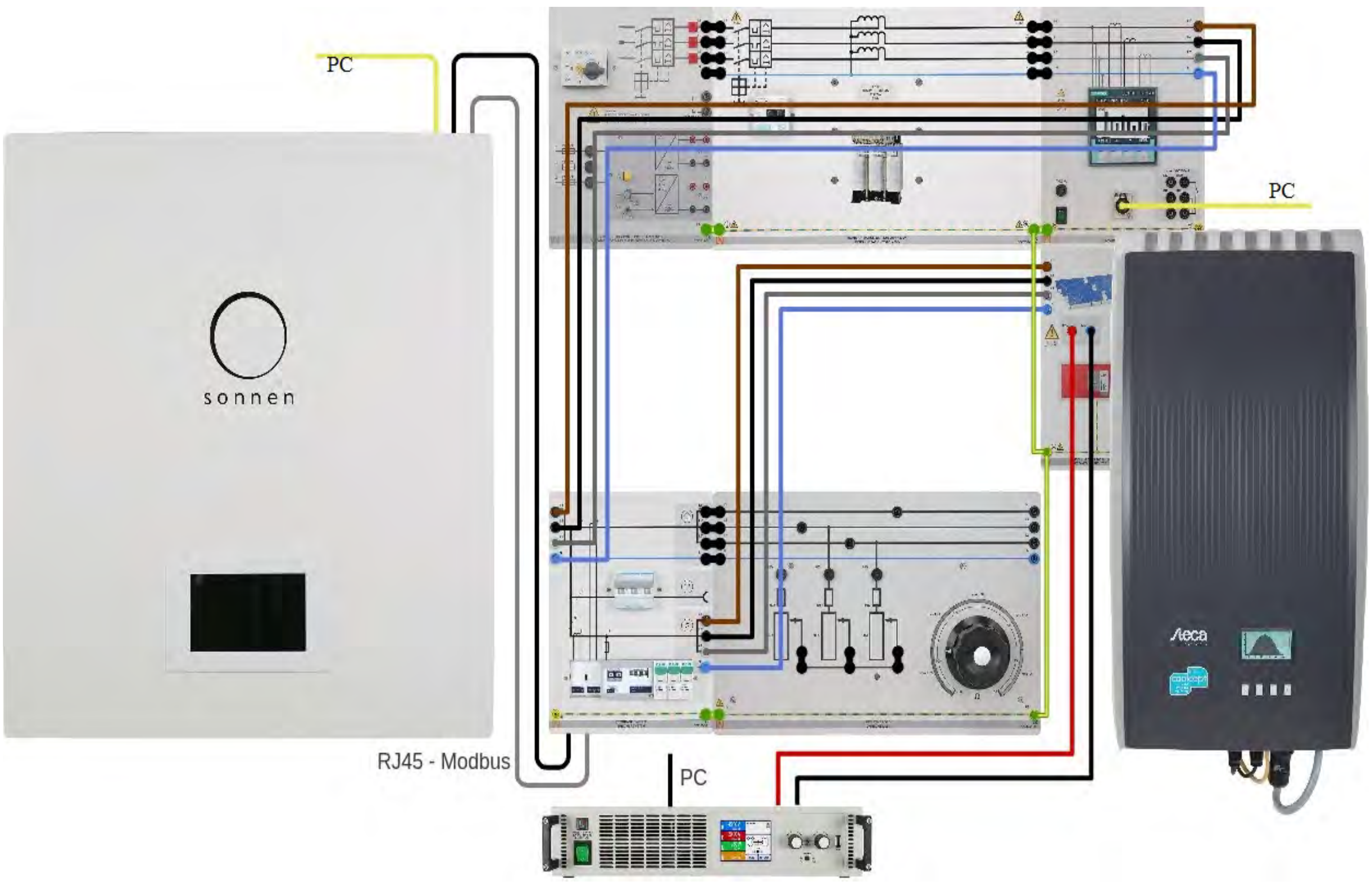


Figure 14

To conduct the subsequent experiments it is recommended that there be a charging level between 50 % to 80 %.

