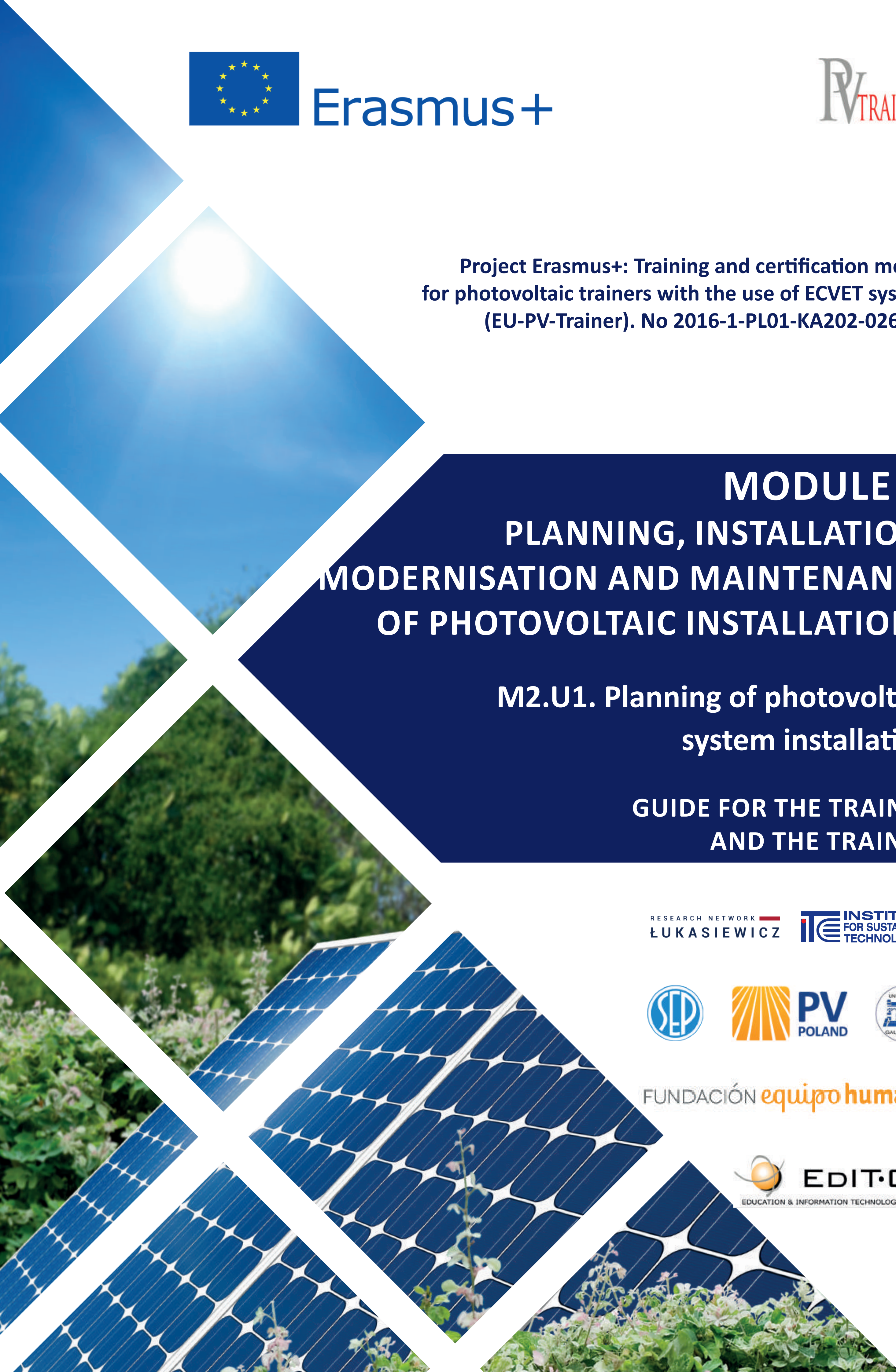

Project Erasmus+: Training and certification model
for photovoltaic trainers with the use of ECVET system
(EU-PV-Trainer). No 2016-1-PL01-KA202-026279

MODULE 2.
PLANNING, INSTALLATION, MODERNISATION AND MAINTENANCE OF PHOTOVOLTAIC INSTALLATIONS

M2.U1. Planning of photovoltaic system installation

GUIDE FOR THE TRAINEE AND THE TRAINER

Erasmus+
Cooperation for innovation and the exchange of good practices
Strategic Partnership for vocational education and training

"Training and certification model for photovoltaic trainers with use of the ECVET system (EU-PV-Trainer)"
No. 2016-1-PL01-KA202-026279

Intellectual Output O4.

Bank of training modules for the photovoltaic trainer with regard to ECVET requirements (stationary learning)

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2018-2019

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GUIDE

FOR THE TRAINEE AND THE TRAINER

2018-2019

Course: Photovoltaics trainer

Module 2. PLANNING, INSTALLATION, MODERNISATION AND MAINTENANCE OF PHOTOVOLTAIC INSTALLATIONS

M2.U1. Planning of photovoltaic system installation

Guide for the trainee and the trainer

2018-2019

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The guide constitutes a didactic development for the modular unit **M2.U1. Planning of photovoltaic system installation** included in the module **M2. PLANNING, INSTALLATION, MODERNISATION AND MAINTENANCE OF PHOTOVOLTAIC INSTALLATIONS** contained in the modular curriculum for the course **Photovoltaics Trainer**.

2018-2019

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TABLE OF CONTENTS

1. INTRODUCTION

While commencing performance of professional tasks assigned to the PV trainer in the modular education system, as a training participant you shall acquire necessary knowledge and professional skills included in two modules:

- M1. Planning, organisation, conducting and assessment of professional training,
- M2. Planning, installation, modernisation and maintenance of the photovoltaic installation.

Every module is divided into modular units composed of teaching material, checklist, exercises and progress test.

The study contains materials developed for the modular unit **M2.U1. Planning of photovoltaic system installation** included in the module **M2. Planning, installation, modernisation and maintenance of the photovoltaic installation.**

Prior to the commencement of learning, as a training participant you should get familiar with initial requirements and detailed learning outcomes, i.e. knowledge, skills and attitudes that you shall acquire after the end of learning in a given modular unit.

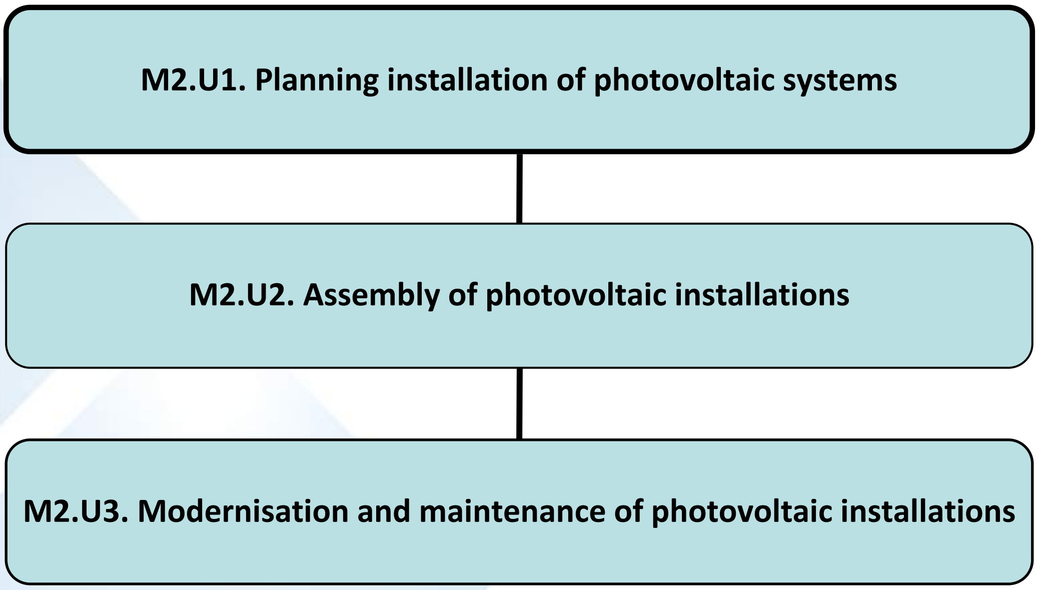
While developing the teaching material, experience of the project partners within the scope of teaching classes on courses preparing future photovoltaic installation installers. Teaching material has been supplemented with e-learning training including e.g. instructional videos.

Prior to the performance of exercises, check if you are properly prepared. To this end, use checklists after each teaching material. Every subject is ended with a progress test that shall enable you to define the scope of acquired knowledge and skills. If your results are positive, you can go to the next subject. If not, you should repeat the content necessary for specific skills.

Passing the test in an e-learning version constitutes the basis for passing the modular unit.

Note: in case of teaching content including references to legal acts, it should be kept in mind that they are valid as at the date of study development and must be updated. The teaching content in the module is compliant with the legal status as of 15 August 2018.

The Guide has been developed under the project "**Training and certification model for photovoltaic trainers with use of the ECVET system (EU-PV-Trainer)"** co-funded by the European Union in the Erasmus+ programme *Cooperation for innovation and the exchange of good practices Strategic Partnership for vocational education and training*.



Scheme of the modular unit system in the module **M2. Planning, installation, modernisation and maintenance of photovoltaic installations**

List of modular units and approximate number of teaching hours

Name of module	Name of modular unit	Planned number of teaching hours
M2. Planning, installation, modernisation and maintenance of photovoltaic installations	**M2.U1. Planning of photovoltaic system installation**	28
	M2.U2. Assembly of photovoltaic installations	20
	M2.U3. Modernisation and maintenance of photovoltaic installations	16
	Total:	**64**

2. INITIAL REQUIREMENTS

While commencing implementation of the curriculum of the modular unit **M2.U1. Planning of photovoltaic system installation** included in the module **M2. Planning, installation, modernisation and maintenance of photovoltaic installations,** you should be able to:

- use various sources of information,
- determine your own rights and obligations,
- recognise basic legal acts,
- participate in discussion, presentation and defence of your own position,
- feel responsible for your and other's health (life),
- apply basic ethical principles (reliable work, punctuality, keeping one's word, honesty, responsibility for consequences, truthfulness),
- cooperate in a group with consideration of the division of tasks,
- use computer at a basic level.

3. DETAILED LEARNING OUTCOMES

M2.U1. Planning of photovoltaic system installation

After taking classes in the modular unit, the trainee shall achieve the following learning outcomes:

Knowledge (it knows and understands):	Skills (it can):
– History and prospects of photovoltaic development in Europe and in the world. – Economic, environmental and social benefits of photovoltaic applications. – National regulations and standards for the use and use of photovoltaics. – Regulations regarding health and safety at work, fire protection and the environment used during installation – identification of hazards. – Examples of product certification systems (eg Solar Keymark). – Basic terms and definitions for photovoltaic systems. – Basic knowledge of low voltage electrical installations and photovoltaic installations (General electrical engineering related to photovoltaic installations). – Project records (documentation). – Solar cell – construction and principles of operation. – Types of photovoltaic cells and modules. – Types of photovoltaic systems. – Equipment and components of photovoltaic systems. – Selection of technical solutions. – Energy profiles of receivers. – Dimensioning the system. – Connecting the photovoltaic system to the power grid. – Standards and technical specifications related to the thematic group. – Current-voltage characteristics of modules. – Factors affecting work efficiency. – Cooperation of photovoltaic installation with alternative sources of electricity.	– Using project documentation and technical materials (operating instructions, DTR, etc.). – Linking cells into modules and modules into sets. – Measurement of cell / solar module parameters under standard conditions (STC). – Choosing the type and power of photovoltaic modules, configuring the solar generator. – Determining the required cross-section of connection cables. – Defining the requirements for lightning protection, grounding (earth) and system (installation) of surge suppression. – Calculation of the system surface and the nominal size of the system, necessary subsystems and devices and the appropriate equipment. – Select inverter / inverter as an energy converter; inverter / inverter safety functions; determining the efficiency of the inverter / inverter. – Adjusting the generator to the inverter / inverter – Evaluation of the system operation - analysis of quality indicators.

Social competence:
– Be responsible during the work preformation. – Demonstrate a good professional doing. – Propose alternatives with the objective to improve results. – Maintain the work area with the degree of order and cleanliness required by the organization. – Participate and collaborate actively in the work team. – Interpret and execute working instructions.

4. TEACHING MATERIAL

4.1. General issues. Basis for the use of photovoltaic systems

History of photovoltaics

Photovoltaics has a long history that started in 1839 from observations of Edmond Becquerel, son of Antoni Cesar Becquerel and father of Henri Becquerel, both famous physicists. Becquerel noticed that if two platinum electrodes were placed in the solution and exposed to the sunlight, current flowed. That effect was very small and had no practical meaning in that time, however it has not been forgotten.

The name of photovoltaics was formally used for the first time by A. Einstein in his paper from year 1905 published in the journal *Annalen der Physik* under the title of "*On a Heuristic Viewpoint Concerning the Production and Transformation of Light*". He explained the external photoelectric effect as the emission of electrons from the metal surface through its performance of the work function under the impact of particle radiation with proper wave length. Therefore, photovoltaics is the field of science and technology occupying with the research of direct conversion of solar radiation energy to electrical energy. The first solar cell was built in 1954 in Bell Laboratories in Murray Hill, USA, by researchers Chapin, Fuller and Pearson. The solar cell achieved the efficiency of 6%, which was soon improved and increased to 10%. Back then, space technology constituted the most important application of solar cells. The beginning was in 1958, when first 108 cells were installed on the Vanguard satellite. Results went beyond expectations – cells provided the satellite with electrical energy for much longer than it was originally assumed. It allowed for the development of a limited market of photovoltaic cells, however characterised with high quality.

Due to its high costs, application of photovoltaics on Earth had been rejected for a long time as unrealistic. However, its benefits were fascinating scientists and public opinion, so research on it has never been fully abandoned. Step by step, solar cells found its way to autonomous applications in supply systems independent on the network. It started with calculators and watches, and then it was used in larger devices, such as parking meters. Emergence of the first fuel crisis in 1973 was accompanied by thinking about the use of solar cells on Earth, and shortly afterwards there were launched production plants of silicic cells and modules. At the beginning of 1980s, global trade in solar cells was at the level below 20 MWp/year. In 2008, an annual trade in solar cells achieved more than 7000 MWp. It constituted an increase by 400 times over only 27 years. In 2017, total power of installed PV systems came to 40 GW. A key role in development of photovoltaics was played by the solar energy market promotion, which began in 1990 from the program 1000 Roofs in Germany. That program was very successful and then it was implemented in many countries. A short time later, on the turn of 1998 and 1999, the program 100 Thousand Roofs was introduced, and in 2004 the Renewable Energy Act (EEG) came into effect. EEG appeared to be the most appropriate tool for promotion of photovoltaics. The market noted down a dynamic increase.

For many decades, efforts have been made to replace silicon with other materials. Materials of high light absorption are searched for in order to make cells thinner and cheaper. That searches result in thin layer cells that are 100-times thinner than those from crystalline silicon. The first solar cell was made from amorphous silicon already in 1976 by David Carlson and Chris Wronski. However, in 1980s high expectations concerning that material were not realized. Another thin layer material that is still at an early stage of market implementation is CIS (copper indium selenide), known also as CIGS, if it contains an addition of gallium. These cells are characterised with high stability and achieve, at least in laboratory, high efficiencies. Cadmium telluride is another thin layer material from which solar cells are produced. So-called micromorth photovoltaic cells (structure from amorphous and microcrystalline silicon) are also present on the market.

Fields of application of PV systems independent on the network constitute usually autonomous systems in developing countries, leisure (camping, sailing, etc.), telecommunications systems, as well as PV/diesel fuel hybrid systems. The role played by photovoltaic cells in consumer products (watches, toys, etc.) should not be underestimated. In the past, photovoltaic systems were almost exclusively installed on existing roofs, so they were regarded as additional elements. However, for several years photovoltaic products are available, which can be applied directly as roof covering, so they constitute an integral part of roof. There are also PV components in the form of dormer windows. Moreover, all main glass producers offer photovoltaic elements that can be easily integrated with warm or ventilated facades.

In today's world, energy priorities are changing. New technologies, cleaner, more quickly installed and better adjusted to local needs attract interest of investors and local authorities, slowly competing with monopolised and centralised energy sector. While comparing various energy options, economic costs are gradually no longer a vital criterion – factors which economic value is difficult to be calculated directly, such as energy independence, diversification of energy sources or stability of supplies, are more and more important. It is particularly important against the possible appearance of another energy crises.
Throughout the year 2017, almost 100 GW of power was installed all over the world, which constitutes another record for global photovoltaics. Total installed PV power came to 400 GW at the end of year 2017, which means an increase by 25% as compared to 2016. In 2017, 9.2 MW of new PV installations was established in Europe.

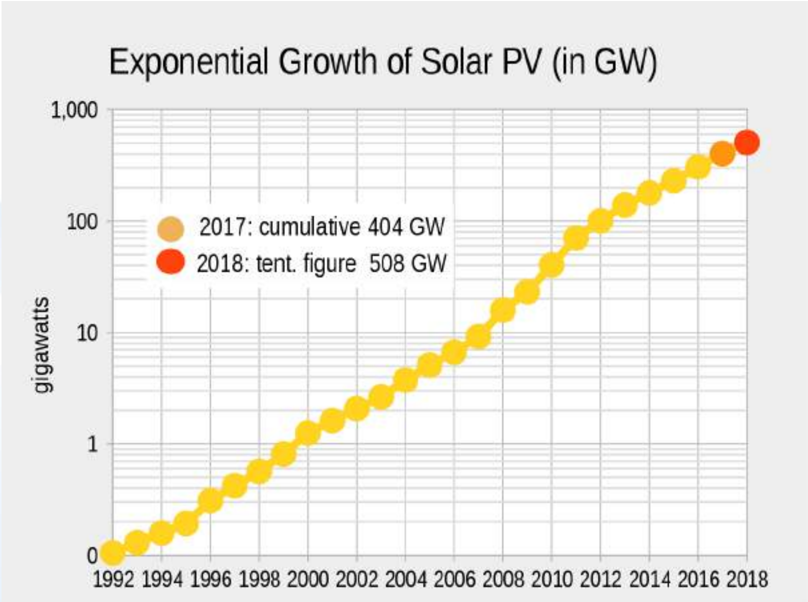


Fig. 1. Total installed PV power from 1992 to 2018
Source: https://en.wikipedia.org/wiki/Growth_of_photovoltaics#/media/File:PV_cume_semi_log_chart_2014_estimate.svg [access: 20 June 2018]

The advantages of PV are manifold:

- Primary energy supply of the sun is larger than from all other energy sources.
- It is available in all regions of the world.
- Its modular design varies from miliwatt (mW) in consumer products to gigawatt (GW) in a utility-scale power plants.
- During operation, it produces electricity with no atmospheric emissions and no waste production.
- It requires virtually no maintenance.
- It is silent during operation.
- It requires no water to generate electricity.
- PV systems offer a carbon footprint that is 10 to 20 times lower than conventional energy generation technologies.
- The energy payback time of PV systems is between 0.5 and 1.5 years depending on technology and location.
- It has a proven technical lifetime of 30+ years.

Photovoltaics in systems of scattered energy generation

Liberalisation of the European energy market means that there will be more intense competition in the energy sector in the area of production, distribution and sales of electrical energy. New players shall appear due to an open access to energy networks on the market. They shall increase the current tendency of increasing the share of scattered energy generation. Photovoltaic systems may become a significant part of energy infrastructure in this process.

4.2. Photovoltaic cell – structure and operating principle

Fundamentals of Solar Energy Use

One of the most important tasks at present is the development of strategies and systems to provide energy on an ecologically sound basis. From today's perspective, only renewable energy sources such as the sun and the wind satisfy all the conditions, which must be placed on the energy supplies for the future. Further, these energy sources are inexhaustible, whereas the exploitation of fossil fuel reserves can continue only for a limited period.

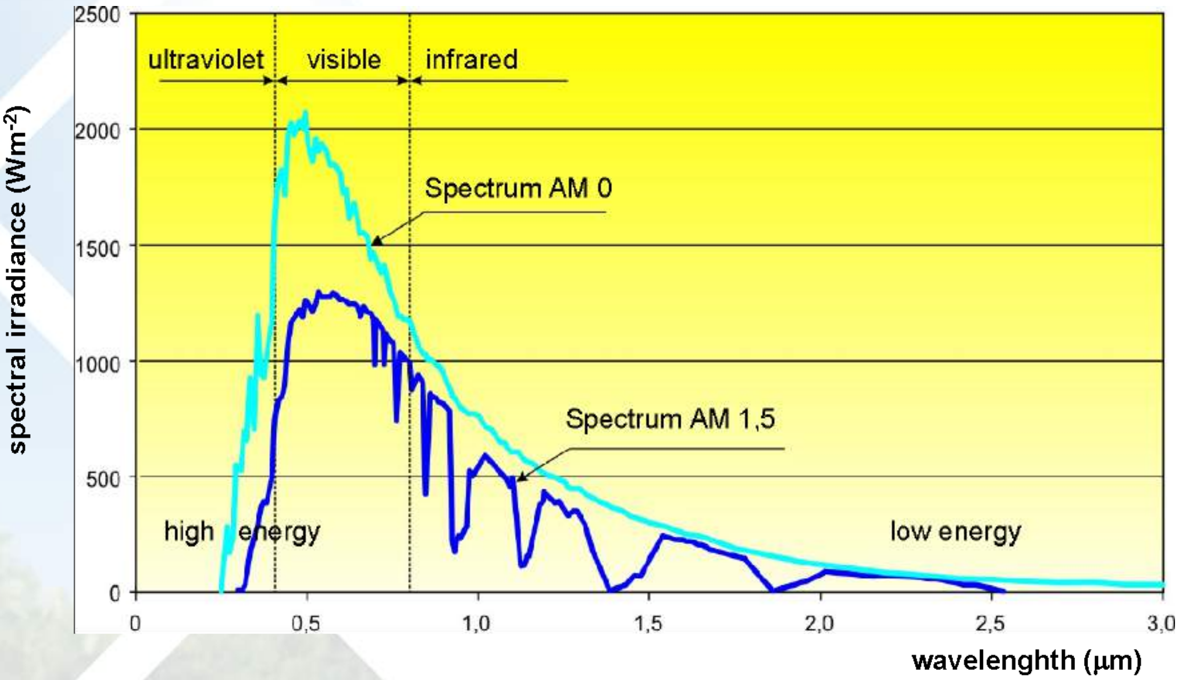


Fig. 1. Solar radiation spectrum
Source: Fraunhofer ISE, Freiburg, Germany; Solarpraxis AG, Berlin, Germany.