Depending on the battery's condition, the available power can vary according to a number of parameters such as charge level, cell voltage, temperature, humidity, etc. Consequently, it might take some time to attain the desired power level. Note the installation conditions for the storage system in the operating instructions.

If the PV inverter shows an error message, turn off power supply unit CO3212-5U7, and turn it on again after one minute. If the fault persists, refer to "CO3208-1N7" in the section on equipment.

The storage system can be charged to the desired charged level using the SCADA-file EPH4_Charge.pvc.

When disconnecting the storage system from the electricity grid and powering down it is imperative to comply with the guidelines in the instruction manual!

2. Connect all circuit breakers.
3. Turn on the mains voltage via power supply CO3212-5U7 for electrical machines.Wait until the storage system has been synchronized with the grid.

Synchronization takes approximately one minute.

4. Switch on the storage system as follows:
   - ❖ Press button S1 and keep it pressed during the steps described next.
   - ❖ Turn on fuse switch F1.
   - ❖ Keep button S1 pressed for at least another 5 seconds.
   - ❖ Release button S1.
5. Switch off the storage system as follows:
   - ❖ The storage system is deactivated by turning off fuse switch F1.

When powering down the storage system make sure to follow the guidelines in the instruction manual!

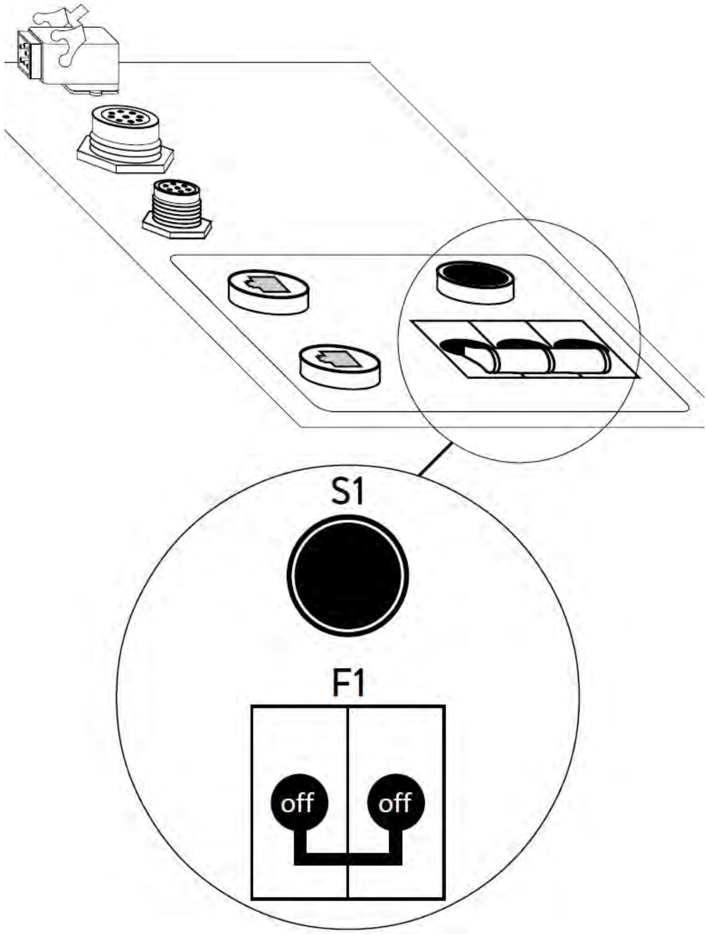
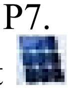


Figure 15:
Fuse Switch F1 and Button S1 for Switching the Storage System On and Off

Procedure

<u>Case 1: Energy Storage System with PV System</u>

1. Keep the assembly and wiring plan from the Figure 14, and put the system into operation.
2. Remove the jumper of the neutral point on the variable resistor as in Figure 16.
3. Record the storage system's values for *production, consumption, charge and discharge* Power in Table 14.
4. Turn on solar panel emulator CO3208-1P7.
5. Open the *Solar Panel virtual* instrument  .
6. Carry out the following settings:

Shadow	0 %
Shaded modules	0
Irradiance	50 %

7. Activate the *Solar Panel* virtual instrument via its *POWER* button.
8. Wait until the PV inverter has synchronised itself with the grid and is supplying the set power.