Solar radiation on the earth's surface

The radiation intensity changes continually according to the time of day, the season and the weather conditions. This radiation intensity is measured in watts or kilowatts per square metre [Wm^{-2}, kWm^{-2}]. The radiation energy, i.e. the power generated over a certain period of time, is given in watt-hours (also kilowatt-hours, joules) per square metre. It should be noted that in common usage, the term 'radiation' is applied to both the radiation intensity and the energy.
The radiation intensity outside the earth's atmosphere is between 1325 and 1420 Wm^{-2}. The mean of this so-called extra-terrestrial radiation is the solar constant.

$$\text{solar constant: } E_0 = 1367 \text{ kWm}^{-2}$$

Reflection, scattering and absorption by the atmosphere reduce this value by about 30 %, so that about 1000 Wm^{-2} is incident on the earth's surface at midday when the sky is cloudless. The so-called global radiation consists of two components, the direct and the diffuse radiation. Direct (or beam) radiation comes directly from the sun, whereas diffuse radiation is incident from all sky directions; the sky thus appears to be equally bright in all directions.

The diffuse component can be seen on sunny days as the blue sky. When the sky is completely overcast, only diffuse radiation reaches the earth's surface.

Tab. 1. Radiation intensity for various weather conditions

Sky			
Weather	Cleary blue sky	Hazy/cloudy, sun visible as whitish yellow disc	Overcast sky, dull day
Global irradiance	600 – 1000 Wm^{-2}	200 – 400 Wm^{-2}	50 – 150 Wm^{-2}
Diffuse fraction	10 – 20%	20 – 80%	80 – 100%

Source: Fraunhofer ISE, Freiburg, Germany; Solarpraxis AG, Berlin, Germany.

The annual distribution and the total amount of solar energy are determined by climatic and meteorological factors which depend on the location and the season. These differences in the weather over the earth are due to the changes during the year of the sun's position and the length of daylight, which in turn are caused by the tilt of the earth's axis relative to its orbit around the sun.

In sunny regions such as deserts in Africa or southern USA, twice as much energy is available on average as in Central Europe.

There are differences in the distribution of the energy over the year (Fig. 4). In Central Europe, the amount of solar energy incident in the months between November and January is about five times less than in the summer months, whereas the radiation supply is much more uniform at low latitudes.

Optimum use of direct radiation is only achieved when the receiver surface is always perpendicular to the incident radiation. The more oblique the incident angle, the smaller is the amount of useful energy. In Central Europe, as the sun is low in the sky in winter even at noon, a large tilt angle is advantageous, whereas in summer, a small tilt angle is better (Fig. 2).

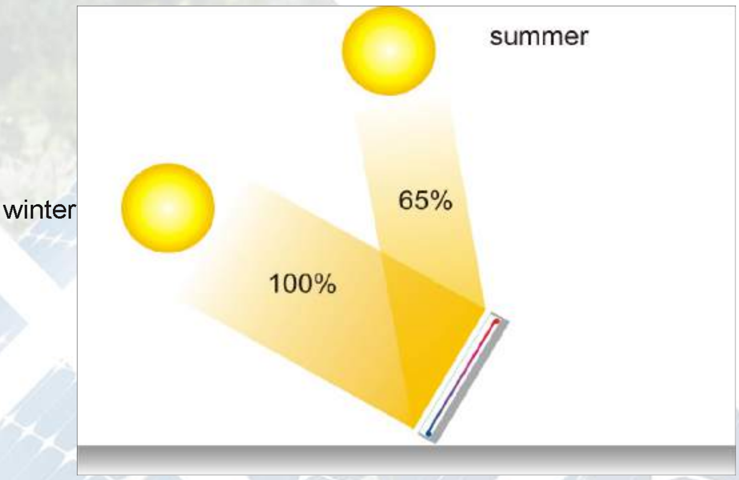


Fig. 2. Direct radiation on a tilted receiver
Source: Fraunhofer ISE, Freiburg, Germany; Solarpraxis AG, Berlin, Germany.

So-called tracking receivers, for which the orientation and tilt can be continuously adjusted such that they always point toward the sun, are generally only justified in climatic regions where the direct radiation fraction is very high, e.g. in deserts. Although tracking also increases the amount of received energy in Central Europe (by about 30%), its value is arguable, as it demands considerable technical complexity.
For stationary mounting of the receiver, the optimum tilt angle depends on the operating conditions of the system (Table 2).

Tab. 2. Receiver tilt angle for different conditions (in Central Europe)

Boundary conditions	Angle
Maximum total annual energy yield	30°
Optimisation for winter months	60°
Good performance in spring and autumn	45°

These values depend on the location; the closer the system is to the equator, the smaller is the optimum tilt angle.

Optical air mass (AM) – length of the distance through the Earth's atmosphere covered by an optical beam of direct solar radiation, expresses as multiple distance covered to the point on the sea level, at the sun in zenith. AM is specified in the formula:

$$AM = \frac{P}{P_0} \cdot \frac{1}{\sin\theta}$$

Where:
P – local atmospheric pressure (Pa),
$P_0 = 1{,}013 \cdot 10^5$ Pa (normal pressure),
Θ – angle of incidence of the Sun.

The AM value is equal to 1 **(AM 1)** at the sea level, at cloudless sky, when the sun is in zenith and atmospheric pressure $1{,}013 \cdot 10^5$ Pa (IEC 60904-3).

If the Sun is perpendicularly set to the Earth's surface, sunlight goes through the optimal air mass **(AM – air mass)** only once. Such a condition has the symbol AM 1. In other cases, distance of solar radiation through the air. This distance depends on the height at which the sun is. AM 2 shows that the distance of the sunlight through the air is twice longer than AM 1. The same happens when the Sun is at an angle of 30° over the horizon (γ_s=30°).

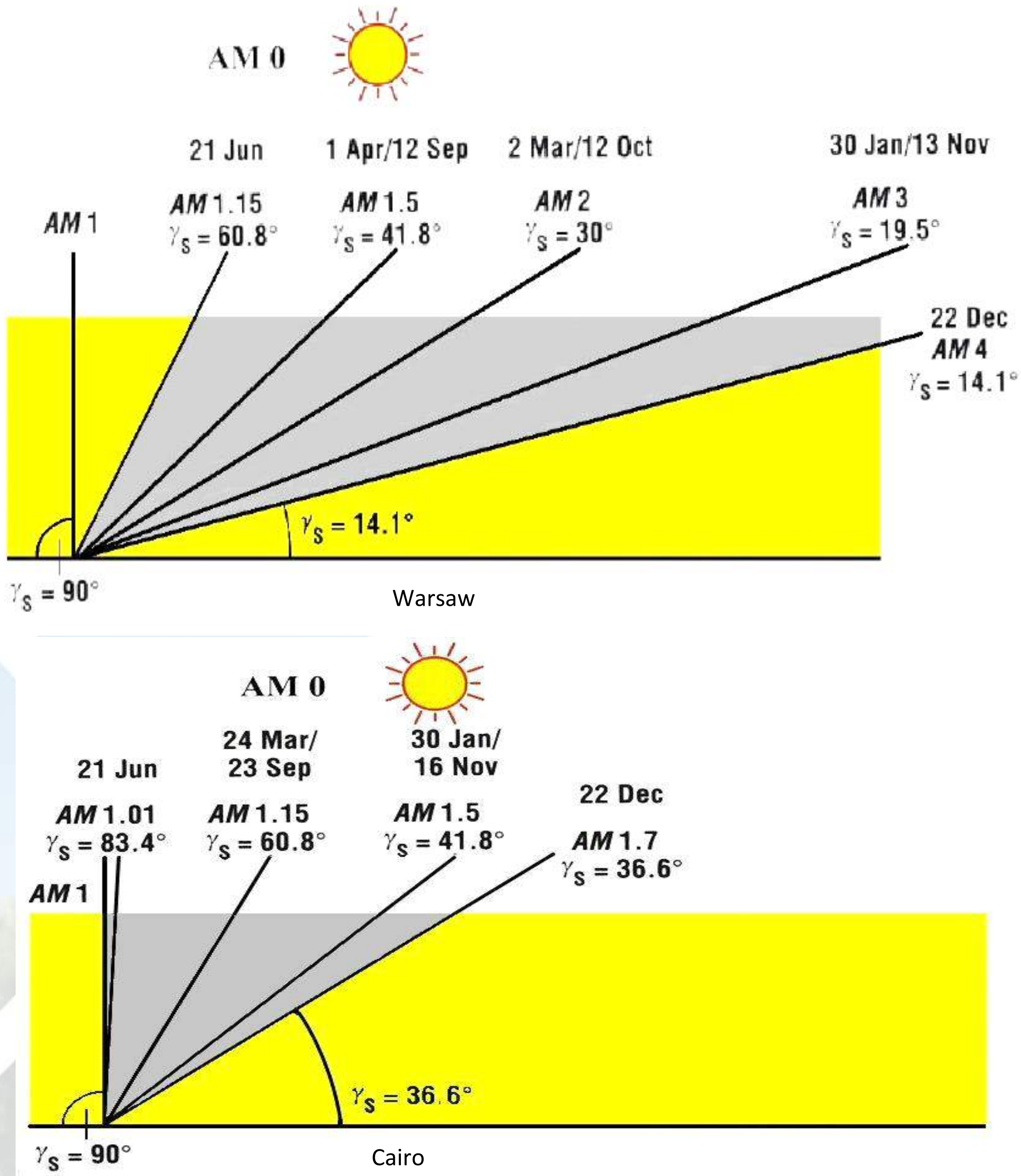


Fig. 3. Distance of radiation depending an angle of beam atmospheric entry for Warsaw and Cairo
Source: *S.M. Pietruszko (red.): Projektowanie i instalacja systemów fotowoltaicznych. Przewodnik dla instalatorów. Warszawa, 2016.*

Solar cell technologies and their properties

"Solar cell" stands for a device which, under light irradiance, acts as a generator of electricity. Many kinds of solar cells are possible, but the cell based on a silicon semiconductor diode is the most common version. It has been invented 50 years ago, in 1954.

General aspects and definitions

Solar cells convert light to electrical energy. Generally, this is a three-step process which can be explained by means of Fig. 4.

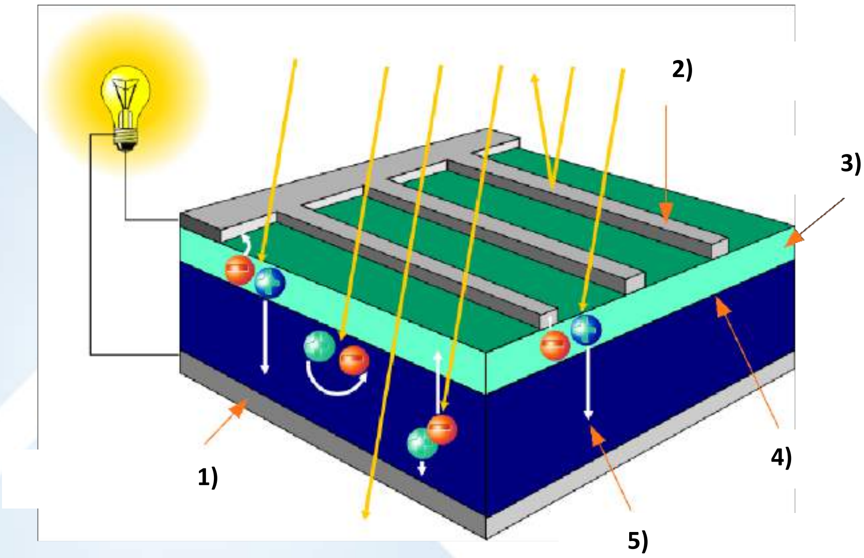


Fig. 4. Cross-section of a crystalline silicon solar cell, where: 1) positive electrode, 2) negative electrode, 3) n-doped silicon, 4) p-n junction, 5) p-doped silicon.
Source: Solarpraxis AG, Berlin, Germany.

- **Absorption of light**, delivering electrons in an excited state.
- Locally **separation of** positive and negative **charges.**
- **Conduction of the charges** to an external circuit.

Absorption: In most cases the absorber is a *semiconductor*, and the used transitions are *interband transitions*. The excited state comprises an electron in the conduction band and a hole in the valence band.
Charge separation: Electrons and holes in semiconductors are separated by *diffusion* or by *drift* of the charge carriers in the *space charge regime* of a *p-n-junction* or in a *hetero junction* of two materials.
Conduction of the charges: The charge separation leads to the generation of a voltage between the both sides of a solar cell. Contacts have to be applied to conduct the charges to an external circuit. This is not always easy since the contacts should have a very *low contact resistance* to avoid electric losses within the device. It is obvious that at least one of the contacts must have a high optical transmittance to allow light to reach the absorber inside the device. One means is to use thin conducting oxides (TCO) as transparent contacts, the other technique is to use small metal fingers ("*grid*") on top of the cell, tolerating some shadowing (4 to 7%).

The solar cell as a power generator

Since the solar cell is intended to deliver the highest possible amount of electric power (at a certain level of incident light), it is useful to analyse the I-V-characteristic with respect to the power which can be extracted. If the operating point of a solar cell is shifted along the I-V characteristic curve (by changing an external load resistor), electrical power generated in the external load can be found by multiplying the current by the voltage in the operating point. This has been done in the graph on Fig. 5. The power that can be extracted goes through a maximum at a certain point, the *Maximum Power Point (MPP)*. It is characterised by P_{MPP}, the *maximum power*, by I_{MPP}, the *current at maximum power*, and by V_{MPP}, the *voltage at maximum power*.

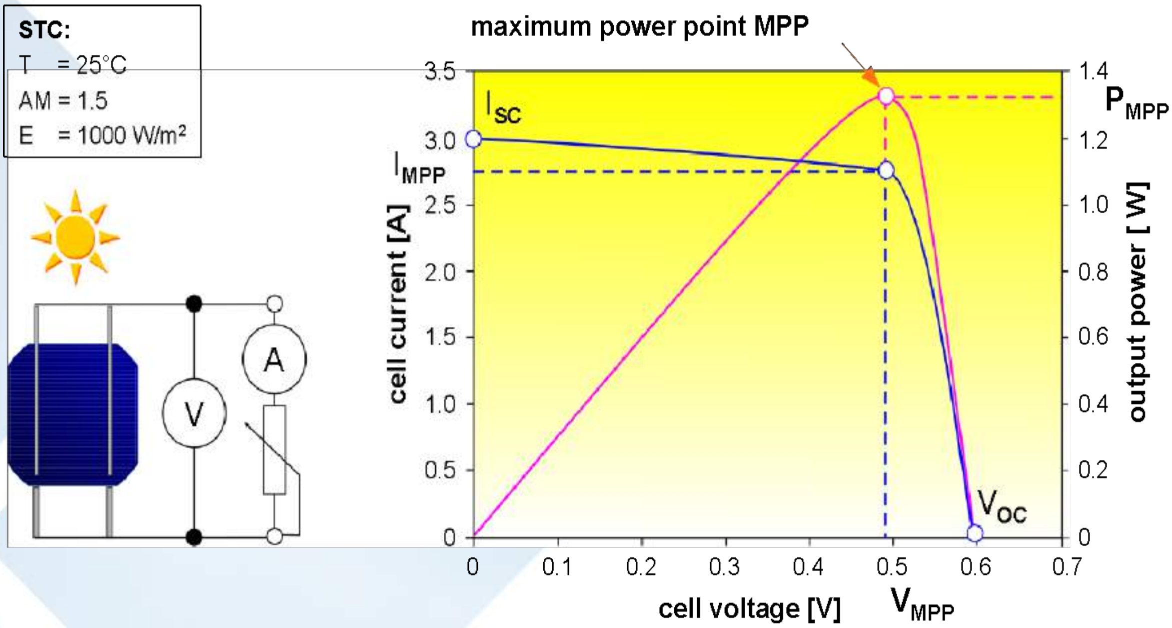


Fig. 5. Power generated by a solar cell as a function of the operating point
Source: Solarpraxis AG, Berlin, Germany.

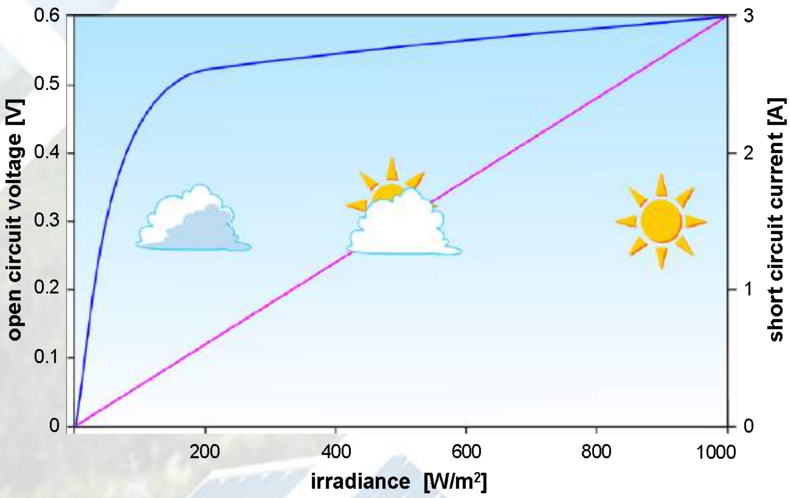


Fig. 6. Dependence of V_{OC} and I_{SC} on the light intensity
Source: Solarpraxis AG, Berlin, Germany.

All electrical parameters of the solar cell depend on the intensity and the spectrum of light, as well as the temperature of the solar cell. The dependence of current and voltage on the illumination level are shown in Fig. 6. Whereas the current of the cell is linearly dependent on the irradiance, the voltage and the MPP are not, and therefore the description of the behaviour of a cell under different illumination level is complicated.

For different levels of irradiance but constant cell temperature, this leads to a set of characteristic curves as shown in Fig. 7.

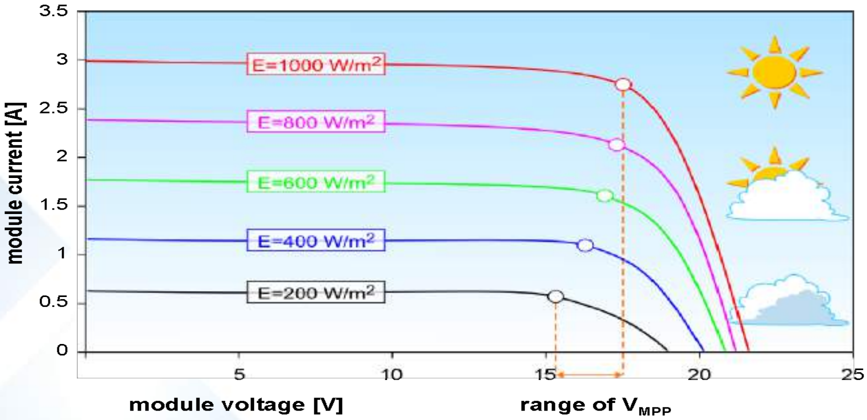


Fig. 7. I-V-curves of crystalline silicon module at different irradiance levels and constant temperature
Source: Solarpraxis AG, Berlin, Germany.

As can be seen, the short circuit current is straight proportional with rising irradiance and the characteristic curves are shifted parallel. The open circuit voltage changes only little with varying irradiance. As a result, the MPP-Voltage swings within a small range.

Most properties of semiconductors are strongly temperature dependent – therefore, the short circuit current, the open circuit voltage as well as the maximum power and the appendant current and voltage are also temperature dependant. This has to be taken into account when calculating the energy yield of a solar generator or when selecting a PV-module for battery charging under extreme climatic conditions.

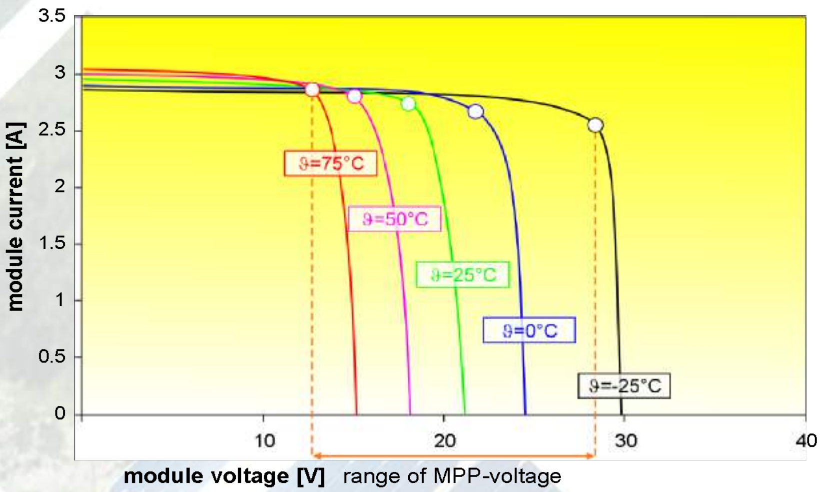


Fig. 8. I-V-curves of a crystalline silicon module for different cell temperatures at constant irradiance
Source: Solarpraxis AG, Berlin, Germany.

The efficiency of solar cells and its measurement

The "efficiency" (η) is the most important property of a solar cell. It describes which part of the incident light is converted to electric power. The definition is easy:

η = generated maximum electric power/incident light power.

Three conditions have to be known when measuring the parameters of a solar cell: temperature, level of illumination, spectrum of the light. Since the comparison of solar cells should be possible worldwide, standard test conditions (STC) have been defined which are accepted by all institutions that characterise and certify solar cells. These ***STCs*** are:

Temperature:	25°C
Illumination level:	1.000 W/m^2
Light spectrum:	Air Mass AM1.5

The maximum power (at MPP) measured under STC conditions is called the *peak power*, and the unity is *peak-Watt* (W_p).

Solar cell materials and technologies

Many semiconductor materials can be used to fabricate solar cells, the basic device for photovoltaic electricity generation. Today, many types of materials, device structures, and production technologies are under development, and it will take some time until a few most profitable versions will remain on the market place.

For an evaluation of the different technologies a number of criteria have to be taken into account. The most important are:

– a good potential for a high efficiency,
– good availability of the required materials,
– acceptable price for the materials,
– potential for low-cost production techniques,
– stability of the device for decades,
– environmental compatibility of the products and of the production techniques.

4.3. Types of photovoltaic cells and modules

For nearly five decades people have been searching for the optimum material for solar cells. Hundreds of materials have been tested, but only a few classes of materials finally remained, showing good photoelectric properties and at the same time good productivity.

Crystalline silicon cells

As mentioned before, silicon remains to be the most important material for solar cells. Silicon is produced in huge amounts for applications in metallurgy, and in high purity form it is the basis of most electronic and microelectronic devices.

Advantages and disadvantages:

– well-developed technologies based on common semiconductor processing,
– good efficiencies obtained in production,
– excellent efficiencies above 24% obtained in the laboratory,
– very stable efficiency,
– unlimited source for starting material,
– good environmental compatibility,
– due to the low absorption coefficient fairly thick layers (>100µm) are needed for good efficiencies; the requirement of large amounts of expensive high purity silicon is the main cost driver.

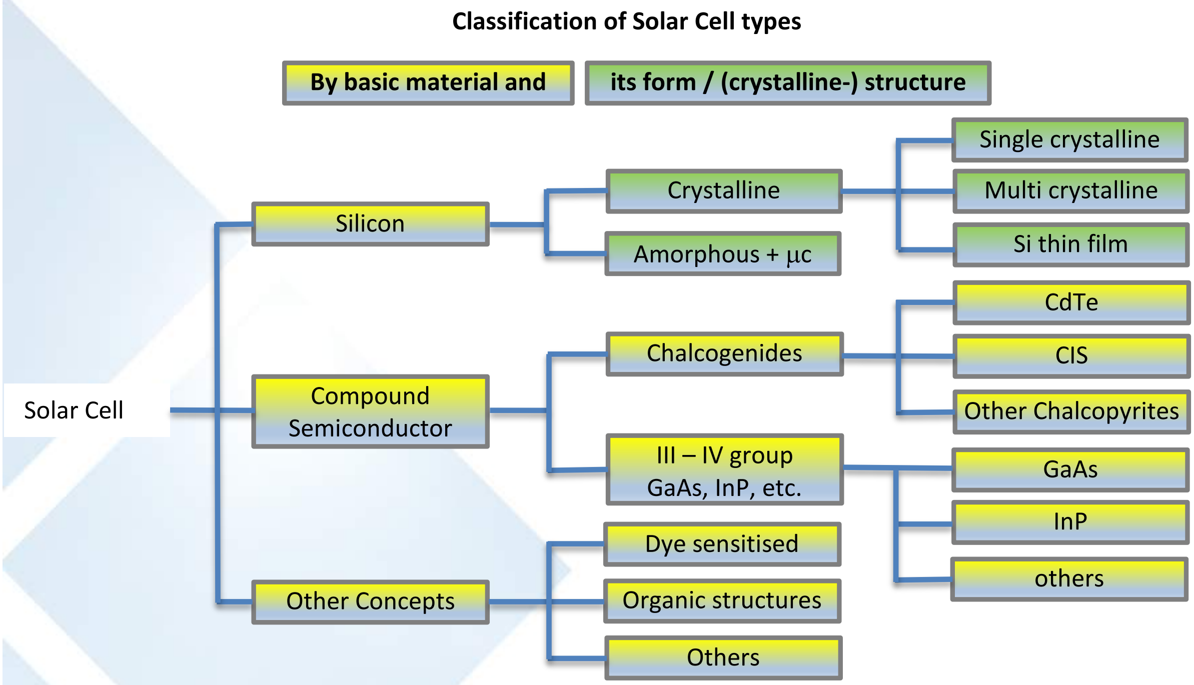


Fig. 1. Materials used for the fabrication of solar cells
Source: S.M. Pietruszko (red.): Projektowanie i instalacja systemów fotowoltaicznych. Przewodnik dla instalatorów. Warszawa, 2016.

Monocrystalline silicon solar cells

Round silicon crystals are grown by the Czochralski technique (Cz-Si) from the melt starting from a small seed crystal and pulling the growing crystal under rotation from the surface of the melt. Industry is able to deliver crystals of a diameter of up to 30 cm and a length of more than one meter. The round crystal is cut to a square rod and then sliced by multi-wire saws into wafers of a thickness of about 0.3 mm.

Advantages and Disadvantages:

– monocrystals have excellent properties but are relatively expensive,
– good efficiencies obtained in production (14-17.5%).

Multicrystalline Silicon Solar Cells

If a silicon melt in a crucible is cooled down the silicon solidifies in a coarse grain structure which is called "multicrystalline" (mc-Si) which means polycrystalline with large grains in the mm to cm range.

The technologies for the fabrication of solar cells are quite similar to those applied to monocrystalline wafers, but due to the slightly inferior materials quality the obtained cell efficiencies are smaller. Since the mc-Si wafers are cheaper than those from monocrystals, the mc-Si technology has become the dominant technique in industry.

Advantages and disadvantages:

- lower cost for the production of mc-Si wafers than with monocrystalline Si,
- due to the lower quality obtained cell efficiencies are 1 to 2 percentage points below those of mono-Si cells,
- all steps in the process are easily scaled up.

Amorphous silicon cell

The amorphous Silicon (a-Si) solar cell is under development since the early 1980s. The a-Si solar cell has its fascination since it promises to combine the well-known silicon with a very cheap substrate using large-area deposition techniques. In spite of great development efforts and big investments the results are still limited with respect to quality of the products and of cost of fabrication.

Structure and fabrication

Amorphous silicon is prepared by plasma deposition of thin layers from silane (SiH_4). Cheap soda lime glass can be used as a substrate because the deposition is performed at rather low temperature. A high amount of hydrogen is incorporated during the plasma process, and this hydrogen is essential to electrically compensate defects thus improving the materials quality considerably.

Very thin layers in the range of one to two µm are sufficient since the a-Si has a high absorption coefficient. The conductivity of pure layers is intrinsic (i-type), but they can be doped p- and n-type by addition of boron or phosphorous compounds, respectively, to the reactor gas.

Advantages and disadvantages

- large area deposition rather easy,
- very few material needed since a layer thickness of 1 µm is sufficient,
- series integration by cell separation and structured contacting well developed,
- in production efficiencies are always below 10%,
- efficiency degrades under illumination, and stabilised module efficiencies are mostly around 6 to 8% for multijunction cells, and below 6 % for monojunction cells,
- multijunction cell show better efficiencies and better stability but production costs are distinctly higher.

Current Market Share of Technologies

Crystalline silicon in its three varieties Cz-Si (mono-Si), multi-Si and ribbon is dominating the market with a share of over 92%. In this category, the share of multicrystalline silicon is growing steadily on the expense of monocrystalline silicon. The part of Si sheets (ribbons) remains small. For many years now, the part of thin-film cells, mostly amorphous silicon, is diminishing. CdTe and CIS cells play a minor role being both far below 1% of the total market.

Market products and their advantages and disadvantages

The basic product in the photovoltaics market is the "module" which contains solar cells interconnected to provide useful electric output and encapsulated to protect them from the environment.

Most producers of solar cells fabricate also modules, and they use their own solar cells. Only part of the solar cell production is found on the market, and independent module producer use this source for their products. Sometimes, module producers have difficulties to find a secure source of solar cells for their purpose.

Many semi-conductive materials can be applied for the production of solar cells, constituting basic elements producing electrical energy through photovoltaic conversion. Currently, there

are conducted development works on many types of materials, cell structure or production technologies, and some time must go by so that the most advantageous of them stay permanently on the market.
In order to compare various technologies, several criteria should be considered. The most important of them include:

- possibility of obtaining high efficiency,
- accessibility of applied materials,
- acceptable cost of materials,
- possible implementation of cheap techniques in the mass production process,
- multi-year (counted in decades) stability of elements,
- compatibility of products and their manufacturing technologies with environmental requirements.

PV modules and PV generators

Depending on the technology used, a single solar cell generates a MPP voltage of approx. 0.5 to 2 V. Hence, electrical loads can rarely be run directly at this low voltage unless they are small devices or toys. In general, a higher voltage is necessary. It can be provided by arranging multiple cells in series, as is done with batteries.
To ensure the desired solar generator output power, several modules or strings can be connected in parallel, thus increasing the current. This modular interconnection allows photovoltaic generators to be designed with outputs from miliwatts to megawatts – all with the same basic technology.

Series connection

Current-voltage (I-V) characteristic

Solar cells and solar modules are connected in series to produce greater overall voltages.
In a series connection, the current is the same in all of the cells so that the overall voltage – as shown in Figure 2 for three similar cells – is the result of the sum of the individual voltages.

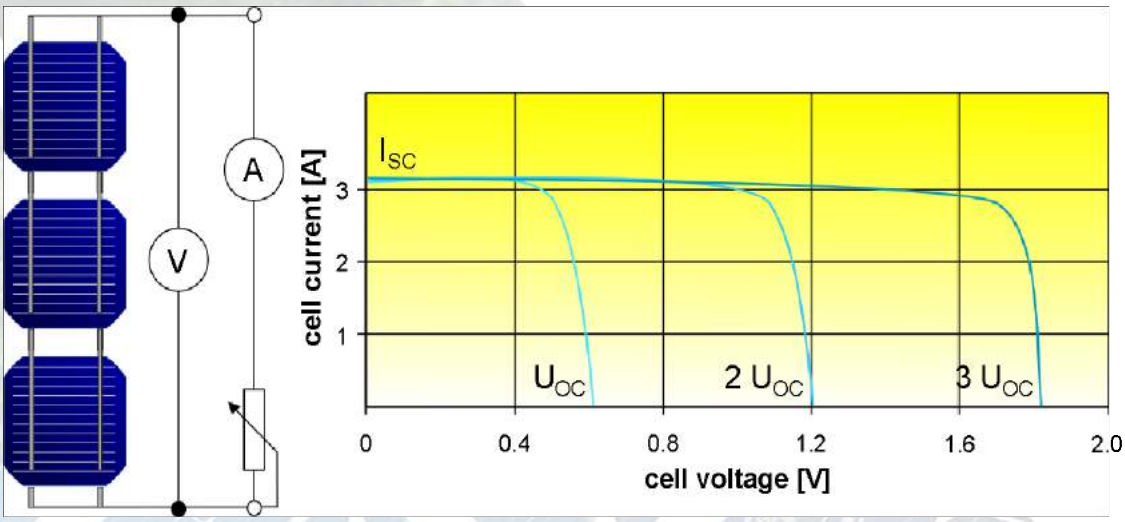


Fig. 2. Series connection of three similar solar cells and their current-voltage (I-V) diagram
Source: Solarpraxis AG, Berlin, Germany.

Connection in parallel

If the system has to produce greater currents, the modules or strings can be connected in parallel as shown in Figure 3. In parallel connections, all of the cells have the same voltage, and the overall current is the result of all of the individual currents.

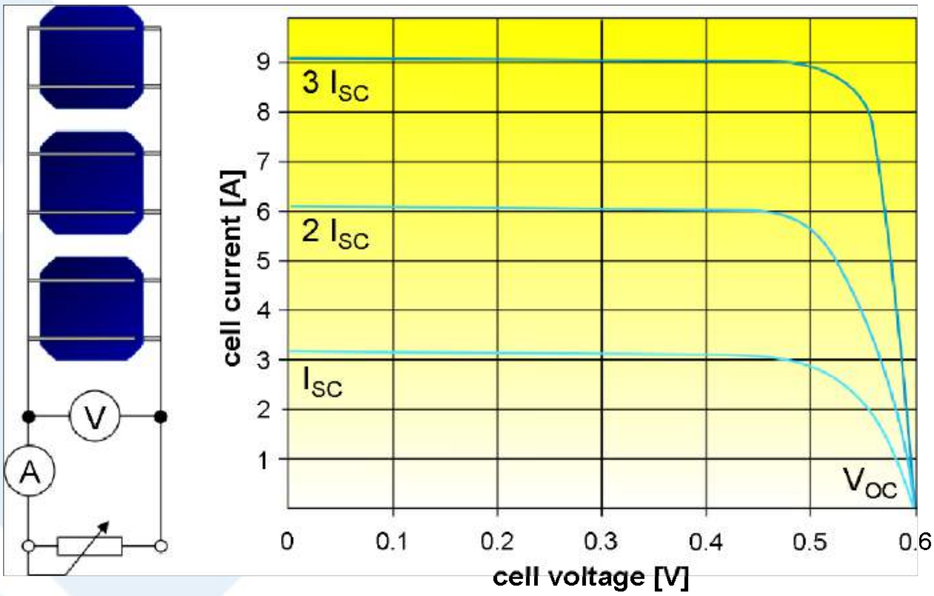


Fig. 3. Parallel connection of three similar solar cells and their current-voltage diagram
Source: Solarpraxis AG, Berlin, Germany.

The wiring diagram and the resulting current-voltage characteristic curves for a solar generator with several solar modules connected in series and in parallel are shown in Figure 4.

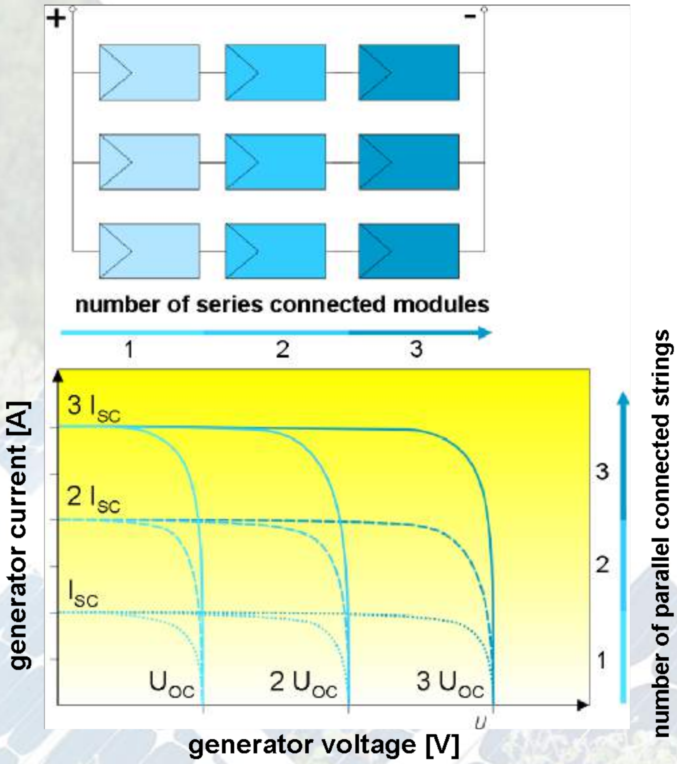


Fig. 4. Modules connected in series and in parallel and their current-voltage characteristics
Source: Solarpraxis AG, Berlin, Germany.

4.4. Types of photovoltaic systems

Photovoltaic systems must deliver clean energy for small and large consumers. All over the world, many PV systems are already operating, producing energy for housing residences, estates, offices and public buildings. Today, fully functional photovoltaic installations operate both on built-up areas and on areas where connection to the grid is difficult or where there is no energy infrastructure.
Among photovoltaic systems, one may distinguish islanding systems cooperating with the network or hybrid systems, including other sources of electrical energy, apart from the photovoltaic installation. Islanding systems are usually composed of three basic elements. They contain the photovoltaic generator, energy storage (usually battery) and charge controller. It is a basic configuration for receivers powered with DC voltage.
If it is necessary to power the receiver with AC voltage, an islanding photovoltaic inverter must be installed. Photovoltaic systems connected to the electrical grid are the most popular. Systems are characterised with simple construction, including two main elements: photovoltaic generator and photovoltaic network inverter. Depending on the installation performance, produced electrical energy may be entirely sold or a part of produced energy may be consumed for one's own needs.
Appearing new structural solutions for photovoltaic inverters are possible thank to advanced algorithms of energy flow regulation. These devices are intended mainly to be used in microinstallations.
Configurations of photovoltaic systems may also include additional energy sources, such as wind power plants, fuel cells or electric power generators. Installation type shall depend mainly on the investor's needs. Cognition of many configuration options of photovoltaic systems, together with detailed discussion on advantages and disadvantages of particular cases, shall constitute the fundamental knowledge about the options for use of photovoltaic systems and relevant design of the photovoltaic system meeting the investor's expectations.

Advantages and disadvantages of ON-GRID and OFF-GRID systems

Systems connected to the grid – on-grid – (grid connected) use photovoltaic power due to economic profitability, power safety or ecology. Other differentiation can be made between individual (prosumers) and industrial users.

Systems connected to the grid supply energy to the electrical grid, introducing it to the grid through the inverter. These may systems of power coming to several kW, installed usually on building roofs, creating a scattered energy systems, or centralised systems of power coming to MW. In these systems, elements of existing buildings, such as roofs, facades and noise barriers on roads, or special dedicated frame structures set in the open may be used for the PV module assembly.
Autonomous photovoltaic systems **off-grid** are used in places where it is impossible to connect them to the grid (or where grid pulling is more expensive than adjustment of the PV system), e.g. on rural areas or in countries with very poorly developed energy infrastructure. When such systems have large powers, such terms as **autonomous systems** and **microgrid** are used.

Photovoltaic systems directly supplying the electrical load

These are the simplest systems equipped with the photovoltaic panel and electrical load allowing for the use of electrical energy only when the sun shines.

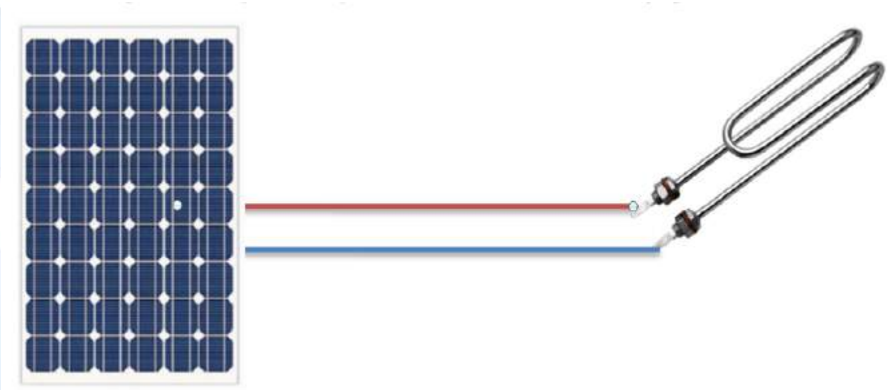


Fig. 1. Example of the system directly supplying loads
Source: own development

Autonomous photovoltaic systems with energy storage with DC receivers

The system is additionally equipped with charge controller and electrochemical batteries allowing for storage of electrical energy surpluses and its use in a different time when solar radiation is insufficient for the production of required energy or when there is no radiation at all.

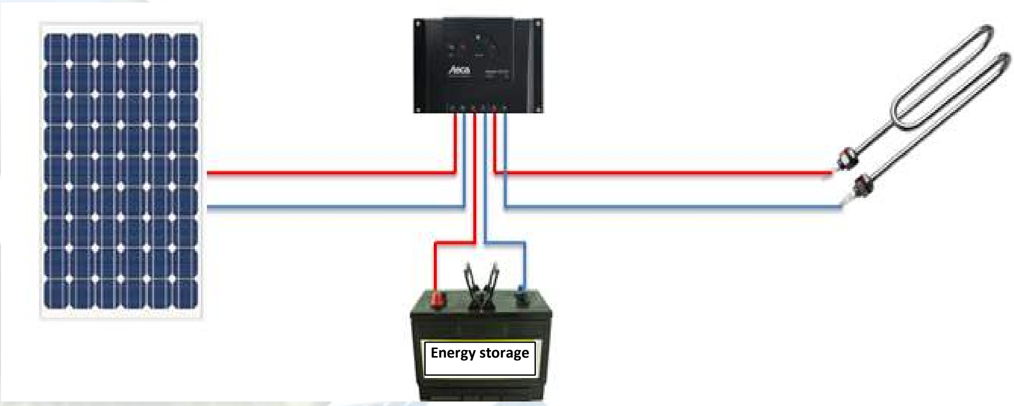


Fig. 2. Example of the DC autonomous system with energy storage
Source: own development

Autonomous photovoltaic systems with energy storage with AC receivers

The system additionally equipped with the DC/AC inverter allowing to supply AC receivers, but not necessarily connected to the electrical grid. It allows for powering of AC facilities like from the classical electrical grid.

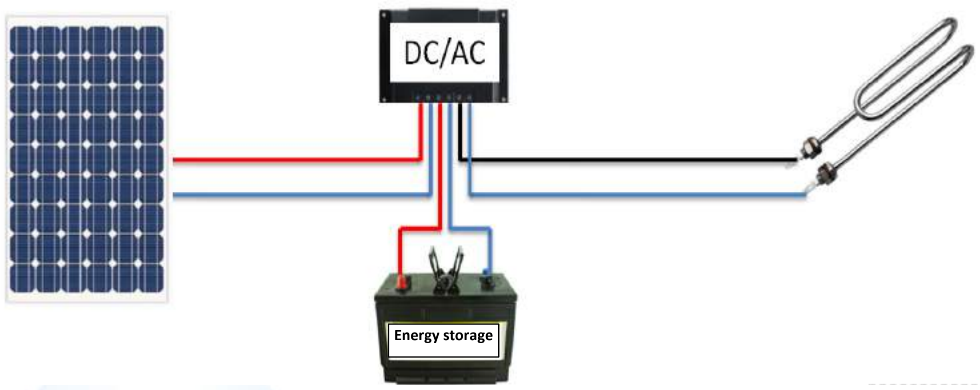


Fig. 3. Example of the AC autonomous system with energy storage
Source: own development

Autonomous photovoltaic systems with standby power

If it is necessary to ensure power continuity in autonomous systems where there is no access to the electrical grid, the solution is to apply an engine generator as a standby power source in order to produce energy when production from PV is insufficient.