This may take up to 5 minutes.

9. Record the storage system's values for *production, consumption, charge and discharge* Power in Table 14.
10. Record the active power exchanged with the grid in Table 14.

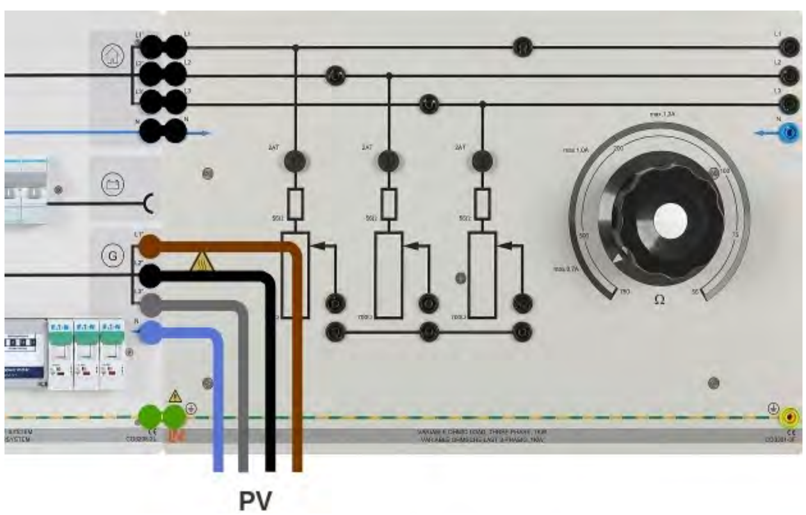


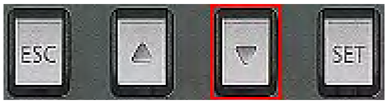
Figure 16

Storage System without PV System			
P_{prod} (W)	P_{con} (W)	P_{ch} (W)	P_{disch} (W)
Storage System with PV System			
P_{prod} (W)	P_{con} (W)	P_{ch} (W)	P_{disch} (W)
Grid Active Power			
P_{grid} (W)			

Table 14

Case 2: Storage System with Consumer

1. Re-insert the jumper of the neutral point on the variable resistance as seen in Figure 17.
2. Turn off the Solar Panel virtual instrument via its POWER button.
3. Wait until the PV inverter disconnects the grid and the DC voltage is 0 V.
   - ❖ For this, invoke the "PV voltage" menu by pressing the downward arrow button on the PV inverter.



4. Turn the variable resistor fully counter-clockwise. (Max value of 750 Ω.)
5. Record the storage system's values for *production, consumption, charge and discharge* Power in the presence of a consumer in Table 15.

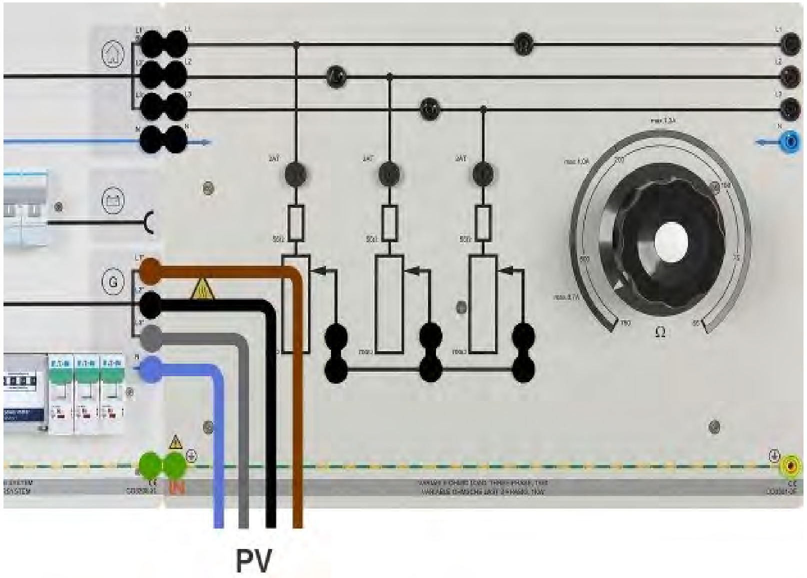


Figure 17

Storage System with Consumer			
P_{prod} (W)	P_{con} (W)	P_{ch} (W)	P_{disch} (W)