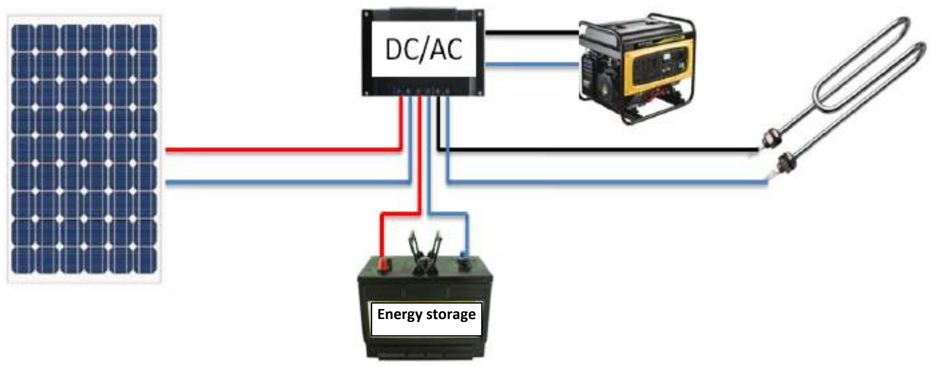


Fig. 4. Example of the AC autonomous system with energy storage and standby power
Source: own development

Photovoltaic systems connected to the electrical grid

The system additionally equipped with the DC/AC inverter allowing to power AC receivers, connected to the electrical grid. It allows for powering of AC receivers from the synchronised electrical grid and PV installation and giving energy produced in this installation to the electrical grid.

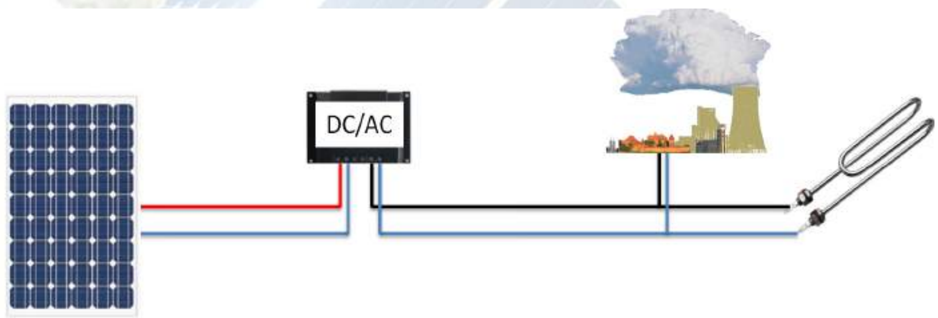


Fig. 5. Example of the AC system connected to the electrical grid
Source: own development

Photovoltaic systems without satisfaction of one's own requirements – total sales of electrical energy to SEE

Systems that give all the produced energy to the electrical grid constitute a special example of the PV system. This is one of simplest solutions of the PV installation. Such systems are applied when the photovoltaic installation's investment purpose is the sales of entire produced electrical energy to the power system (SEE).

Photovoltaic systems partially satisfying one's own requirements

The solution presented herein allows for the use of electrical energy production in PV systems for partial satisfaction of one's own requirements. The remaining part of energy is supplied from the electrical grid. Thanks to such a solution, the consumer may reduce its energy bills through the use of production from the PV system for its own needs.

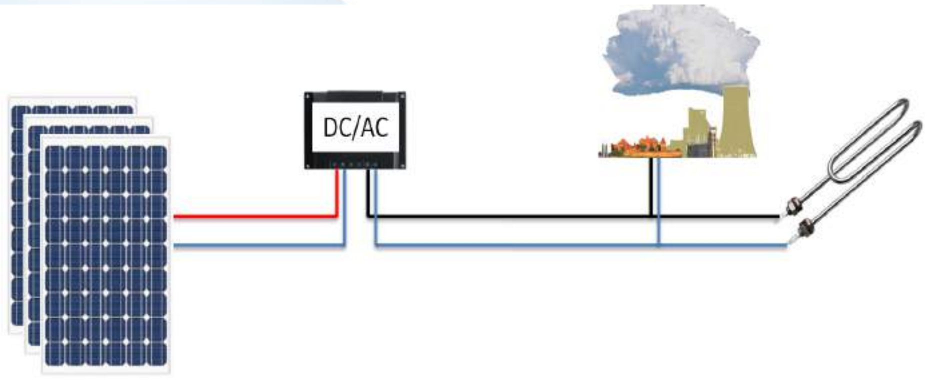


Fig. 6. Example of the AC system connected to the electrical grid partially satisfying one's own requirements (more modules)
Source: own development

Energy storage in systems connected to the electrical grid

Electrical energy storage occurs with use of batteries. There are available many battery types, starting from acid, gel, through nickelic, to lithium batteries. Every technology is characterised with its lifetime counted in years, number of charge and discharge cycles, discharging depth, maximum output current, etc. Selection of a good battery should be preceded with an analysis of the above parameters in reference to the planned battery purpose. Currently, the global market offers a wide range of energy storages of any scale. The lithium-ion technology, ensuring safe, maintenance-free operation of storage with a large number of cycles reaching up to 15,000 cycles, is the dominant technology.

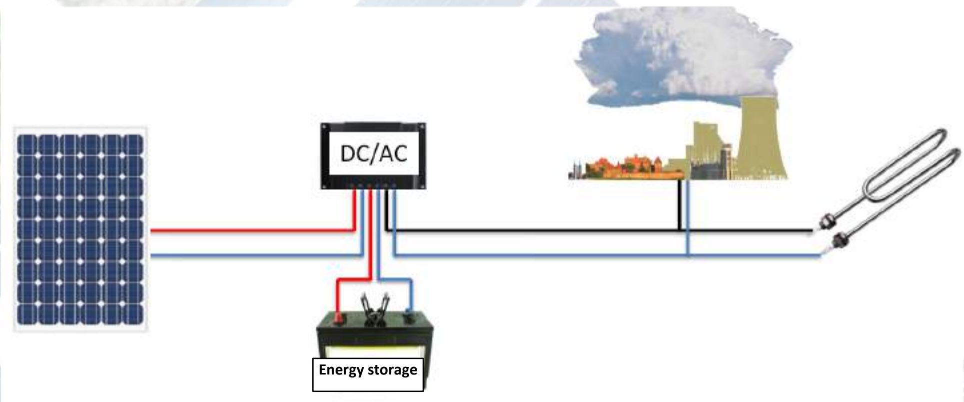


Fig. 7. Example of the AC system connected to the electrical grid with energy storage
Source: own development

Hybrid systems with the photovoltaic source

Hybrid systems with the photovoltaic source allow for many variants of use of the photovoltaic installation.

Depending on the requirements, energy produced from the PV system may:

a) power the receiver directly,
b) power the energy storage,
c) power the receiver and give to the network,
d) give to the network,
e) power the receiver, power the storage and give to the network.

Cooperation of wind turbines with the photovoltaic installation

In order to improve efficiency of obtaining energy from RES, systems integrated with the wind turbine may be built. Such an installation requires the use of inverter, which, apart from possible cooperation with PV modules, can cooperated with the wind generator. If there is no such an inverter, the solution is the application of two separate inverters (one to the PV system, the second for the wind system) with an additional driver integrating operation of these both sources.

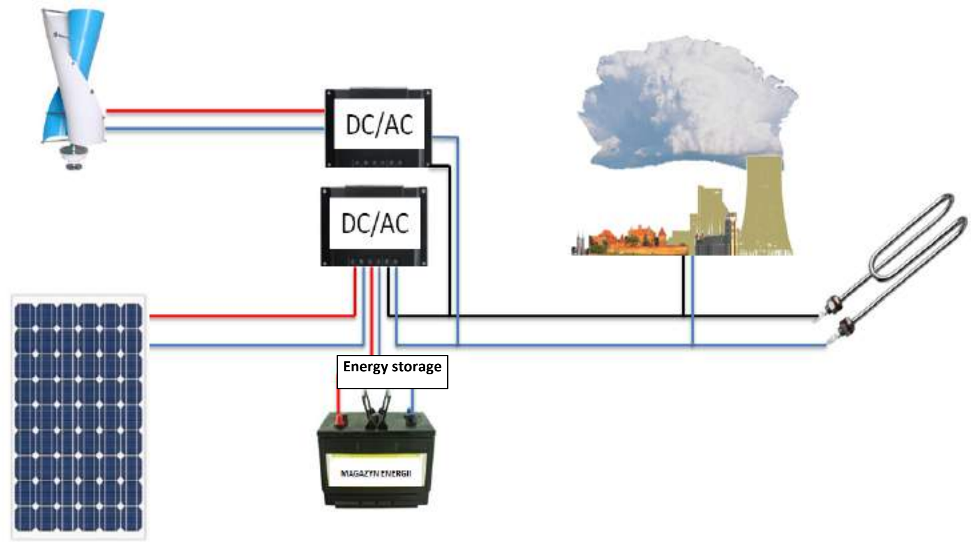


Fig. 8. Example of the AC hybrid system connected to the electrical grid with energy storage and wind generator

Source: own development

Cooperation of power generating unit and fuel cells with the photovoltaic installation

Such an installation allowing for cooperation with the power generating unit and the fuel cell constitutes a special type of the PV installation. In such a case, it is necessary to install a special driver managing energy flow between these active elements of the grid in order to optimise the energy use and such a switch of its particular elements in order to provide the consumer with the continuity of supplies of electrical energy.

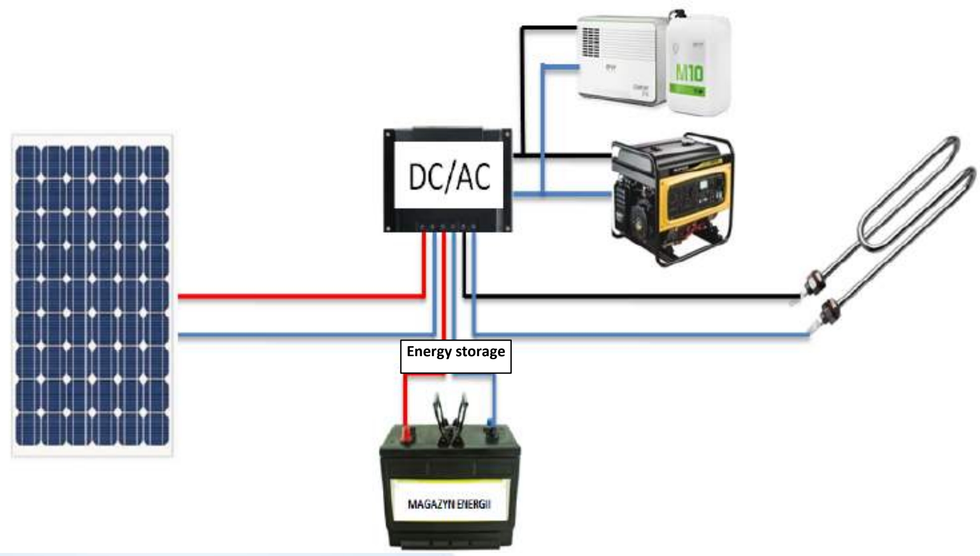


Fig. 9. Example of the AC system connected to the electrical grid with fuel cell, power generating unit and energy storage
Source: own development

Structural solutions for systems integrated with the building

On built-up areas, photovoltaic systems may be installed on the upper roof part (building adjusted to photovoltaic systems – BAPV) or may be integrated into the building elevation or roof (known as PV systems integrated into the building – BIPV). Modern photovoltaic systems are not limited to square and flat panels. They must be curved, flexible and integrated into the building's structure shape. Innovative architects and engineers propose in their designs still new methods of integration of PV and create buildings that are dynamic, beautiful and ensure free and clean energy during the lifetime.

Building-Applied Photovoltaics (BAPV) and Building-Integrated Photovoltaics (BIPV) constitute photovoltaic systems, in which modules are installed on buildings in order to perform the function of main or ancillary source of energy. These solutions are very economical, because they do not require an additional area, just use the already existing, often not used surfaces, such as roofs or facades. BAPV are installations assembled on existing building elements, such as roofs, skylights, facades, balconies, shelters, etc.

BIPV is composed of photovoltaic elements that replace standard building materials, becoming a part of the building. These may be e.g. cells in the form of roof tiles, cladding tiles, glass panes, etc. Such surfaces as roofs, facades, skylights, etc., may be constructed of them. They are usually installed in new buildings, but they can also be assembled in already existing structures, e.g. in the course of renovation. The BIPV advantage is a part of costs of such a system cover funds saved on materials replaced by PV elements. They are also often characterised with aesthetic appearance.

Fig. 10. Building-Integrated Photovoltaics (BIPV)
Source: http://www.wfosigw.lodz.pl [access: 10 May 2018]

Systems not integrated with buildings

These are systems constructed directly on the ground as free-standing installations. They enable the investors to build photovoltaic power plants of powers coming event to several hundred MWp.

In addition, it does not exclude the construction of small (home) or medium industrial installations. These systems are constructed on specially designed assembly systems, which, depending on a climatic zone, base or other environmental conditions, may differ from each other.

Fig. 11. Free-standing system
Source: http://tarnow.naszemiasto.pl/tag/farma-sloneczna-wierzchoslawice.html [access: 10 May 2018]

4.5. Elements and devices of photovoltaic installation

Diversity of configurations of photovoltaic systems forces the application of a various type of sub-assemblies mounted in photovoltaic installations. Electrical energy produced in the photovoltaic generator must be adjusted to parameters required by the receiving device, while in some cases it should be stored and available outside the working time of the photovoltaic generator. Discussion on particular installation elements should include a detailed description of operation and tasks performed by them in the photovoltaic system. The photovoltaic installation should be properly connected and secured against results of overloads, short circuits, power surges and lightning.

Elements of photovoltaic systems

Basic elements of photovoltaic installations, their nomenclature and meaning are defined in the standard PN-HD 60364-7-712:2016-05 Low-voltage electrical installations – Part 7-712: Requirements for special installations or locations - Photovoltaic (PV) systems

According to the mentioned standard, the following elements may be distinguished in the photovoltaic installation:

- **PV cell** – basic element of the PV system that produces electrical energy in the conditions of exposure to light such as solar radiation,

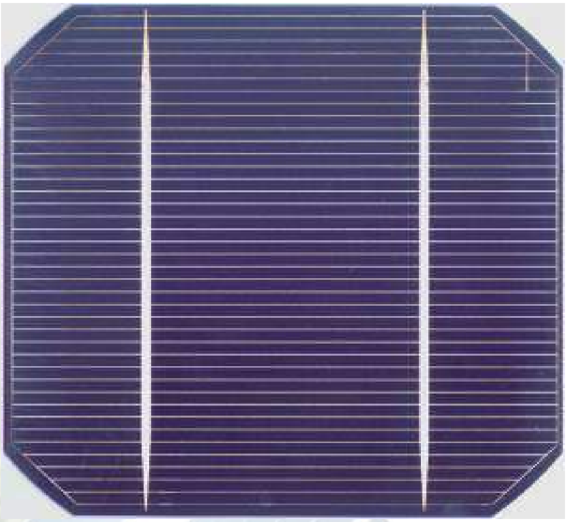


Fig. 1. Exemplary appearance of a single PV cell
Source: https://pveducation.org/pvcdrom/manufacturing/single-crystalline-silicon [access: 20 June 2018]

- **PV module** – the smallest, fully protected against environmental impact set of interconnected PV cells,

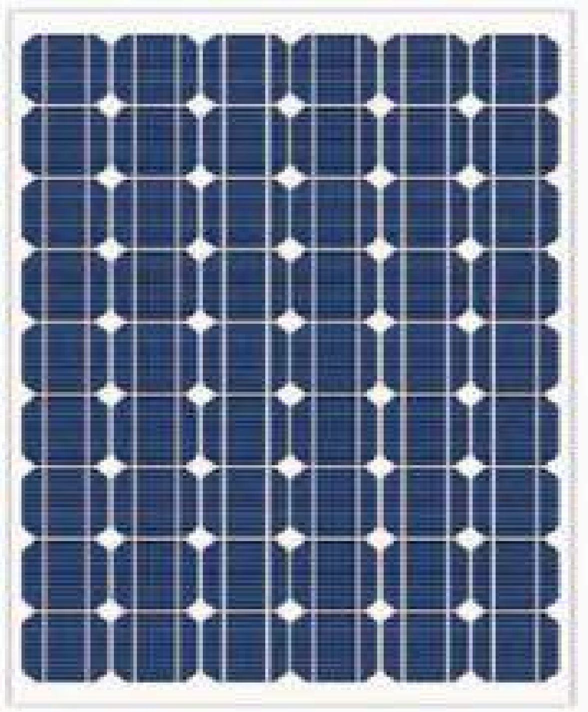


Fig. 2. Exemplary appearance of the PV module
Source: http://www.photon-solar.eu/ [access: 20 June 2018]

- **PV chain** – circuit in which PV modules are connected in series in order to produce required output voltage in the PV collector,

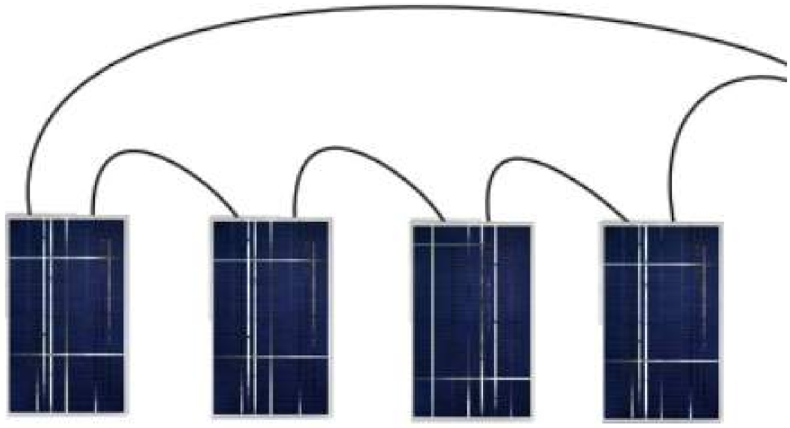


Fig. 3. Exemplary appearance of the PV chain
Source: http://www.nuvisionenergy.co.uk/ [access: 20 June 2018]

- **PV collector –** mechanically and electrically integrated set of PV modules and other necessary elements that create a unit supplying with direct current,
- **junction box of the PV collector** – casing in which all PV chains of any PV collector are electrically connected and where, if needed, protection can be applied,

Fig. 4. Exemplary appearance of the DC junction box
Source: https://www.leoni-solar-windpower.com/en/products-services/generator-combiner-boxes/general-information/ [access: 20 June 2018]

- **PV generator –** set of PV collectors,
- **PV chain wire** – wire connecting PV modules that create a chain,
- **PV collector wire** – output wire of the PV collector,
- **main DC wire of the PV system** – wire connecting the junction box of the PV generator with DC clamps of the PV inverter,
- **PV inverter** – device converting DC voltage and current to AC voltage and current,

Fig. 5. Sample types of PV inverters
Source: https://www.ecosoch.com/types-of-solar-on-grid-inverters-micro-string-central-2/ [access: 20 June 2018]

- **PV power cable** – cable connecting clamps of AC and PV inverter with receiving circuits of electrical installation
- **AC module of the PV system** – integrated set module/inverter where all connection clamps are AC clamps. There is no access to the DC side
- **PV installation** – installed and connected devices of the PV power supply system

A separate issue in the photovoltaic installation is constituted by criteria of selection of protection type and selection of protection value in the photovoltaic installation in order to ensure safety of users and devices of the photovoltaic system. Special attention should be paid to the principles of selection of overload protections and protections against reversible currents.

Operating principle of the photovoltaic inverter

DC/DC or DC/AC converter is a device that converts electrical energy obtained from the photovoltaic generator. Regardless of a nature of output voltage, on the converter input there is the maximum power point tracker (MPPT) resulting from the current-voltage characteristics of the photovoltaic generator. Correct operation of the MPPT system allows for the maximisation of energy yields from the photovoltaic installation through the maintenance of production of electrical energy at the highest level achievable at changing conditions of sunlight exposure. Another energy electronic systems are responsible for the adjustment of the voltage level corresponding with the scope of voltages of battery charging – if applies. In case of supplying devices with alternate current, it is necessary to apply the voltage formation system (inverter). The ON-GRID inverter output is connected directly to circuits supplied from the electrical grid or the separated network. Connection of the inverter to the grid is equivalent with connection of the AC voltage source to the existing system. In such a case, it is necessary to apply synchronisation systems that are integrated into ON-GRID inverters. OFF-GRID inverters do not have such systems, that is why the OFF-GRID inverter output cannot be connected directly with the electrical grid. Devices having both operating functions – OFF-GRID and ON-GRID – are exceptions.
DC/DC or DC/AC converter is a device that converts electrical energy obtained from the photovoltaic generator. Regardless of a nature of output voltage, on the converter input there is the maximum power point tracker (MPPT) resulting from the current-voltage characteristics of the photovoltaic generator. Correct operation of the MPPT system allows for the maximisation of energy yields from the photovoltaic installation through the maintenance of production of electrical energy at the highest level achievable at changing conditions of sunlight exposure. Another energy electronic systems are responsible for the adjustment of the voltage level corresponding with the scope of voltages of battery charging – if applies. In case of supplying devices with alternate current, it is necessary to apply the voltage formation system (inverter).

Among produced inverters, their three basic types may be distinguished:

Grid inverters (ON-GRID)

The ON-GRID inverter output is connected directly to the electrical grid or the separated network. Connection of the inverter to the grid is equivalent with connection of the AC voltage source to the existing system. In such a case, it is necessary to apply synchronisation systems that are integrated into grid inverters. Grid inverters adjust generated voltage to the model taken from the electrical grid. In addition, grid inverters have protections preventing from voltage generation in case of loss of power supply in the electrical grid. This is dictated by the safety of persons performing repair works during intentional voltage disconnections.

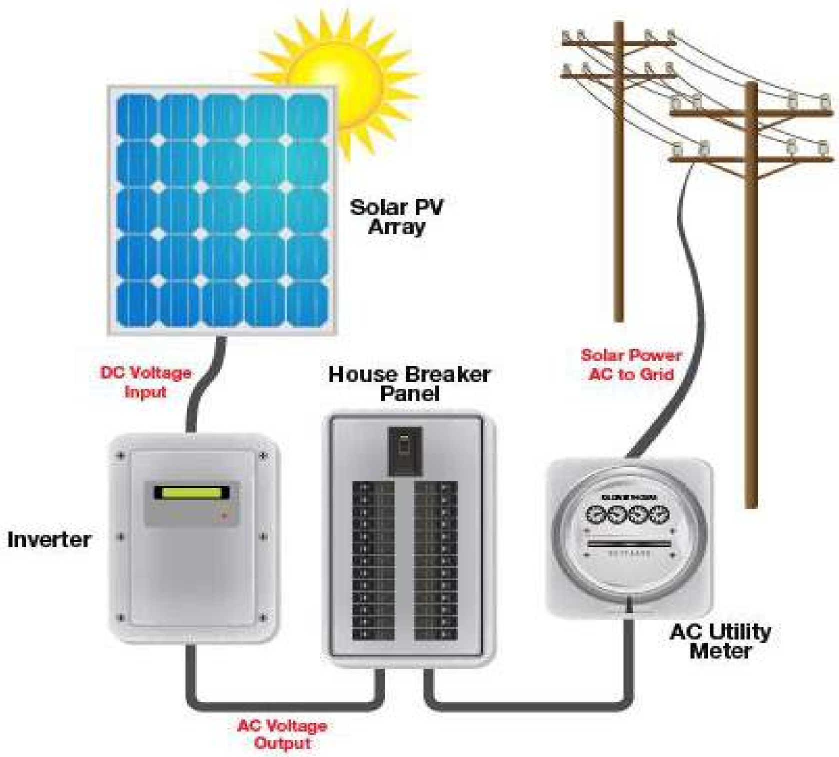


Fig. 6. ON-GRID inverter in the PV installation
Source: http://alternateenergycompany.com/how-solar-pv-panels-works-with-the-grid/ [access: 20 June 2018]

Islanding inverters (OFF-GRID)

Grid inverters are adjusted to generation of voltage sinusoidally alternate based on the programmed voltage model. Due to the lack of synchronisation systems on the islanding inverter output, it is impossible to connect it to the electrical grid. It would pose a risk of damage to the inverter output.

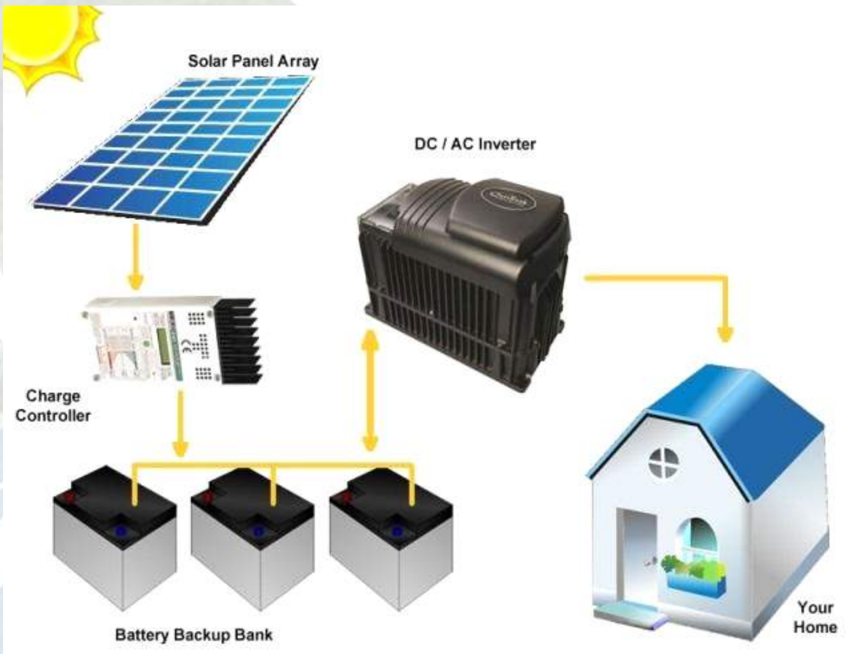


Fig. 7. OFF-GRID inverter in the PV installation
Source: https://www.quora.com/How-does-off-grid-solar-plant-work [access: 20 June 2018]

Hybrid inverter

Hybrid inverter is the most advanced structure.
This device may operate as OFF-GRID and ON-GRID.
In addition, it can cooperate with energy storage.

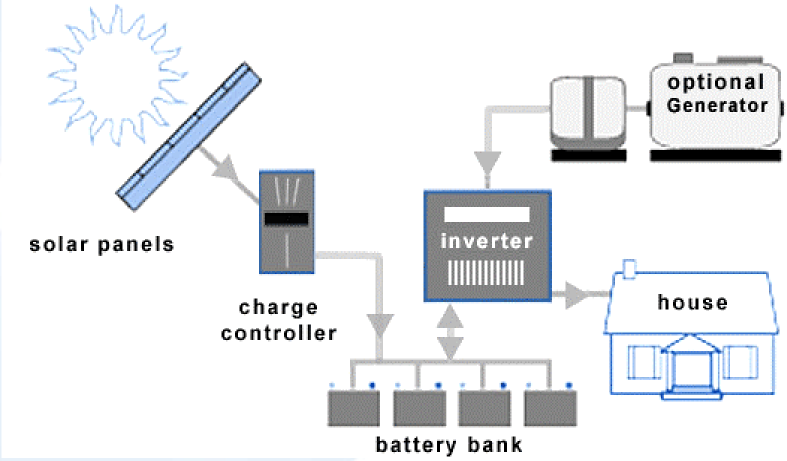


Fig. 8. PV installation with the hybrid inverter
Source: http://energyinformative.org/wp-content/uploads/2012/05/off-grid-solar-system.png [access: 20 June 2018]

MPPT systems in photovoltaic inverters

Regardless of an inverter type, on the converter input there is the maximum power point tracker (MPPT). The maximum power point tracker of the photovoltaic generator changes under the influence of such factors as intensity of solar radiation, temperature of the PV cell, angle of incidence of solar radiation, etc. Correct operation of the MPPT system allows for the maximisation of energy yields from the photovoltaic installation through the maintenance of production of electrical energy at the highest level achievable at changing atmospheric conditions.

4.6. Selection of technical solutions

Knowledge about available technical solutions within the scope of system components and their assembly constitutes the basis at the planning, design and performance of the photovoltaic installation. Planning starts from the estimation of the installation size and selection of its location.

Selection of the installation site

Location of the photovoltaic installation should allow to direct photovoltaic modules to the south. The installation moved to the south shall operate with performance as lower as its location deviates from the southern direction.
While selecting the installation site, elements resulting in installation overshadow, such as trees, neighbouring buildings or even overhead power lines, should be avoided on the way of sunlight to PV modules.
The photovoltaic installation should be located not far from the planned or present place of its connection to the network – it does not concerns autonomous installations.

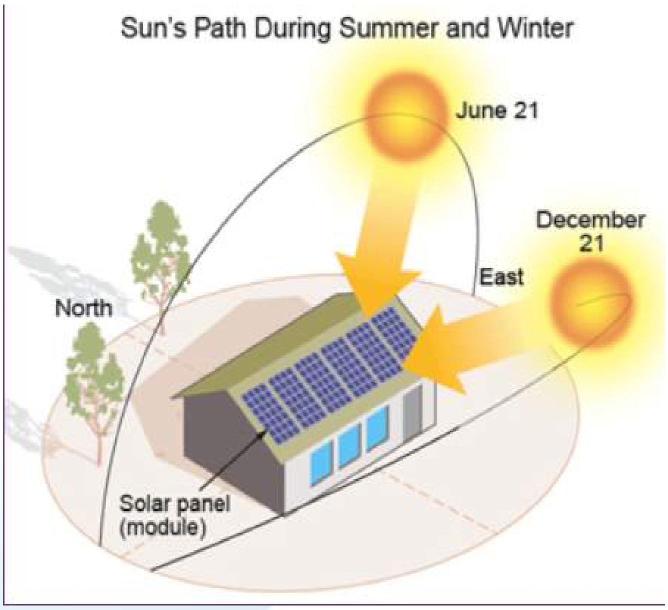


Fig. 1. Location of the PV installation
Source: http://www.thesolarplanner.com/array_plaement.html [access: 20 June 2018]

For the selected location, the value of sunshine duration is estimated, based on which planned energy yields can be estimated. Currently, all over the world there is a lot of software (delivered by system producers and by entities specialised only in this) allowing for very exact estimation of energy yields from the given installation.
Moreover, this software enables to use external meteorological data, such as snowfall, rainfall, average annual nebulosity, temperature. An analysis of atmospheric conditions and technical conditions allows for the selection of an appropriate setting of photovoltaic modules and their type.
Another element is the initial distribution of photovoltaic modules and detailed analysis of possible overshadowing, which can be affected by existing buildings, trees, overhead power lines, etc. Here we can also use the entire range of specialist software supporting the above actions.

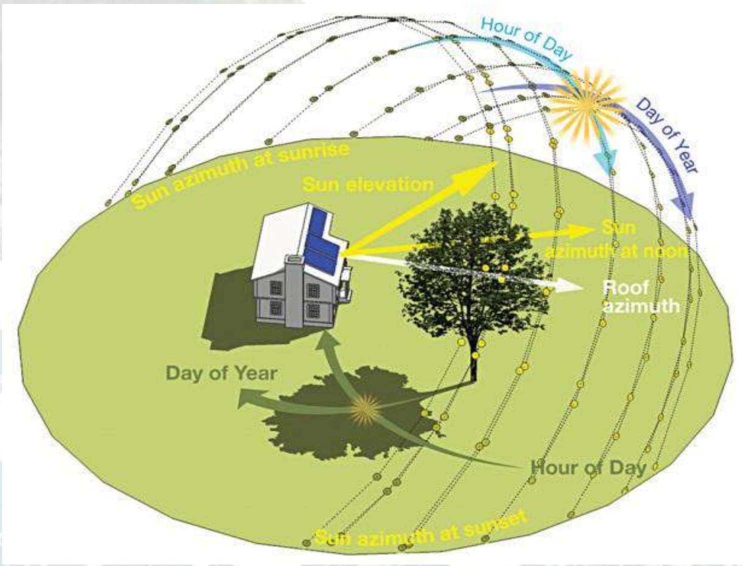


Fig. 2. Examples of overshadowing of the PV installation
Source: https://www.homepower.com/articles/solar-electricity/design-installation/energy-basics-shading-and-solar-electric-systems [access: 20 June 2018]

In case of roof or facade installations, the installation mass and impact of planned installation on structural strength of the building should be determined. In case of roof and facade installations, it is recommended that the photovoltaic installation is assembled in the zone protected by the lightning installation. In practice, the lightning installation is not necessary, but it depends mainly on components applied in the photovoltaic installation.
In addition, for roof installations, depending on a tilt angle of the roof, there should be defined a target tilt angle of installed modules and an appropriate assembly installation ensuring maintenance of this angle should be selected. Moreover, there should be determined a target direction of PV module setting

Estimation of the photovoltaic installation area

While installing on the roof, we have at our disposal its limited area, additionally reduced by necessary assembly margins and technological obstacles, such as chimneys, roof windows, structural breakdowns not allowing for the assembly of PV modules.

Fig. 3. Available roof surface for the PV installation
Source: https://news.energysage.com/is-my-roof-even-suitable-for-solar/ [access: 20 June 2018]

Initial distribution of photovoltaic modules

Another step is constituted by the initial distribution of photovoltaic modules on a given roofline. If the four-side roof has one roofline oriented towards south or with small deflection from it, assembly on other directions may appear ineffective, which should be indicated by computer simulation. If a given roof is not oriented towards south, the installation in east-west direction shall be the most optimal.

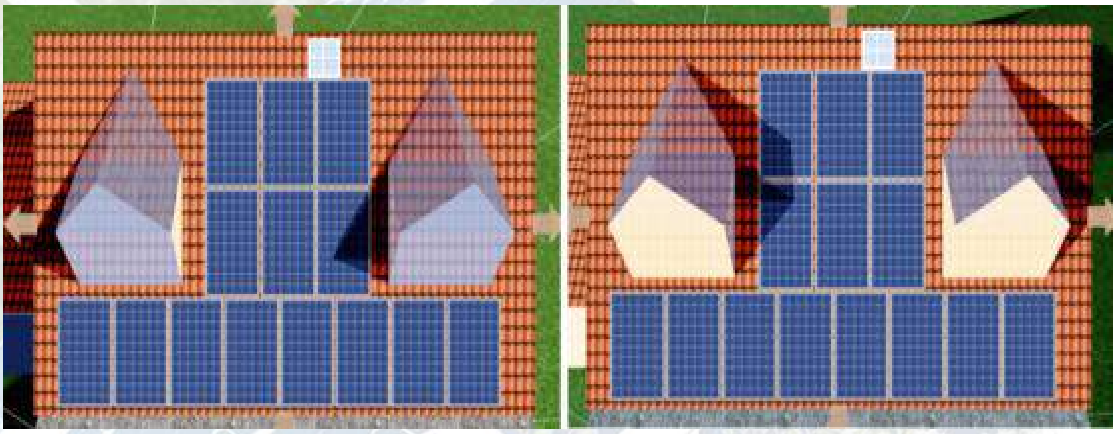


Fig. 4. Available surface for the PV installation
Source: http://aberdeensolar.com/solar-pv/home-suitable/ [access: 20 June 2018]

Analysis of technical conditions for the installation connection

In the following step, electrical connection, to which a given PV installation shall be adjusted, should be analysed. Selection of a corresponding inverter depends on the value of connection power. If it is necessary to modify it, it should be requested (if necessary) in the issuance of technical conditions for connection or an appropriate request should be made to the electrical energy distributor. In case of autonomous installations, a connection analysis shall be limited to the same receivers of electrical energy that are to be supplied from the PV installation.

Wind impact on modules and supporting structure

Wind load is a significant problem and should be considered during the design of solar installations free-standing or on building roofs. Wind power increasing with square of its speed, depends on a type, size and layout of nearby facilities and from the direction of its flow. Depending on a form and tilt angle of the installation, thus the roof, a windward side of the installation is exposed to wind pressures, while a leeward side is exposed equally to wind suction.

Snow build-up on building roofs

The second important factor that should be considered during the photovoltaic installation design is constituted by weight of not only PV cells (having the mass approx. 10 ÷ 20 kg/m2, thus the pressing force coming to 100 ÷ 200 N/m2) and structural elements, but also periodically occurring snowfalls to which the installation shall be exposed. For free-standing systems, the supporting system will have to sustain mechanically the pressured of the entire weight of its components and snow. For installations integrated with the building, this load is taken by the roof structure that must be adequately selected already at the stage of design of the structure. As snowfall size is different for different world areas (in some it never appears, in some it is possible all over the year), so particular countries develop standards defining acceptable values of snow load for the structure. In places where we have to do with snowfall, this problem should be considered as snow build-up from the electrical point of view constitutes overshadow for the module. That is why, deciding on the photovoltaic installation in places where snow occurs, we may choose the application of traditional modules, keeping in mind that in case of its build-up on modules, we will not have current production or the selection of more expensive modules with a heating system preventing from water freezing on the module surface.

Types of assembly systems of photovoltaic modules

Basic division of assembly systems for photovoltaic modules looks as follows:

Roof assembly systems

Fig. 5. Example of a roof assembly system dedicated for roof tile

Source: http://www.instsani.pl/519/system-montazu-dla-dachu-pokrytego-dachowka-ceramiczna [access: 20 June 2018]

Free-standing assembly systems

Fig. 6. Example of a ground assembly system
Source: https://www.indiamart.com/proddetail/aluminium-solar-mounting-structure-10795911762.html [access: 20 June 2018]

Mobile assembly systems

Fig. 7. Exemplary assembly system based on trackers
Source: http://www.iparu.com/dual-axis-tracker-pst-2al [access: 20 June 2018]

Assembly systems integrated with the building

Fig. 8. Exemplary assembly system integrated with the building BIPV
Source: https://www.solarpowerworldonline.com/2014/12/quick-run-bipv/ [access: 20 June 2018]

Mechanical resistance of assembly systems of photovoltaic modules

As every mechanical structure, an assembly system of photovoltaic modules must meet adequate standards so that they can be applied for the PV project implementation. Assembly systems should have certificates ensuring proper and permanent mounting of photovoltaic modules.

Principles of arrangement of photovoltaic modules on building roofs

The basic role of photovoltaic systems is the production of electrical energy from solar radiation. That is why, when installing the system on the building roof due to limited active surface for use, we should arrange modules according to the following principles:

- avoidance of module overshadowing by elements and vegetables protruding outside the roof plane,
- all modules connected to one maximum power track point should have ensured the same conditions of sunshine duration (they should be set at the same angle vertically and horizontally),
- provision of necessary assembly and technological margins in order to allow for further operation of the PV installation.

Avoidance of overshadowing

The basic issue is to arrange photovoltaic modules so that their surface is not overshadowed throughout the year, at least in summer, late spring and early autumn periods, when sunshine duration is the strongest. However, usually, despite significant "free" roof surface, it is periodically overshadowed by a series of existing elements, such as ventilation chimneys, roof windows, antenna masts, base telecommunication stations, air handling units, additional storeys, high ledges, attic styles, etc.

Avoidance of mutual overshadowing

PV module sets arranged in series one after another may overshadow each other. The higher the given series, the higher the risk. In order to avoid it, sets of PV modules must be drawn apart from each other to a larger distance. At low falling winter sun, therefore relatively longer light and shadow, this distance should come to at least three heights of a PV module set constituting a shading series).

Consideration of atmospheric conditions

Moreover, such a set must be elevated at some height to eliminate negative consequences of snow and water build-up. Tilt of modules increases the PV installation height, however it takes relatively more horizontal level of the roof.

Satisfaction of requirements of mechanical loads

Here one should keep in mind also structural requirements concerning maximum loads that can be withstood by the flat roof. Other limitations are constituted by technical conditions and structural standards concerning e.g. elevation relations between roofs or air conditioning educations and building roof elements. Apart from the location on traditional roofs, PV modules are more and more often applied in the area of glass roofs. It constitutes another step in development of the PV technology in construction industry and architecture.

4.7. Energy profile of consumers

Prior to the determination of the photovoltaic installation power, a consumer's energy profile should be analysed, determining its demand for electricity. This is best done in daily, weekly, monthly and annual cycle. Proper determination of the demand for electricity shall constitute the basis for selection of power of the photovoltaic generator and possible capacity of energy storage. Optimal performance of an analysis, proper selection of an installation type and its components shall allow for quick return on investment and correct operation of the photovoltaic system compliant with the investor's expectations.

Consumption of electricity in households

Annual consumption of electricity at home depends on a number of its residents, types of owned electrical devices and how long these devices are used and with what frequency.

Annual consumption of electricity at home

According to official statistics, the household 2+2 consumes from 1900 kWh to 2500 kWh per year (two parents and two children). Single persons consume approx. 1000 kWh per year, while a family 1+1 from 1200 to 1500 kWh. Therefore, a number of family members is very important for the consumption of electricity. Reduced consumption of electricity is possible through the change in habits of family members or investments in devices with a high class of energy efficiency.

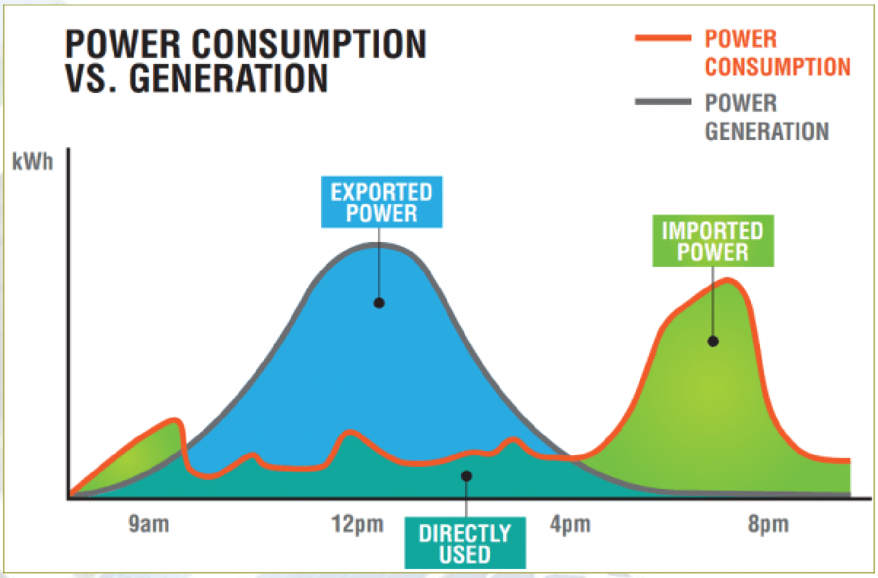


Fig. 1. Exemplary consumption of electricity in household
Source: http://thatpowerguy.nz/solar/solar-power-system-size/ [access: 20 June 2018]

Consumption of electricity in industrial plants

Industrial facilities consume 33% of global energy, which is more than in other client segments, such as transport, utility buildings or residential buildings. Owners of enterprises are usually aware of the impact of consumption of electricity on the costs of company's operation, however they do not use many options of improvement of their energy efficiency.

According to the sector, consumption of electricity has a different nature. There are plants that work in a continuous mode 24/7 and there are plants that work from Monday to Friday. Some companies work one shift from 6 am to 2 pm, some - two shifts from 6 am to 2 pm and from 2 pm to 10 pm. Office facilities work from 8 am to 6 pm.