Table 15

Case 3: Examination of Current Sensors for Power Measurement

1. Modify the experimental set-up as depicted in Figure 18.
2. Do not yet connect the PV system.
3. Keep the variable resistor fully counter-clockwise. (Max value of 750 Ω.)
4. Select the menu "Total, S, P, Q1 INST - 7.0" on the power quality meter (CO5127-1S). Refer, in particular, to Figure 13 on installing the battery storage device with a PV system.
5. Record the storage system's values for *production, consumption, charge and discharge* Power for current sensors in Table 16.
6. Record the total active power from power quality meter (CO5127-1S) in Table 16.

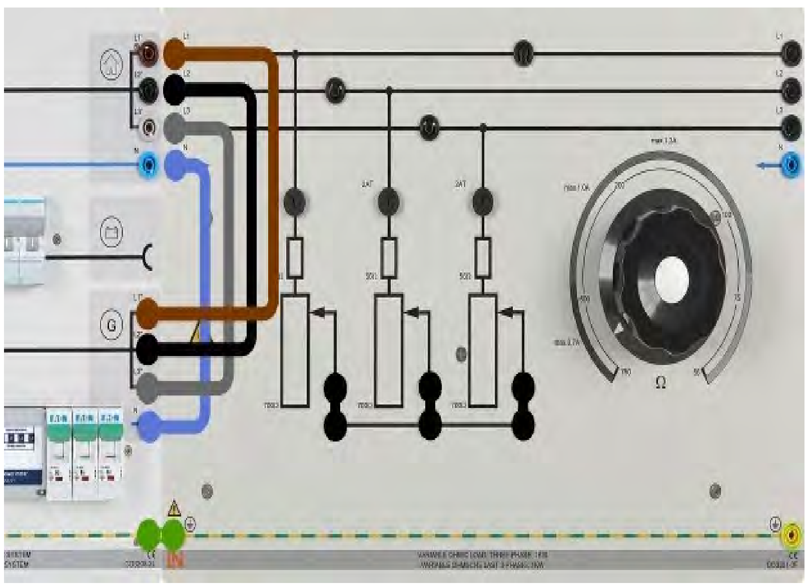


Figure 18

Storage System for Current Sensors			
P_{prod} (W)	P_{con} (W)	P_{ch} (W)	P_{disch} (W)
PQM Active Power (CO5127-1S)			
ΣP (W)			