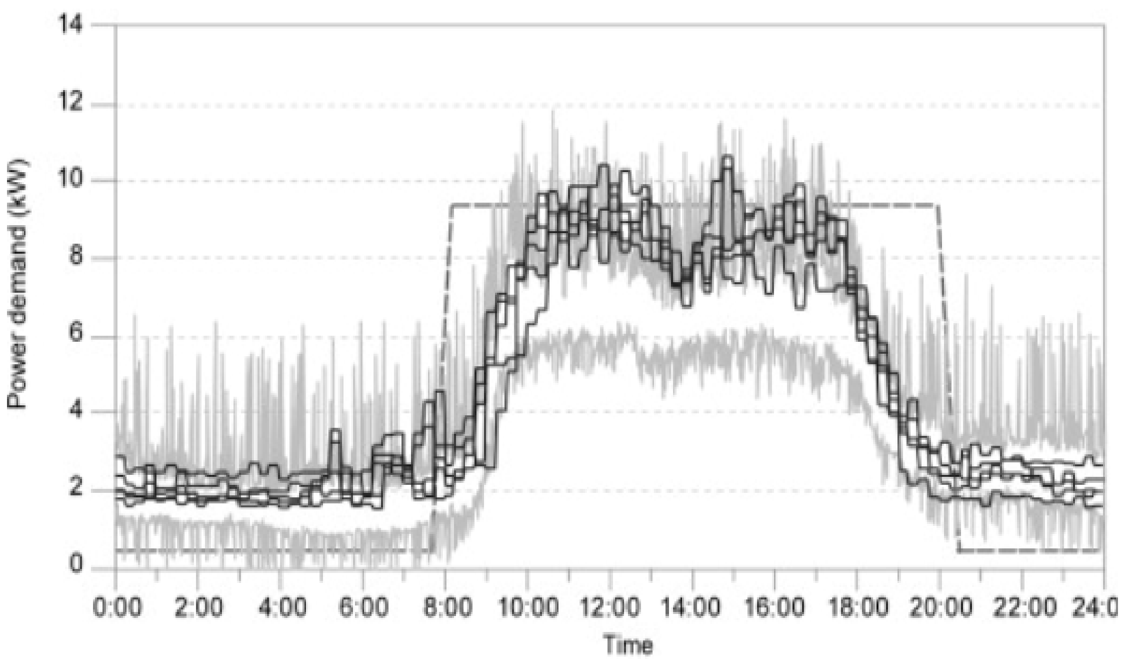


Fig. 2. Exemplary daily consumption of electricity in industrial plant

Source: https://www.sciencedirect.com/science/article/pii/S0378778814001224#fig0025 [access: 20 June 2018]

Energy profiles of selected receivers

A client's energy profile can be composed of energy profiles of particular devices applied by clients. For households the following receivers may be distinguished:

- **vacuum cleaner** (standard) has the power of approx. 1500W. Assuming house vacuuming for 15 minutes every three days, vacuum cleaner operates 30.4 hours (h) per year. Consumption of electricity during the year: 30.4 h x 1.5 kW = 45.63 kWh;
- **fridge** – energy consumption by fridge depends mainly on its **class of energy efficiency**, from the place it occupies in house (the farther from windows and heaters, the lower the energy uptake), as well as from operating conditions (regular removal of icing, not opening doors every minute), consumption of electricity during the year comes to 300-400 kWh;
- **electric water boiler** is a very energy-consuming device. Average device power is 2000 W, while water boiling lasts two minutes. Used approx. three time a day, it generates annual consumption of electricity at the level of: 365 x 3 x 2 x 2 kW = 2190 min x 2 kW = 36.5 h x 2 kW = 73 kWh;
- **lighting –** at use of energy efficient bulbs with power of 4-10 W, lighting does not generate a large consumption of electricity. Lighting is used approx. five hours a day, without division into winter or summer period. In house, there are approx. more than a dozen of bulbs, while only 8 of them work for the assumed five hours per day. Consumption of electricity during the year: 5 h x 365 days x 6 W = 10.95 kWh;
- **TV set –** if working time of devices is only considered, the rate would be lower, but unfortunately these devices consume energy even when we do not use them, as they are

in the so-called stand-by mode. This is intensified by amplifiers. 15 W during one hour constitutes the average energy uptake in the stand-by mode. During working it is approx. 25 W. Let's assume that the TV set is one for six hours per day, while for 18 hours it is in the stand-by mode. Consumption of electricity during the year: 25W x 6h x 365 days = 54.75 kWh + 10W x 18h x 365 days = 65.7 kWh. During its work, the TV set consumes less energy than for remaining hours of the day in the stand-by mode.

- **washing machine** used twice a week does 104 washings during the year. An average washing machine of energy class A consumes 1.2 kWh per washing. Consumption of electricity: 1.2 kWh x 104 = 124.8 kWh.

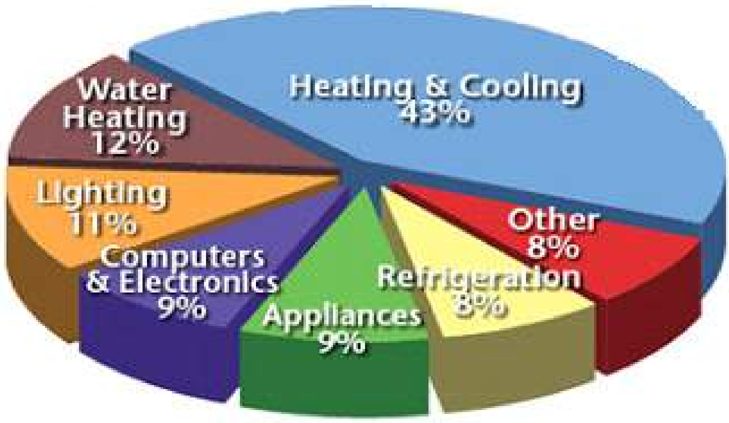


Fig. 3. Exemplary consumption of electricity by some receivers
Source: https://greenpowerworksinc.com/energy-efficiency-for-residential/ [access: 20 June 2018]

Demand for electricity in the daily cycle

Daily variability of loads is affected mainly by the rhythm and life activity of human beings. In addition, a distinct impact of seasonality on the course of daily energy uptake can also be observed. Nevertheless, on the chart below there are clearly noticed two peaks - morning and afternoon.

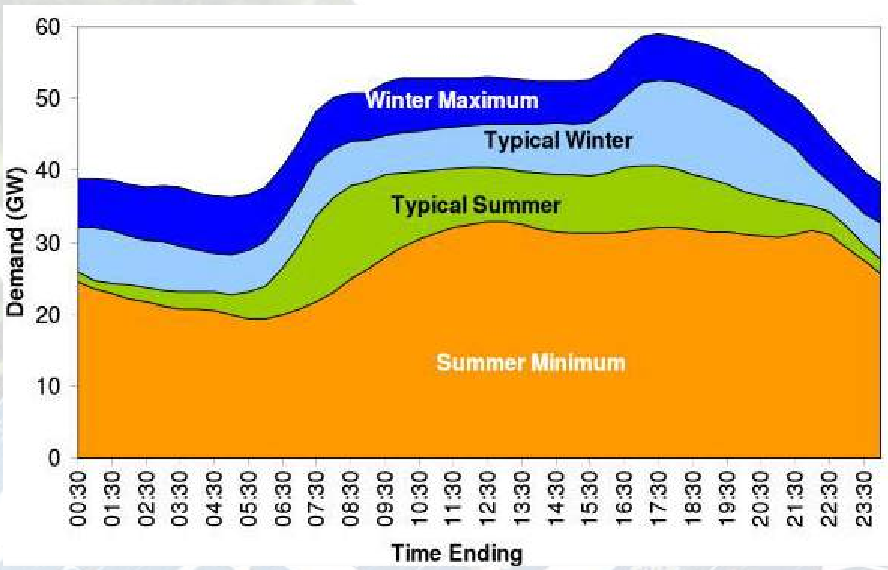


Fig. 4. Exemplary daily demand for electricity (summer and Winter Daily Demand Profiles in 2010/11)
Source: https://energymag.net/daily-energy-demand-curve/ [access: 20 June 2018]

Demand for electricity in the weekly cycle

Weekly variability of loads results mainly from the occurrence of working days and public holidays and the work cycle and intensity related to it. Energy uptakes from Monday to Friday are decidedly higher than the weekend period, when activity of society is decidedly smaller (Fig. 5).

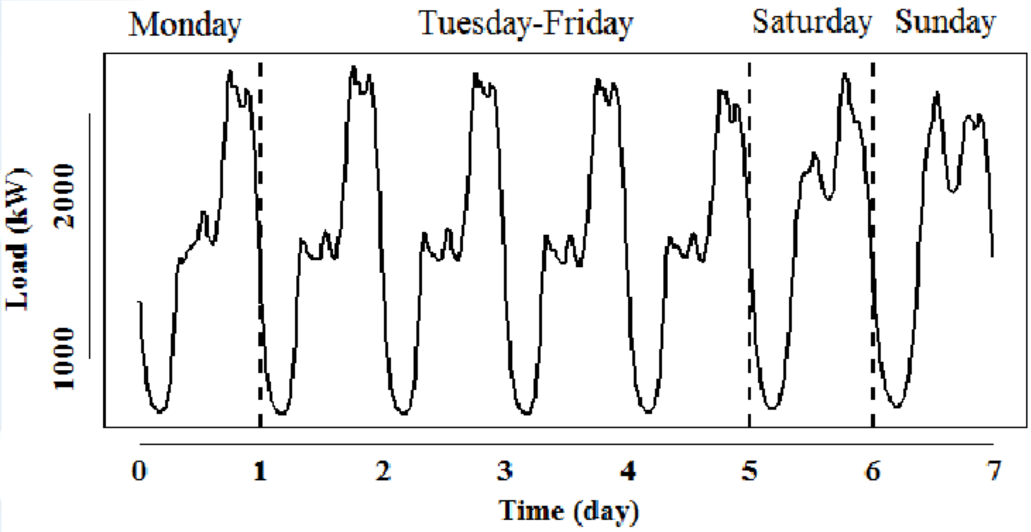


Fig. 5. Exemplary weekly demand for electricity

Source: https://www.researchgate.net/figure/Mean-weekly-profile_fig1_313453567 [access: 20 June 2018]

Indicators characterising variability of the client's load

A characteristic feature of electricity loads is their high variability in time. These changes may be regular or random. Regular changes of load result from astronomic factors, human customs or from other reasons easy to predict. Random changes occur irregularly and they are caused by random factors, such as atmospheric conditions or failures in the electrical grid. Basic indicators, the most often used for characterising the daily variability of loads include:

- daily energy A_d,
- daily peak power P_{ds},
- daily average power $P_{dśr}$,
- daily power of basic load P_{do},
- average daily degree of load m_d,
- daily degree of balance of basic load l_{do},
- daily degree of basic load m_{do},
- daily peak degree of balance l_{ds},
- daily coefficient of irregularity k_{dn},
- daily time of use of peak power T_{ds}.

4.8. PV system sizing

Proper sizing of the photovoltaic system constitutes a complex process. In order to ensure proper operation of the system, there should be selected an appropriate technology of photovoltaic modules, inverter type, assembly system and protection systems according to

the technical and economic conditions. Selection criteria should include technical aspects of particular system elements, quality of performance, conditions for guarantee and price. There should be kept in mind that there is a dependency between the module efficiency and the area occupied by them. In order to obtain a given generator power, its surface shall increase together with reduction of efficiency of photovoltaic modules. While selecting modules, their electrical parameters should be considered. At the connection of photovoltaic modules in series or in parallel, their current and voltage efficiency should be similar. In case of large discrepancies among electrical parameters of modules, the photovoltaic installation shall not operate properly. While connecting in series, voltage of the photovoltaic chains shall be a sum of voltages of connected modules, while the maximum chain current shall correspond with the module of the lowest current efficiency. At the parallel connection of modules or chains, voltage of modules/chains should be the same. Otherwise, in the photovoltaic collector there shall appear equipotential currents flowing between branches connected in parallel, reducing current efficiency of the photovoltaic generator. Parallel connection of photovoltaic chains of the same voltage causes that currents from particular chains sum up, and in a wire connecting the photovoltaic collector with the inverter current flows of the value equal to the sum of currents from particular photovoltaic chains.
Both voltage and current of a single module may be changed due to changes in solar irradiance and changes of temperature. That is why connection of modules in series and in parallel should be performed only for modules characterised with equal exposure to sunlight. So, working surfaces of modules are set in the same direction, at the same tilt angle to the horizon line, and none of modules is overshadowed.

Impact of variability of weather conditions on the production of electricity in the photovoltaic installation

Amount of solar radiation reaching the Earth's surface is variable depending on the season of the year, climatic conditions in a given latitude, and in a significantly shorter scale (minutes, seconds) from clouds moving on the horizon.
Climatic conditions, and in particular average annual sums of sunshine duration reaching the horizontal plane, are the main determinants of economic profitability of mentioned PV systems.

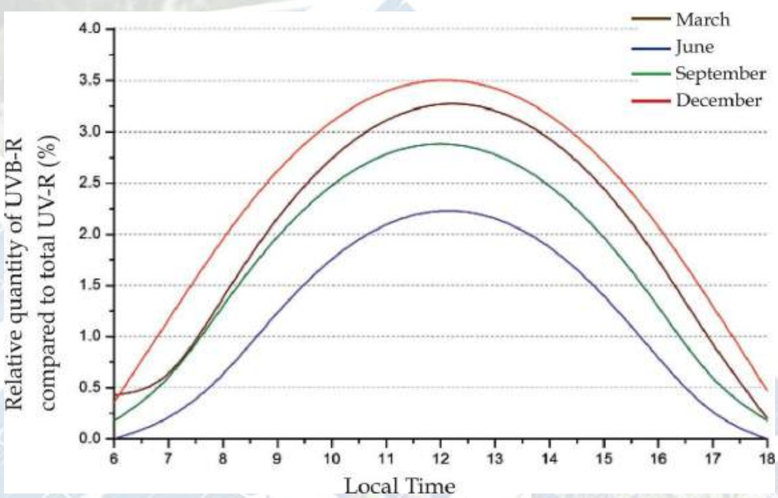


Fig. 1. Distribution of sunshine duration during the year
Source: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0365-05962015000300297 [access: 20 June 2018]

Available weather databases

There are many available weather databases both with a global and local scope for a given country. The World Weather Information Service (WWIS) is one of them. It collects official meteorological observations, weather forecasts and climatological information for selected towns. Data are provided by the National Meteorological and Hydrological Services (NMHS), functioning all over the world and delivering official meteorological information for particular countries. On the WWIS website, there are also available links to official websites of weather services of the Meteorological Services. In April 2018, the WWIS delivered official weather information for 2191 towns. At the same time, 135 meteorological services sent forecasts for 2052 places. Climatic data were available for 1985 towns provided by 169 participating services.

Commercial software for analysis of meteorological conditions

One of databases is constituted by the base of the European Institute for Energy and Transport, founded by the European Commission. Databases concerning an annual sum of sunshine duration on the vertical and optimally inclined plane are publicly available and may be used e.g. via Internet apps such as PVGIS (Photovoltaic Geographical Information System). These apps allow for the assessment of resources of solar energy in a selected locations and estimate energy yields from photovoltaic power plants, depending on their power and location.

Determination of average radiation values for a given location

In order to correctly select the value of maximum power of the photovoltaic installation, average solar radiation values for a given location should be determined in a monthly cycle.

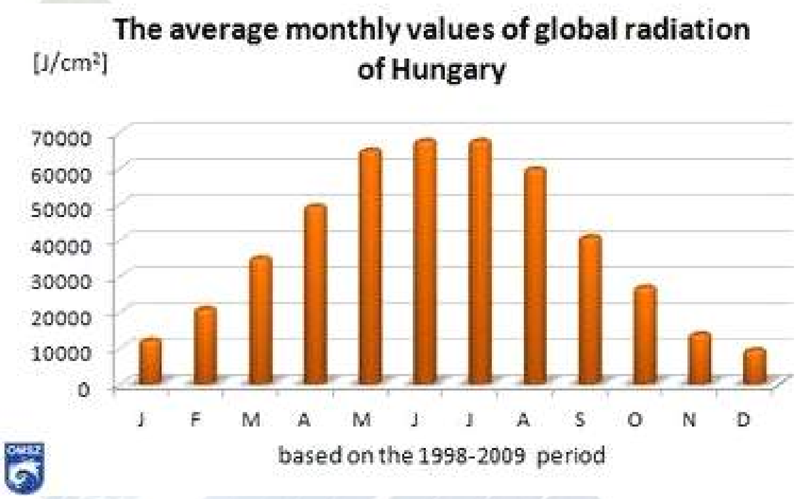


Fig. 2. Average monthly radiation values
Source: https://www.met.hu/en/eghajlat/magyarorszag_eghajlata/altalanos_eghajlati_jellemzes/sugarzas/ [access: 20 June 2018]

Efficiency of the photovoltaic installation

Efficiency of the photovoltaic system depends on the efficiency of its particular elements. Elements and devices constituting the photovoltaic system convert the solar radiation energy to electrical energy, generating losses.
Efficiency of photovoltaic modules sold today is within the limits of 17-21% for silicic cells. Efficiency of photovoltaic inverters is within the limits of 96-98%.

Due to low efficiency of conversion of the solar radiation energy in photovoltaic cells, all efforts should be made to make losses related to transmission of produced electrical energy as small as possible. It is mainly about proper selection of connections and about careful performance of connections in the photovoltaic system. Care about quality of performance of connections in the photovoltaic installation shall result in reduced energy losses and simultaneously shall increase effectiveness of conversion of the solar radiation energy.

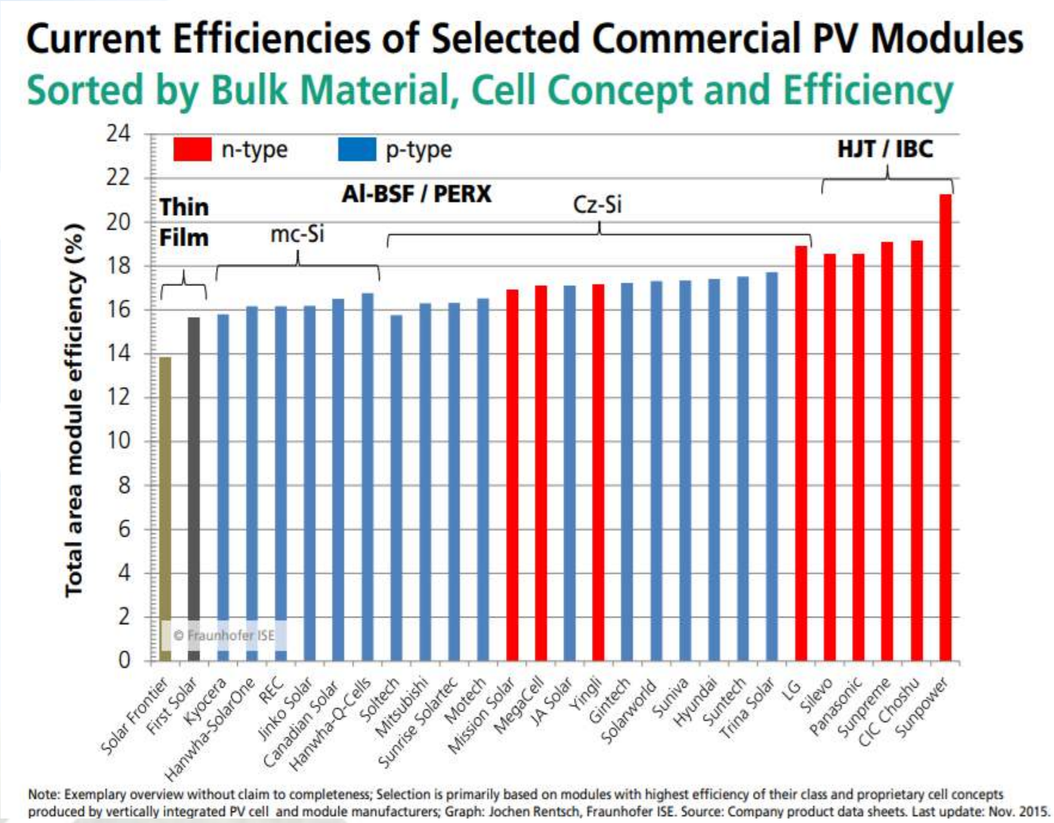


Fig. 3. Efficiency of modules of different producers for different technologies
Source: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf [access: 20 June 2018]

Determination of the energy yield based on average values of solar radiation

Having at disposal average values of solar radiation for particular months in a given location, there may be determined energy yield of a given installation, assuming the most favourable tilt angle of photovoltaic modules and their azimuth.

Impact of a tilt angle of photovoltaic modules to the horizon on the production of electrical energy

In the condition, an angle of solar radiation falling on a surface of the module installed permanently is characterised with daily and annual changes. Depending on the time of the day, of the year and place of the installation mounting, an angle of sunbeams on the module surface may change within the scope from 0 to 180°. Photovoltaic modules obtain the highest efficiency of conversion of solar radiation at an angle of solar radiation equal to 90° against the module surface. Maintenance of this angle in a daily and annual cycle is possible only thanks to the application of track systems following positions of the Sun. In installations where photovoltaic modules are mounted permanently – stock-still, an angle of solar radiation is changing, and, consequently, efficiency of conversion of the solar radiation energy decreases.

Impact of an azimuth angle of photovoltaic modules on the production of electrical energy

Provision of the southern direction, i.e. the direction that is the most recommended due to efficiency of photovoltaic cells is usually (especially for roof installations) impossible. Knowing the azimuth angle as deflection of the PV panel surface from the southern direction, we can define its impact on the production of electrical energy.