Table 16

Case 4: Daily Characteristic

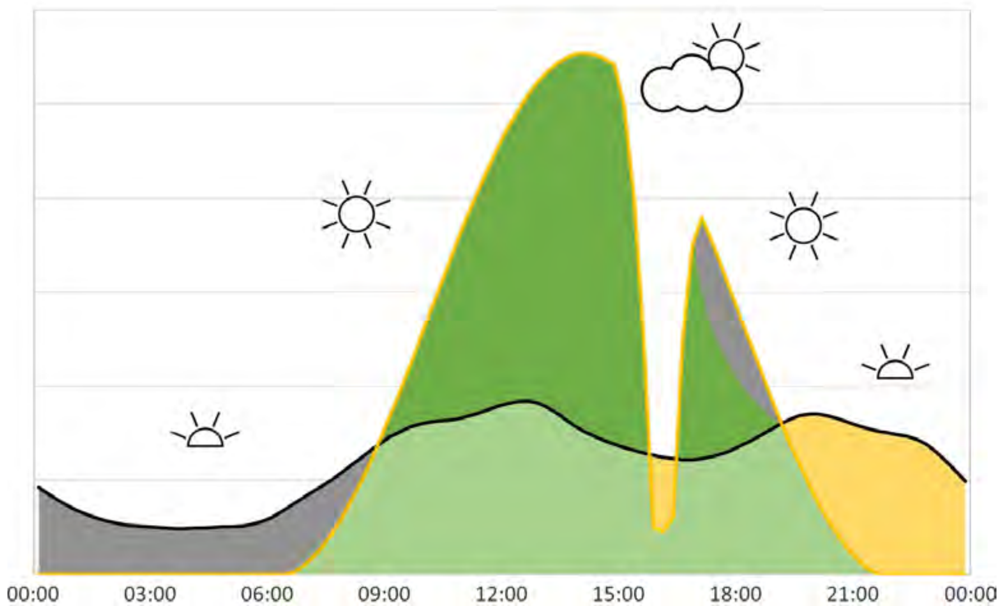


Figure 19:
Daily Characteristic

A typical daily profile including consumption at a household with a PV facility is to be observed and recorded with the SCADA logger.

- For this purpose, the 24 hours of a day are scaled to 12 minutes.
- The PV system's solar profile is defined in the *solar panel*.
- Recording with the SCADA *logger* is automatically started with the *solar panel*.
- According to the elapsed time ⇔ time of day, the consumption values must be set by hand via the variable resistor.
-

> To allow timely synchronization of the PV inverter with the grid despite the temporal scaling, the solar profile's irradiance is raised by 5%. Synchronization should take place within 3 minutes. Otherwise disconnect power supply unit CO3212-5U7 and connect it again after 1 minute. This resets the PV inverter's connection conditions and causes synchronization to start after 60 seconds. To remember here is the storage system's synchronization, which must be completed before the experiment is started!
>
> The connection conditions apply only within the permissible grid parameters in Europe, and may vary in other countries.

1. Restore the assembly and wiring plan from the Figure 14 as seen in Figure 20 below.

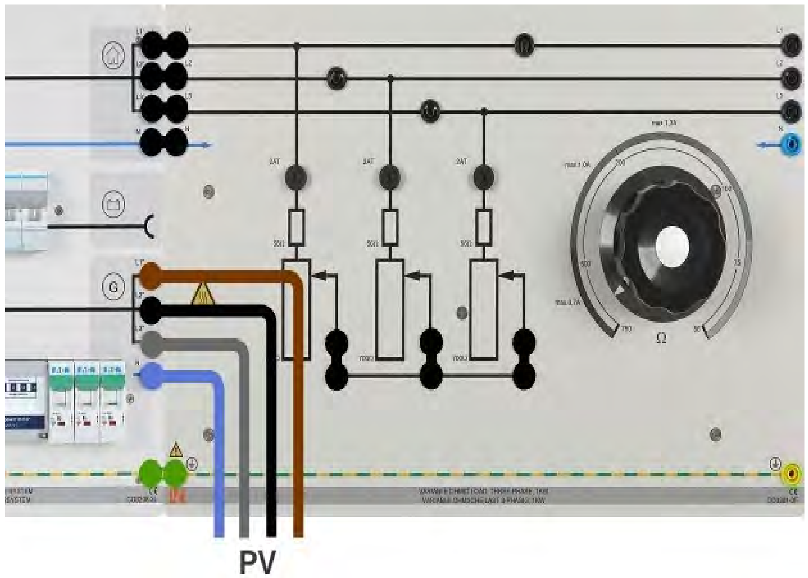


Figure 20

If the PV inverter shows an error message, turn off power supply unit CO3212-5U7, and turn it on again after one minute. If the fault persists, refer to "CO3208-1N7" in the section on equipment.

2. Save the file from the link "EPH4_Daytime.pvc" to a working directory on your PC.
3. Open the SCADA viewer and select the file named "EPH4_Daytime.pvc".
    - ❖ File → Open...
    - ❖ Navigate to the location of the file and open it.
    - ❖ SCADA user interface will look as Figure 21.
4. You might have to set the communication interface and/or address of the equipment in the device manager (F8).
    - ❖ For related instructions, refer to the chapter on SCADA for PowerLab.
5. Activate SCADA via the start-stop symbol or F5.
6. Open the SCADA logger if necessary.
    - ❖ Select *Instruments → Logger*
7. Save the file from the link "EPH4_Solarprofil.ovpn" to a working directory on your PC.
8. Open the *"Solar Panel"* virtual instrument and select the file named "EPH4_Solarprofil.ovpn".
    - ❖ File → Open
    - ❖ Navigate to the location of the file and open it.

9. In this process, select *USE PROFILE*.
10. Use the SCADA *logger* to set the consumption.
11. Set the variable resistor according to the consumption as indicated in Table 17 below.
    - ❖ In the logger, 0 s to 180 s correspond to ⇔ 00:00 to 06:00 hours.
12. Start the experiment via *POWER* on the solar panel.
    - ❖ SCADA logger starts automatically at the same time.
13. After the simulation carried out all measurements, copy/save the graphic of the SCADA logger's measurement results.
14. Deactivate SCADA via the start-stop symbol ▶ or F5.
15. Deactivate the *"Solar Panel"* virtual instrument via the *POWER* button.

Table 17: Consumption Values

Time		**Consumption [P/W]**
from	**to**	
00:00	06:00	Left Limit (CCW = 750 Ω)
06:00	13:00	800
13:00	18:00	400
18:00	22:00	800
22:00	00:00	Left Limit (CCW = 750 Ω)

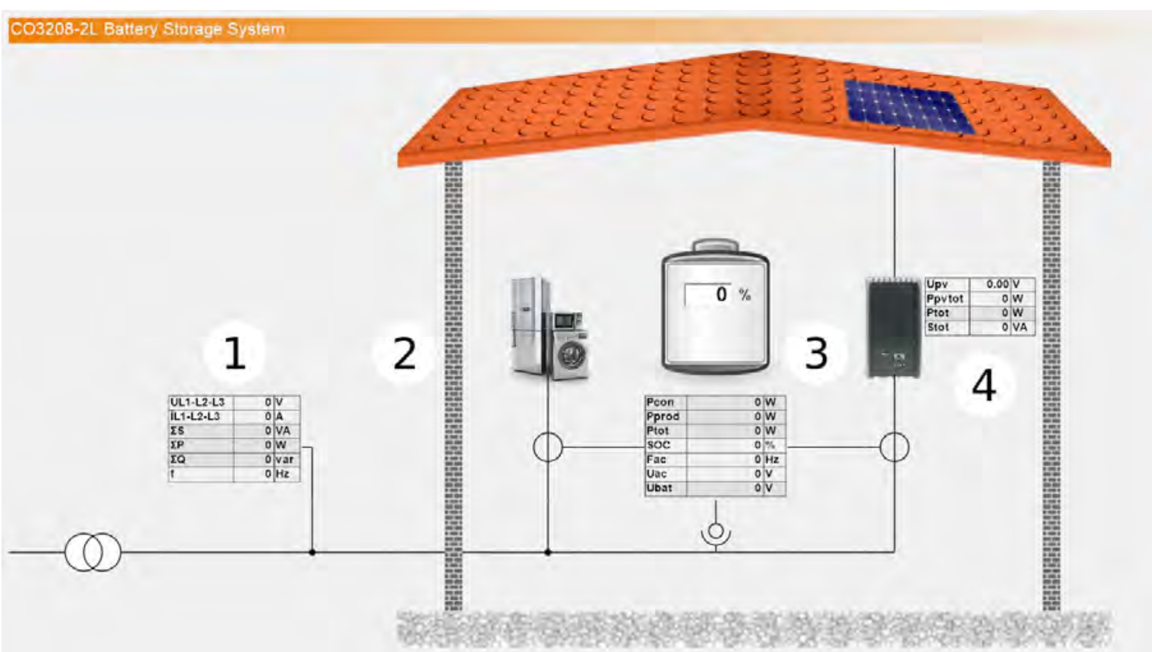


Figure 21:

EPH4_Daytime.pvc

- 1: Grid parameters at the "house connection".
- 2: House system's boundary.
- 3: Parameters of the storage system as well as the connected measuring electronics.
- 4: Parameters of the PV inverter.