Azimuth

Slope	90 °	75 °	60 °	45 °	30 °	15 °	0 °	- 15 °	- 30 °	- 45 °	- 60 °	- 75 °	- 90 °
90 °	56%	60%	64%	67%	69%	71%	71%	71%	71%	69%	65%	62%	58%
80 °	63%	68%	72%	75%	77%	79%	80%	80%	79%	77%	74%	69%	65%
70 °	69%	74%	78%	82%	85%	86%	87%	87%	86%	84%	80%	76%	70%
60 °	74%	79%	84%	87%	90%	91%	93%	93%	92%	89%	86%	81%	76%
50 °	78%	84%	88%	92%	95%	96%	97%	97%	96%	93%	89%	85%	80%
40 °	82%	86%	90%	95%	97%	99%	100%	99%	98%	96%	92%	88%	84%
30 °	86%	89%	93%	96%	98%	99%	100%	100%	98%	96%	94%	90%	86%
20 °	87%	90%	93%	96%	97%	98%	98%	98%	97%	96%	94%	91%	88%
10 °	89%	91%	92%	94%	95%	95%	96%	95%	95%	94%	93%	91%	90%
0 °	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%

Fig. 4. Table of dependencies of relative yield on a tilt angle and azimuth angle
Source: http://www.twojaenergia.pl/poradnik [access: 20 June 2018]

Increase in the production of electrical energy through the application of track systems

In order to improve the amount of produced electrical energy in PV systems, track systems are applied. This device allows for the increase in effectiveness of energy gain even by 30-40%. Mostly, these are biaxial structures allowing for tracking the Sun on the horizon during the day, with simultaneous correction of location depending on the season of the year, i.e. on the Sun position on the horizon.

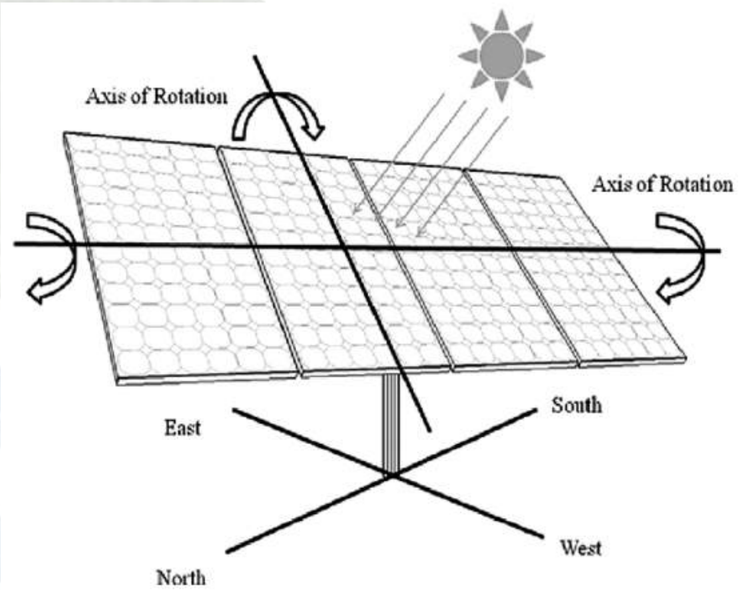


Fig. 5. Explanatory figure of the track system
Source: https://www.semanticscholar.org/paper/Design%2C-implementation-and-performance-analysis-of-Munna-Bhuyan/d143c1d713073ec0ada345f7b28ebdc7428b7c71/figure/0 [access: 20 June 2018]

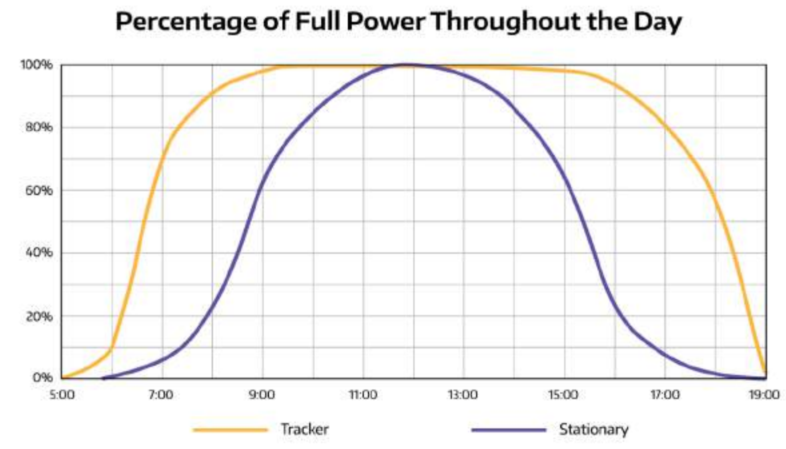


Fig. 6. Comparison of the energy production from PV for the installation with and without track system
Source: https://solarips.com/2016/02/like-a-sunflower-solar-pv-panels-track-the-sun/ [access: 20 June 2018]

Determination of a type of the photovoltaic installation

After determining basic energy parameters that we can gain in a given location, we may commence determination of a type of our installation. Whether it is a roof or ground installation. If it is ground installation, whether it is permanent or with a track system. It is crucial whether a given installation shall work for our needs, transferring small amounts of energy to the network or generally, or maybe opposite – its task is to maximise production with regard to return to the network. Each of these choices entails the necessity of application of specific modules, inverters, which affects the system cost. Now an inverter type should be selected **–** on-grid, off-grid or with energy storage. Moreover, the number of independent MPPT inputs should be determined.

Selection of a type of photovoltaic modules – efficiency, quality of performance, price

Depending on budget, we may select modules thick and thin layer, silicic or made from other semi-conductive, taking our needs into consideration.

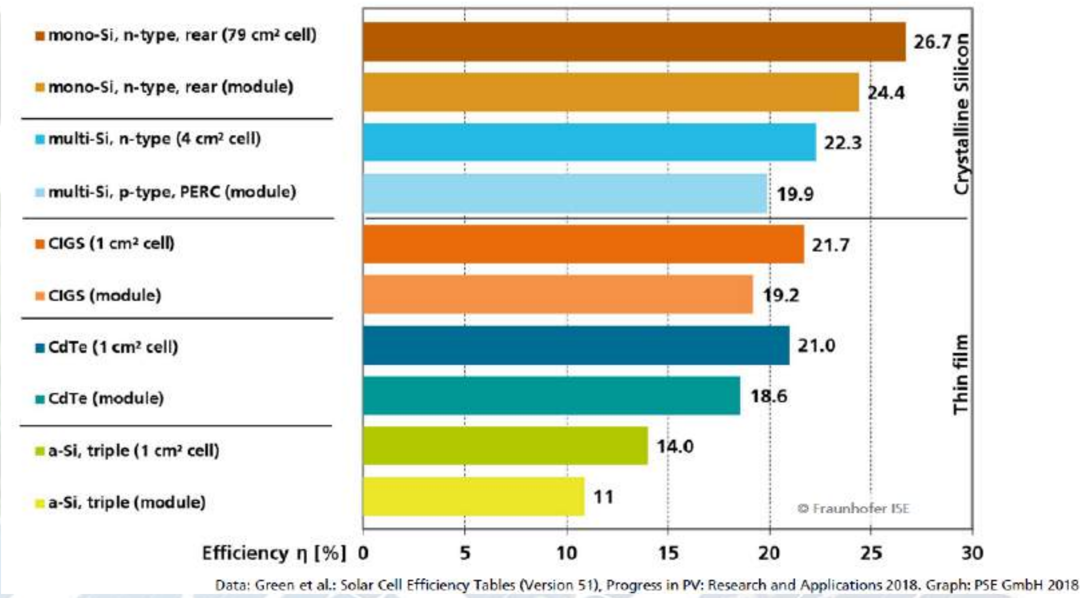


Fig. 7. Effectiveness of various types of PV cells
Source: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf [access: 20 June 2018]

Determination of a number of photovoltaic modules

If a decision on a type of photovoltaic modules is already made, the produced is selected and a catalogue card describing its basic parameters (voltage, currents, efficiency, etc.) is available, a number of modules necessary to gain the assumed system power may be determined. The number of modules is determined by dividing an assumed power of the photovoltaic generator by the power of a selected single photovoltaic module. In order to determine a number of modules, there may also be applied an approach related to a size of the area (roof, elevation, plot of land) where construction of the photovoltaic generator is planned.

Connection of photovoltaic modules in series, with consideration of temperature voltage coefficient

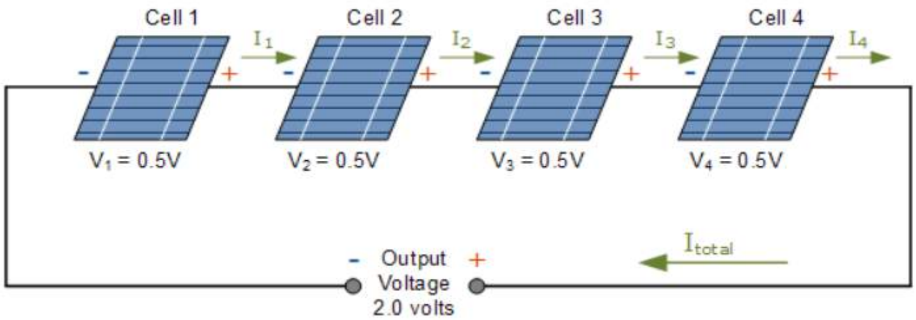


Fig. 8. Connection of PV modules in series
Source: http://www.alternative-energy-tutorials.com/solar-power/pv-panel.html [access: 20 June 2018]

Having a selected inverter with one or several MPPT inputs, there is established a maximum or minimal number of modules for particular inputs of the PV inverter, building chains in series with voltage not exceeding acceptable input voltage specified in the photovoltaic inverter's documentation. While estimating a maximum number of modules in the photovoltaic chains, there should be considered an impact of changes in voltage in the PV module's temperature function.

$$L_{mod\_max} < \frac{U_{MPPT\max}}{U_{OC}\left(1+\left(t_{\min}-t_{STC}\right)\frac{\beta}{100\%}\right)} \quad (1)$$

Where:

- L_{mod_max} – maximum number of modules in the photovoltaic chain,
- $U_{MPPT\max}$ – maximum voltage of the MPPT input system of the photovoltaic inverter,
- U_{OC} – voltage of open circuit of the photovoltaic module,
- t_{min} – minimal temperature of the photovoltaic module assumed by the designer,
- t_{STC} – temperature of the photovoltaic module during the test in STC conditions (t_{STC}=25°C),
- β – coefficient of change in voltage of the photovoltaic module in the temperature function expressed in [%/°C].

During the selection of a number of photovoltaic modules connected in series, it should be kept in mind that voltage produced in the photovoltaic module was higher than voltage of start of the photovoltaic inverter. To this end, a minimal number of photovoltaic modules should be determined.

$$L_{mod\_min} > \frac{U_{MPPT\,min}}{U_N\left(1+(t_{max}-t_{STC})\frac{\beta}{100\%}\right)} \tag{2}$$

Where:

- L_{mod_min} – minimal number of modules in the photovoltaic chain,
- $U_{MPPTmin}$ – minimal voltage of the MPPT input system of the photovoltaic inverter,
- U_N – rated voltage of the photovoltaic module – voltage in the maximum power point,
- t_{max} – maximum temperature of the photovoltaic module assumed by the designer,
- t_{STC} – temperature of the photovoltaic module during the test in STC conditions (t_{STC}=25°C),
- β – coefficient of change in voltage of the photovoltaic module in the temperature function expressed in [%/°C].

Parallel connection of photovoltaic modules, with consideration of temperature current coefficient

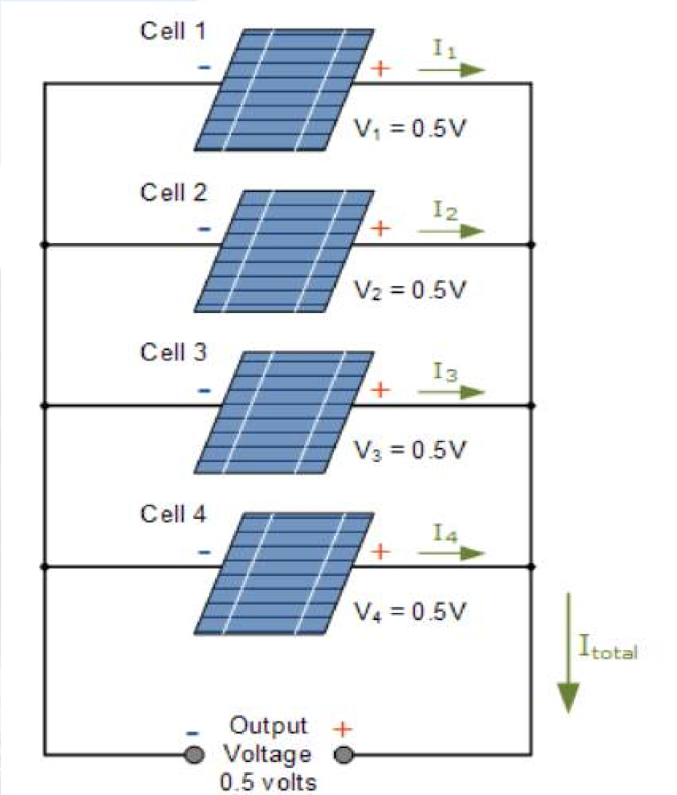


Fig. 9. Parallel connection of PV modules
Source: http://www.alternative-energy-tutorials.com/solar-power/pv-panel.html [access: 20 June 2018]

If the photovoltaic installation is large enough that it is necessary to connect modules in parallel, total output currents generated by every photovoltaic chain should be calculated, considering change in current generated by the module in the module temperature function. Maximum number of in parallel connected chains must be determined with consideration of the maximum input current of the photovoltaic inverter and changes in values of the module current in the temperature function.

$$n \leq \frac{I_{DC\max}}{I_{SC}\left(1+(t_{\max}-t_{STC})\frac{\alpha}{100\%}\right)} n \leq \frac{I_{DC\max}}{I_{SC}\left(1+(t_{\max}-t_{STC})\frac{\alpha}{100\%}\right)} \quad (3)$$

Where:

- n – maximum number of photovoltaic chains connected in parallel,
- $I_{DC\max}$ – maximum current of a single input of the photovoltaic inverter,
- I_{SC} – short-circuit current of the photovoltaic module,
- $t_{\max}$ – maximum temperature of the photovoltaic module assumed by the designer,
- t_{STC} – temperature of the photovoltaic module during the test in STC conditions (t_{STC}=25°C),
- α – coefficient of change in current of the photovoltaic module in the temperature function expressed in [%/°C].

Determination of the maximum current value in the photovoltaic chain's wire

Current of a single photovoltaic chain is equal to at least the value of current of a single photovoltaic module. Therefore, maximum value of the photovoltaic chain is equal to the maximum value of current of the photovoltaic module. While determining the maximum value of current of the photovoltaic chain, changes in the module current in the temperature function should be kept in mind.

$$I_{str\_max} = I_{SC}\left(1+(t_{\max}-t_{STC})\frac{\alpha}{100\%}\right) I_{str\_max} = I_{SC}\left(1+(t_{\max}-t_{STC})\frac{\alpha}{100\%}\right) \quad (4)$$

Where:

- I_{str_max} – maximum current of the photovoltaic chain,
- I_{SC} – short-circuit current of the photovoltaic module,
- $t_{\max}$ – maximum temperature of the photovoltaic module assumed by the designer,
- t_{STC} – temperature of the photovoltaic module during the test in STC conditions (t_{STC}=25°C),
- α – coefficient of change in current of the photovoltaic module in the temperature function expressed in [%/°C].

Determination of the maximum current value in the photovoltaic collector's wire

If at least two chains are connected in parallel in the photovoltaic generator, the photovoltaic collector was created. Maximum current flowing in the photovoltaic collector's wire shall constitute the sum of currents of connected photovoltaic chains creating the collector.

$$I_{k\ \max} = n \cdot I_{str\ \max} I_{k\ \max} = n \cdot I_{str\ \max} \quad (5)$$

where:

- I_{k_max} – maximum current in the photovoltaic collector's wire,
- n – number of connected photovoltaic chains,
- I_{str_max} – maximum current of the photovoltaic chain.

Determination of the maximum current value in the photovoltaic generator's main wire

When the photovoltaic generator is composed of several photovoltaic collectors connected in parallel with each other, the maximum current of the photovoltaic generator is equal to the sum of maximum currents of connected collectors.

$$I_{G\ max} = n_k \cdot I_{k\ max} I_{G\ max} = n_k \cdot I_{k\ max} \quad (6)$$

where:

I_{G_max} – maximum current in the photovoltaic generator's wire,
n_k – number of photovoltaic collectors connected in parallel,
I_{k_max} – maximum current in the photovoltaic collector's wire,

Ampacity of photovoltaic wires

The key parameter characterising the DC wire of the photovoltaic installation is its maximum direct current that can flow in the electrical circuit constructed with use of this wire. As it results from the photovoltaic generator scheme, the smallest current flows in the photovoltaic chain, larger in the collector, and the largest - in the PV generator. While knowing the principles of wire cross-section calculations (included in guidelines of producers of DC cables for PV systems), we calculate voltage drops for particular wires of the photovoltaic installation. It should be ensured that voltage drop on the PV installation wires, both on the DC and AC side, does not exceed 1%. If calculated voltage drops exceed 1%, wire cross-sections should be increased.

$$\Delta U_{\%} = \frac{2 \cdot I \cdot l}{U \cdot \gamma \cdot s} \cdot 100\%$$

Where:

$\Delta U_{\%}$ – relative voltage drop on the analysed wire section [%],
I – long-term current flowing through the wire [A],
l – length of the analysed wire section [m],
s – wire cross-section [mm²],
γ – conductivity of a material from which wires are made [S*m / mm²] (for cuprum = 58.6).

4.9. PV system – connection to the grid

Legal aspects concerning connection of the photovoltaic installation to the electrical grid

Photovoltaic installations connected to the electrical grid (ON-GRID) allow for sales of the produced energy. Integration of the photovoltaic system into the grid is possible only after the obtaining and meeting the connection conditions, for which one should apply to a competent operator of the energy system.

Application for connection to the electrical grid

Depending on a country where this installation is conducted, installation owners may use the simplified (for microinstallations) or the full procedure. In the application for conditions for connection of the installation to the electrical grid, the applicant must provide detailed data concerning a number and type of inverters and a number and type of photovoltaic modules planned for application. It entails earlier performance of a complete design of the photovoltaic installation.
Depending on the energy law applicable in a given country, the design may be performed only by persons having necessary valid powers to conduct this type of works.

Determination of rated values of the photovoltaic installation: rated voltage, power rating

Depending on the installation size, sales of electrical energy may be conducted without concession – for the installation of power smaller than specified by the law of a given country.

For the installation of larger power, it is necessary to obtain a concession for sales of electrical energy according to the local law in a given Member State of the EU. In both cases, it is required to conclude an agreement with a provider for sales of electrical energy. The concession obtaining process, depending on a country, lasts several months and it is better to know this at the very beginning of the investment, obtaining a relevant permit to trade electrical energy.

In a document delivered to the distribution network operator, also rated parameters of the installation should be provided, e.g. power rating, rated voltage (one- or three-phase) and expected annual production of electrical energy which a given installation may deliver to the network. These data shall enable the electrical energy distributor to correctly balance energy in a given area of operation.

Selection of the photovoltaic installation protections on the alternate voltage side

As the on-grid system is connected to the electrical grid of a given operator, the photovoltaic installation design must include necessary protections recommended by this operator.

Within the framework of selection of protections on the AC side, there should be selected:

- overcurrent protection,
- surge protection,
- residual current circuit breaker,

Overcurrent protection – usually defined by the producer in the inverter's technical documentation. It depends on the maximum AC of the PV inverter. If the inverter produced does not define current rating I_{zab} of the protection, the nearest value from a range of protections should be adopted, larger than the maximum AC I_{ACmax} of the PV inverter, according to the dependency:

$$I_{zab} > I_{ACmax}$$

Surge protection is selected according to the estimated risk of occurrence of direct lightning and to the structure of the photovoltaic inverter according to the table below.

Tab. 1. Selection of surge protections

Building-applied photovoltaic installations (roofs, elevations)			
Lightning protection	Inverter equipped with isolation transformer	Type of surge protections DC side	Type of surge protections AC side
Lack of lightning protection*	YES	TYPE 2	TYPE 2
	NO	TYPE 2	TYPE 2
Lightning installation is present, distances from vertical and horizontal terminals are kept	YES	TYPE 2	TYPE 2
	NO	TYPE 2	TYPE 2
Lightning installation is present, distances from vertical and horizontal terminals are not kept	YES	TYPE 1+2	TYPE 1+2
	NO	TYPE 1+2	TYPE 1+2
Ground photovoltaic installations			
Lack of lightning installation	YES	TYPE 2	TYPE 2
	NO	TYPE 2	TYPE 2

* *if the producer of photovoltaic modules recommends their earthing, earthing of PV modules and lightning installation should be performed.*

Surge protections are established on not earthed return wires. If distance of the photovoltaic generator from the photovoltaic inverter is less than 10 m, surge protections are assembled only at the photovoltaic inverter. If distance of the photovoltaic generator from the photovoltaic inverter is more than 10 m, surge protections should be assembled at the photovoltaic inverter and at the photovoltaic generator.
Selection of residual current circuit breaker depends on the structure and properties of the photovoltaic inverter. While selecting the residual current circuit breaker, attention should be paid to recommendations of the inverter's producer within the scope of leakage current. Structure of the inverter is a significant element.

Tab. 2. Selection of residual current circuit breaker

Inverter equipped with isolation transformer	Rated differential current of protection*	Type of residual current circuit breaker
YES	30 mA	AC
NO	30 mA	B

** If the producer recommends a different value of protection, one should adjust to recommendations of the photovoltaic inverter's producer*

On-grid inverters

The inverter is one of two **most important elements of the photovoltaic installation**. Its task is to convert direct current produced by the DC current to alternate current synchronised with the electrical grid.