Case 5: Manual Battery Control in a Smart Grid

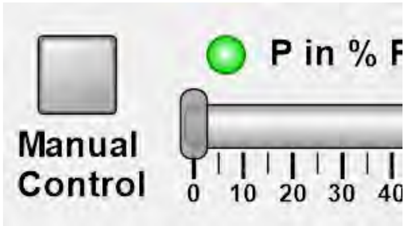
1. Keep the assembly and wiring plan from Figure 14.
2. Save the file from the link "EPH4_RemoteControl.pvc" to a working directory on your PC.
3. Open the SCADA viewer and select the file named "EPH4_RemoteControl.pvc".
   - File → Open...
   - Navigate to the location of the file and open it.
   - SCADA user interface will look as Figure 22.
4. You might have to set the communication interface and/or address of the equipment in the device manager (F8).
   - For related instructions, refer to the chapter on SCADA for PowerLab.
5. Activate SCADA via the start-stop symbol or F5.
6. Open the *"Solar Panel"* virtual instrument .
7. Deactivate the *USER PROFILE* and carry out the following settings:

Shadow	0 %
Shaded modules	0
Irradiance	50 %

8. Activate the *Solar Panel* virtual instrument via its *POWER* button.
9. Wait until the PV inverter has synchronized itself with the grid and is supplying the set power.

The synchronization may take up to 5 minutes.

10. Turn the variable resistor fully counter-clockwise. (Max value of 750 Ω.)
11. In SCADA, turn on manual battery control via "Manual Control".



12. Select storage system discharging at 300 W.
13. Record the resultant power levels in Table 18.
14. Switch over from storage system discharging to charging without changing the power level.
15. Record the resultant power levels in Table 18.
16. Set the storage system so that no exchange takes place via the house connection. ($\Sigma P_{house\ connection} = 0$ W).
17. Record the resultant power levels in Table 18.
18. Deactivate SCADA via the start-stop symbol or F5.
19. Deactivate the "Solar Panel" virtual instrument via the POWER button.

Storage System Discharging at 300 W		
PV inverter	Energy storage system	House connection
P_{tot} (W)	P_{tot} (W)	ΣP (W)
Storage System Discharging at 300 W		
PV inverter	Energy storage system	House connection
P_{tot} (W)	P_{tot} (W)	ΣP (W)
Storage System at No Exchange (ΣP=0)		
PV inverter	Energy storage system	Power in percent
P_{tot} (W)	P_{tot} (W)	P in % P_N

Table 18

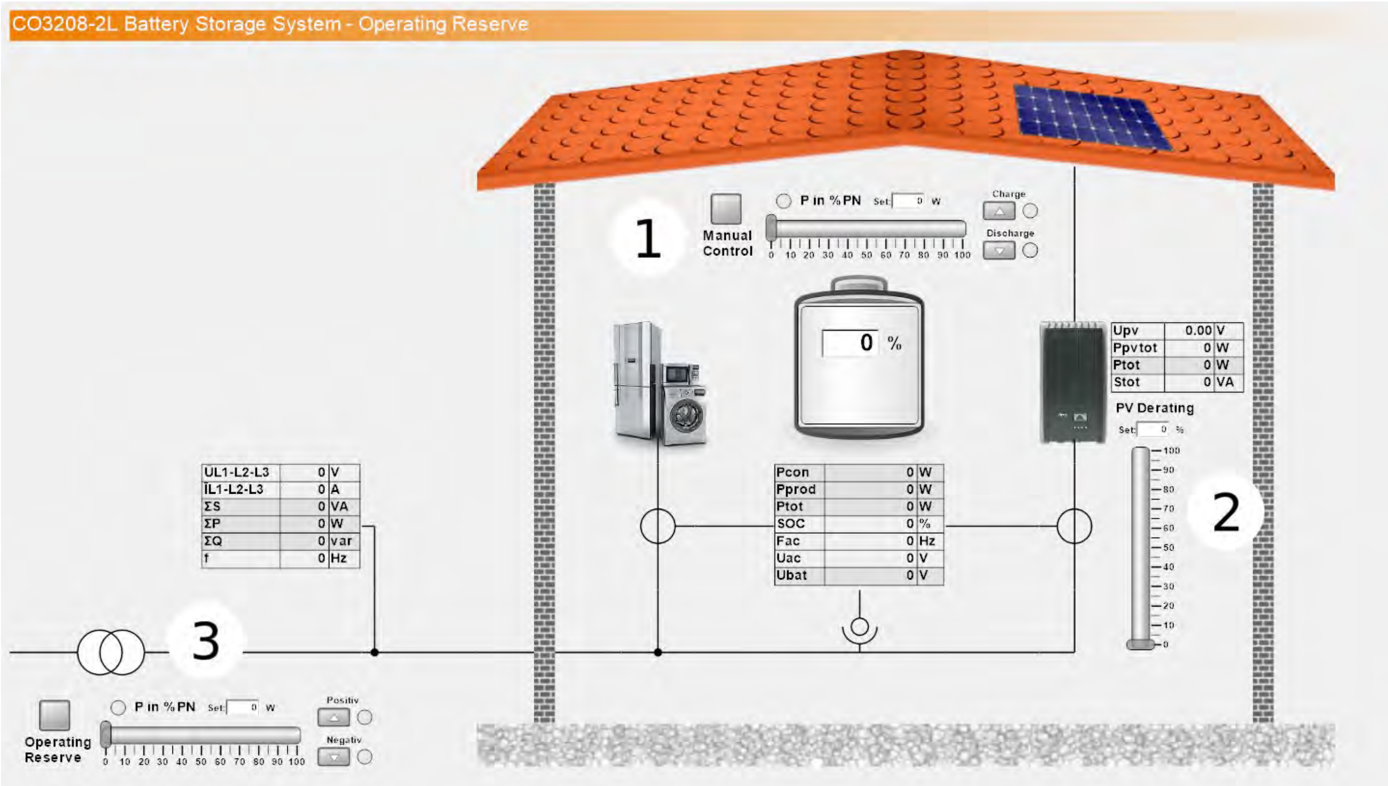


Figure 22:
EPH4_RemoteControl.pvc

- 1: Manual battery control.
- 2: PV power limitation as a percentage of the rated power.
- 3: Operating reserve specification.

Case 6: Provision of Operating Reserve in a Smart Grid

1. Activate SCADA via the start-stop symbol  of F5.
2. Activate the Solar Panel virtual instrument via its POWER button.
3. Wait until the PV inverter has synchronized itself with the grid and is supplying the set power.

The synchronization may take up to 5 minutes.

4. Keep the variable resistor fully counter-clockwise. (Max value of 750 Ω.)
5. By means of the "Operating Reserve" button, switch on the control unit for provision of operating reserve.

6. Select a power of -1200 W.
7. Record the power levels for the house connection and storage system in Table 19.
8. Switch the power's sign to positive while leaving the power setting unchanged.
9. Wait until the values settle to plausible levels. This can take about one minute.
10. Record the power levels for the house connection and storage system in Table 19.
11. Deactivate SCADA via the start-stop symbol  or F5.
12. Deactivate the "Solar Panel" virtual instrument via the POWER button.

Operating Reserve Negative	
Energy storage system	House connection
P_{tot} (W)	ΣP (W)
Operating Reserve Positive	
Energy storage system	House connection
P_{tot} (W)	ΣP (W)

Table 19

Report Questions

1. What can be said about the energy storage system?
2. Which conclusions can be drawn about the storage system's interaction with consumers?
3. What happens to the storage system power consumption during examination of current sensors for power measurement?
4. Name the three main characteistics of the current sensors used in power measurement (Case 3).
5. What happens to the system if the PV system is connected to the consumer's port and the load removed? (Case 3).
6. Display/show the graphic's characteristics of the SCADA logger's measurement results from daily characteistic. (Case 4).
7. What happens at 16:00 hours in daily characteistic's simulation according to the SCADA logger's measurement results?
8. Your conclusions from the curve for the house's *grid connection* in the SCADA logger's measurement results.
9. Which power must be set on the storage system so that no exchange takes place via the house connection?
10. What can be said about the manual battery control in a smart grid?
11. What happens to the system when you switch the power's sign to positive while leaving the power setting unchanged during "Operating Reserve" function? What do you observe? (Case 6)
12. Can the positive power in provision of operating reserve be realized by extending or adjusting the system?

References

Marcela Isaza, *Professional photovoltaics: Modern PV systems in grid-parallel operation*, Lucas-Nülle GmbH, 2019.