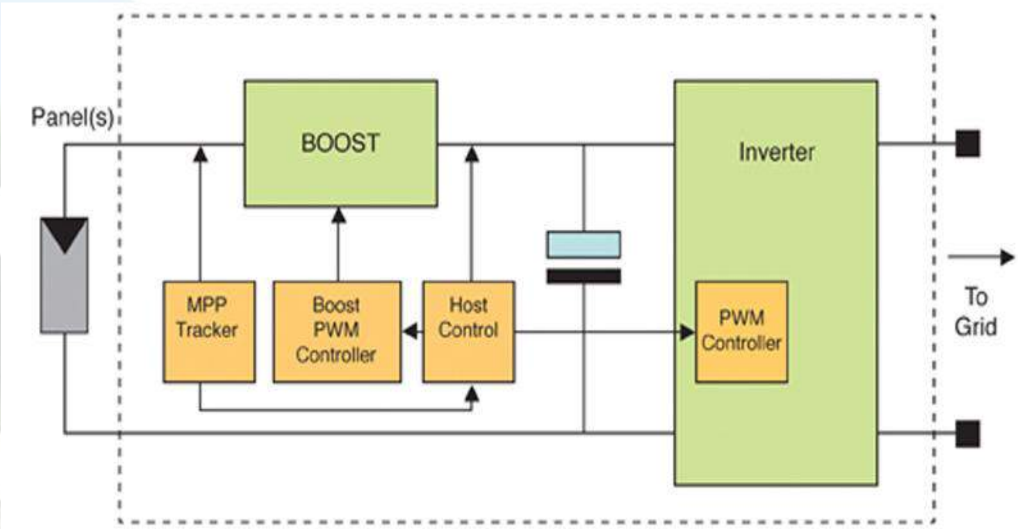


Fig. 1. Basic flow chart of the inverter
Source: https://www.powersystemsdesign.com/articles/the-promise-of-solar-technology/28/6289 [access: 20 June 2018]

On the market, we can see the entire range of inverters:
- with the transformer,
- without the transformer,
- one- or three-phase,
- central and chain,
- having one or more independent MPPT inputs
- microinverters, so-called modular.

Low-power inverter (one- or three-phase) or a group of microinverters shall be needed for small home installations. For industrial installations, inverters of higher power, central or chain, should be applied.
A solar inverter should be characterised with high efficiency and possibility of cooperation with as many types of PV modules as possible. Inverter efficiency is a very important parameter, as it allows to obtain the maximum of energy from the photovoltaic installation at minimum losses. The best low-power inverters achieve efficiency of 97%, in turn inverters with higher power may achieve 98% of efficiency. If we compare inverter with regard to efficiency, it should be done in relation to average efficiency weighed for various inverter load. This efficiency should always be in a catalogue card under the EURO efficiency name.

$$\eta_{EUR} = 0.03\ \eta_{5\%\ of\ load} + 0.06\ \eta_{10\%} + 0.13\ \eta_{20\%} + 0.1\ \eta_{30\%} + 0.48\ \eta_{50\%} + 0.2\ \eta_{100\%}$$

As we see in the above formula, the European efficiency considers the inverter's operation in the entire spectrum of load, which in practice better maps its operation in real conditions.

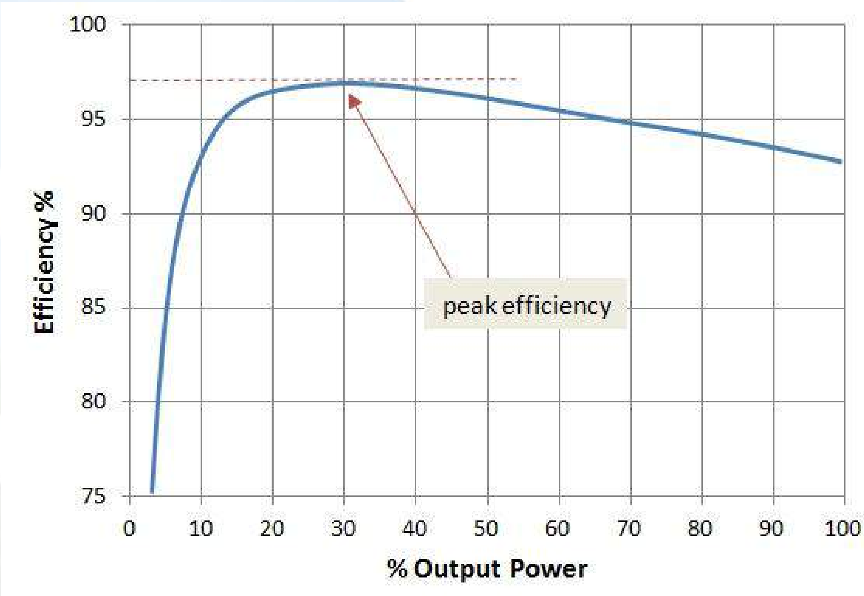


Fig. 2. Description of the inverter's efficiency
Source: https://www.e-education.psu.edu/eme812/node/738 [access: 20 June 2018]

Security functions in grid inverters

According to the EU legislation, inverters should comply with the basic standard describing security of inverters in photovoltaic systems:

– IEC 62109-1:2010, EN 62109-1:2010, DIN EN 62109-1:2011 Safety of power converters for use in photovoltaic power systems – Part 1: General requirements;
– IEC 62109-2:2011, EN 62109-2:2011, DIN EN 62109-2:2012 Safety of power converters for use in photovoltaic power systems - Part 2: Particular requirements for inverters.

According to the applicable law, converters not meeting the above standards cannot be applied in installations.
Key parameters described in the above documents include:

– AC working voltage,
– DC working voltage,
– earthing,

- earthing,
- Over current protection,
- Short circuit protection,
- Thermal protection,
- Touch temperatures,
- Temperature limits for mounting surfaces,
- Protection against electric shock and energy hazards,
- Protection against electric shock,
- Connection to PELV and SELV circuits,
- Pulsating working voltage,
- Protective separation,
- Insulation Including Clearance and Creepage Distances.

Rated data of photovoltaic inverters

There is a series of key parameters of inverters for photovoltaic systems.

The most important parameters of inverters:

Input parameters:

- maximum input voltage (very sensitive to exceeding),
- maximum input power (DC side),
- number of entries/trackers,
- maximum current per one MPP input/tracker,
- range of MPPT voltage.

Output parameters:

- maximum output power (AC side),
- phase system (one-, three-phase),
- range of output voltage synchronisation,
- range of frequencies,
- efficiency.

Other parameters of inverters:

- Security level (IP54, IP65),
- Phase-to-phase output voltage,
- Wsp THD (content of harmonic),
- Dimensions and weight,
- Range of operating temperature,
- Additional AC/DC protections (fuses on inputs, surge protection, insulation monitoring, polarisation control),
- System cooling method (gravity, forced),
- Method of conversion of DC to AC (with a transformer, without a transformer),
- Systems monitoring electrical parameters.

Selection of a number of maximum power track systems in the inverter

According to the roof locations against the southern direction, we may use the inverter with one MPPT system (for an installation entirely oriented towards south) or with two MPPT systems (for an installation with modules placed to the west and east).

Fig. 3. East-west installation
Source: https://www.solarquotes.com.au/blog/an-eastwest-spit-of-solar-panels-on-a-single-string-can-work-well/ [access: 20 June 2018]

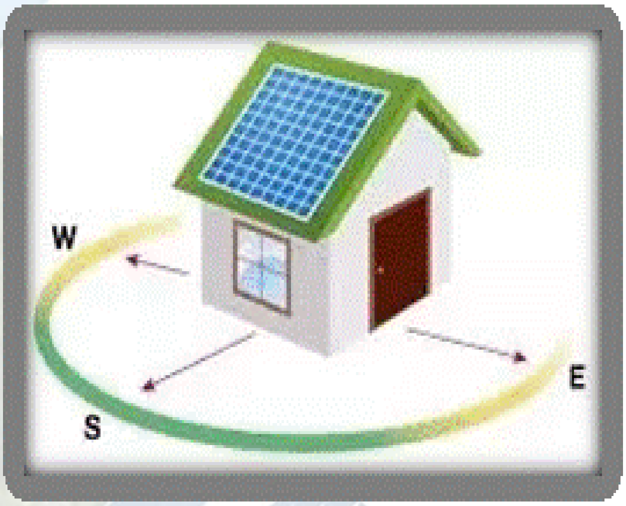


Fig. 4. Southern installation
Source: https://www.quora.com/Why-do-solar-panels-face-south [access: 20 June 2018]

Moreover, for solutions with higher power, where a larger number of independent circuits with DC modules may be distinguished, it shall be necessary to apply inverters with 3 and 4 MPPT circuits.

Efficiency of the inverter depends also directly on an algorithm of searching for a maximum power point. According to the figure below, according to irradiance, operating point changes and the inverter should keep up with these changes thanks to the implemented algorithm.

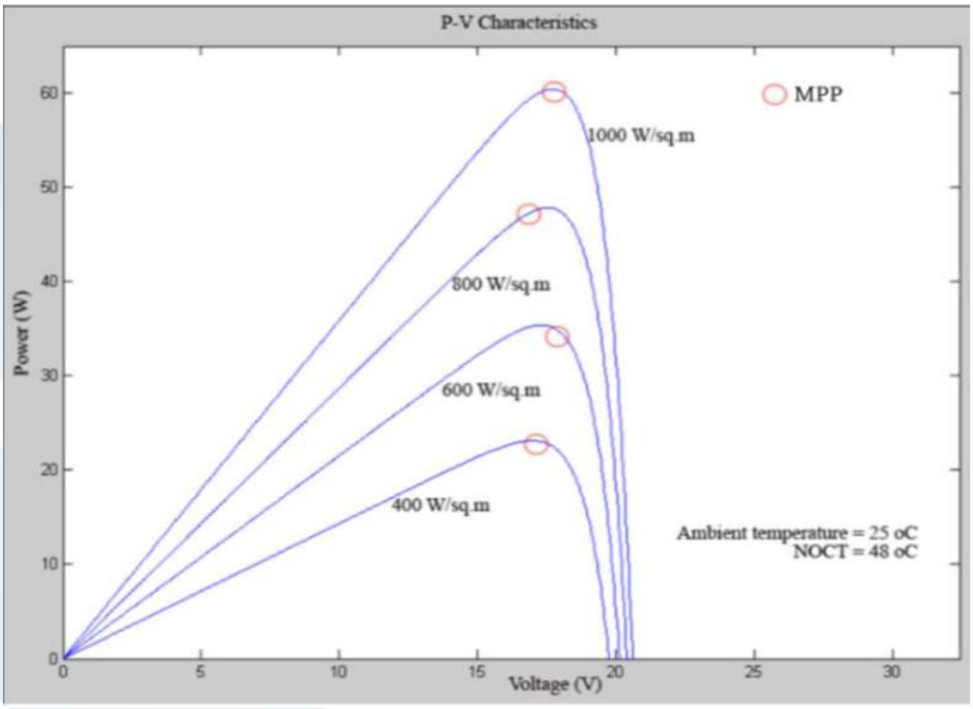


Fig. 5. Variability of the operating point of inverters with the MPPT system
Source: https://www.semanticscholar.org/paper/Maximum-power-point-tracking-controller-using-P-and-Singh-Sarkar/89cc1255f020c31698fc6c90bc6d0872b523b39b/figure/1 [access: 20 June 2018]

Selection of the photovoltaic installation protections on the direct voltage side

Protection of the DC circuit in the photovoltaic installation consists in the selection of:

- surge protection (according to Table 1),
- overcurrent protection.

Properly selected photovoltaic generator does not require the application of overcurrent protections on inputs of the photovoltaic inverter, because the photovoltaic inverter shall not produce more current than the maximum short-circuit current of the generator. Overcurrent protections are applied when parallel connections of photovoltaic chains occur in the generator. If three or more photovoltaic chains are connected, on every connected PV chain there is installed the overcurrent protection preventing from the flow of reverse current with value exceeding 2 x I_{PVmax}. Description of the overcurrent protection should correspond with the description of protections applied in photovoltaic installations, usually described with "gPV" symbols. The protection current I_{zabDC} is selected based on the short-circuit current I_{SC} of the photovoltaic module from a range of protections after meeting the following dependency:

$$1{,}4 I_{SC} \leq I_{zabDC} \leq 2 I_{SC}$$

It is recommended that the value of protection current I_{zabDC} selected from the range is as close to the lower end of the determined range as possible. While selecting a fuse link, it should be kept in mind that operating voltage of the fuse is at least by 20% higher than the maximum voltage U_{DCmax} of the protected photovoltaic chain.

4.10. Standards and technical specifications connected with a thematic group

Division of PV energy producers with regard to the installation size

Microinstallation – installation of a renewable energy source of total installed electrical power not exceeding 50 kW, connected to the electrical grid of rated voltage lower than 110 kV or with attainable thermal power in cogeneration not exceeding 120 kW.

Microinstallations – connection to the grid

- In Poland, provisions of the Energy Law apply to the RES installation connection.
- Lack of a fee for connection of a microinstallation to the network constitutes the basis to refuse a decision.
- Connection of the microinstallation to the network occurs based on the application, when an entity applying for the microinstallation connection is connected to the network as a final consumer, and installed power of the microinstallation is not larger than specified in the issued connection conditions. An application is filed after the installation of appropriate protective systems and a measuring and settlement system (at the enterprise's expense).
- No obligation of obtaining the connection conditions and conclusion of a connection agreement.

Small installation – installation of a renewable energy source of total installed electrical power larger than 50 kW and not exceeding 500 kW, connected to the electrical grid of rated voltage lower than 110 kV or with attainable thermal power in cogeneration larger than 120 kW and not exceeding 600 kW.

Small installations – connection to the grid – conclusion

- Application for a local grid operator for the issuance of connection conditions.
- To the application, an excerpt and map extract from the local spatial development plan allowing for the source location, and in case of no such a plan, decision on land development and management conditions.
- Development plan or design specifying the location of a connected facility.
- The document confirming legal title to use the facility where connected installations are to be applied.

Rights and obligations of the PV energy producer depending on the installation size

Information obligations of a producer in the microinstallation to the distribution system operator (OSD):

- Information on the amount of electrical energy produced in the microinstallation and electrical energy sold to the obligated seller, which was produced from renewable energy sources in the microinstallation and introduced to the grid to the operator of an electrical distribution system – within seven days from the quarter end date
- Information on changes in the activity (type and power of microinstallation, suspension or completion of production) within 14 days from the date of change in these data.
- Information on the date of first production of electrical energy from the microinstallation (production and introduction to the network) or on the date of completion of modernisation of this installation – within 7 days from this date.

Legal regulations for energy enterprises and electrical energy consumers,

Information obligations of OSD to the President of the Energy Regulatory Authority – information

OSD provides information on:

- producers of electrical energy from renewable energy sources in the microinstallation,
- location, type and installed electrical power of microinstallations connected to its network

within 14 days from the date of their connection or notification of connection of the microinstallation to its network,

and on:

- changed type of microinstallation and its installed electrical power,
- disconnection of the microinstallation from its network

within 14 days from the date of obtaining information on data or from the date of microinstallation disconnection from this network.

Information obligations of OSD to the President of the Energy Regulatory Authority – quarterly statements

Within 45 days from the quarter end date, OSD provides the President of the Energy Regulatory Authority a quarterly statement including:

- information concerning the amount of electrical energy produced from the microinstallation by particular producers and total amount of electrical energy sold to the obligated seller produced in the microinstallation and introduced to the distribution network,
- list of electrical energy producers in the microinstallation, with indication of a date of production by particular producers for the first time of electrical energy from renewable energy sources in the microinstallation,
- indication of a microinstallation type and its installed electrical power.

Sanction for non-performance of information obligations by OSD

- The President of the Energy Regulatory Authority imposes a financial penalty for:
- lack of submission of information on time – PLN 1,000,
- lack of submission of statement on time – PLN 10,000.

One may request a review of a decision on penalty to SOKiK.

Connection to the grid – obligation of connection

- Energy enterprises being a network operator is obligated to connect a renewable energy source to its network, if there are economic or technical conditions for connection.
- If there are no technical conditions for connection to the network, the operator must determine a planned date and conditions for performance of modernisation and development of the network and the connection date.
- The operator informs also on the amount of available connection power, when it is smaller than the one requested by an entity applying for connection.
- Connection conditions are valid for two years from the date of their delivery; they constitute a conditional obligation to connect to the network.

Other additional obligations of OSD resulting from the RES Act

- Collection and settlement of the RES fee
- Provision of the President of the Energy Regulatory Authority with applications for the issuance of a guarantee of origin

Certificates of origin and other support systems for RES energy producers

The prosumers sector is supported by discounts mechanism. DOSs are obliged to take the energy from the micro-installations. For 1 kWh feed to the grid prosumers may receive 0.8 kWh in case of systems below 10 kW and 0.7 kWh for systems between 10 and 50 kW. This support mechanism appears to have a relatively low development potential. The significant subsidies come from European and domestic programs that support the development of RES. It is estimated that each year will occur several thousands of photovoltaic microinstallations.

Auctions – general principles

- New projects may participate in the support system **only through the auction mechanism**.
- E.g. installations using biomass with power **exceeding 50 MW** are **excluded** from the auction system.
- By 30 November, the Council of Ministers specifies by way of ordinance the **maximum amount and value** of energy that may be purchase in a next year (25% for installations below 1 MW).
- Auctions (at least once a year) are **organised and conducted by the President of the Energy Regulatory Authority** (separately for sources to and above 1 MW).
- A producer that offers the **cheapest** energy becomes an auction winner.
- Energy price is indicated based on a **reference price specified by the Minister of Economy** at least 60 days before the auction according to the principles determined in the draft RES Act.
- An entity who wants to participate in the auction is **subject to the procedure of formal assessment –** an obligation of delivering documents and establishing bank guarantee or making a deposit.
- The President of the Energy Regulatory Authority issues a certificate of admittance to the auction or refuses issuing it **within 30 days** from the application filing.
- A **complaint may be filed** for the refusal to issue the certificate.
- The certificate is valid for **12 months**.
- Conclusion of a contract with the obligated seller occurs **within six months from the auction closure**.
- Energy is purchased at a **price established on the auction**, subject to the indexation with inflation rate.
- A purchase obligation concerns **only energy in the amount specified in the producer's offer.**
- Settlement of the energy production obligation in the amount provided in the offer occurs **in three-year periods** (under threat of financial penalty).
- The obligated seller and the producer have the **right of coverage of the so-called negative balance**.

The Act of Renewable Energy Sources was amended on 07 June 2018. The main goal of new RES act is to improve the rules of the auction system, which will enable unlock the next auction and the launch of new investment in RES. In the amended Act there is a new rule for the accumulation of public support. One of the conditions is requirement that operating support must be reduced by any previously received investment support. This condition is called the rule of accumulation, the purpose of which is to ensure that assistance (or other type of support) for a single project – granted from various sources – was of a proportional nature. It must be limited to the minimum necessary to carry out this undertaking – provided the Ministry of Energy. The auctions will be divided into several baskets, corresponding to the division made for the purpose of setting reference prices. Photovoltaic is in basket with onshore wind energy. The Ministry of Energy predicts support for photovoltaic power plants with a capacity of up to 750 MW (reference price PLN 420/MWh) and smaller wind farms up to 120 MW (reference price PLN 320 /MWh).

Rights and obligations of the Certified RES Installer in Poland

RES Directive

While determining directions of operation within this scope, the RES Directive (2009/28/EC) imposes on the Member States the creation of mutually recognised certification systems. According to the directive 2009/28/EC concerning the promotion of application of renewable energy sources (RES), there is foreseen the implementation of certification systems or equal systems of qualification of small RES system installers (boilers and biomass-fired furnaces of small scale, PV systems, solar thermal systems, shallow geothermal systems and heat pumps). These certification systems should be completed by the end of 2012; every member state recognises certificates granted in other member states according to the criteria specified in the Directive.

A person installing microinstallations, small installations, installation of a renewable energy source of total thermal installed power not exceeding 600 kW (draft RES Act) may request from the President of the Energy Regulatory Authority the issuance of the installer's certificate.

However, the certificate is not mandatory and energy enterprises that subordinate connection of the installation to the fact of having a certificate **operate without the legal basis**, breaching the regulation of Article 56 section 1 item 4 of the Energy Law (information of the President of the Energy Regulatory Authority no. 40/2013).

The certificate is issued for 5 years and its validity can be expired for the next 5 years.

Conditions for obtaining and renewal of the certificate

Conditions and mode of issuance of certificates to installers of microinstallations and small installations are specified in the Act of 10 April 1997 - Energy Law.

Conditions for obtaining of the certificate of an installer of microinstallations or small installations:

1. full legal capacity and use of all public rights;
2. no conviction by final judgement for deliberate crime against credibility of documents and business trading;
3. possession of one of the following documents:
   - diploma confirming professional qualifications issued pursuant to the provisions of the Act of 7 September 1991 on the Educational System or other equivalent

document confirming qualifications to install sanitary, electrical, heating, cooling or electrical devices or installations;
   - documentation of a three-year professional experience within the scope of installation or modernisation of sanitary, electrical, heating, cooling or electrical devices or installations;
   - certificate of completion of at least 2-term post-graduate course or equivalent, which curriculum concerned issues included in the programme scope of training specified in the provisions issued pursuant to Article 20v item 2;
   - certificate of training completion at a producer of a given type of renewable energy source, which in a theoretical and practical part included the issues within the scope of design, installation, modernisation or maintenance in a due technical condition of the renewable energy source;
4. Completion of the basic training for persons applying for the issuance of the certificate of an installer of microinstallation or small installation, confirmed with a certificate, conducted by an accredited training organiser referred to in Article 20q section 1 or in Article 20 w, within the scope concerning installation of a given type of renewable energy source;
5. Passing an exam set by an examination commission, as appropriate for a given type of renewable energy source, not later than within 12 months from the end date of the basic training.

or

6. full legal capacity and use of all public rights;
7. no conviction by final judgement for deliberate crime against credibility of documents and business trading;
8. possession of one of the following documents:
   - diploma confirming qualifications in the profession of a technician of devices and systems of renewable energetics;
   - diploma confirming professional qualifications within the scope of devices and systems of renewable energetics issued pursuant to the provisions of the Act on the Educational System;
   - diploma of graduation from Master's studies in the field or in the specialisation of renewable energy sources, or sanitary, electrical, heating, cooling, air conditioning or electrical devices and installations, issued pursuant to the provisions of the Act of 27 July 2005 on the Educational System.

EXTENSION OF THE CERTIFICATE

In order to extend the certificate, an application should be filed not later than 30 days before the end date of validity of a previously issued certificate. It should contain the same data as an original application, as well as a declaration that the Installer meets the certificate conditions.

Loss of the certificate – reasons for withdrawal of the certificate

1. Limitation or loss of the Installer's legal capacity.
2. Deprivation of the Installer of its public rights by a final judgement.
3. Conviction of the Installer by final judgement for deliberate crime against credibility of documents and business trading.

4. When the Installer uses the certificate contrary to its scope or there is proven evidence that a microinstallation or small installation is assembled contrary to valid regulations.

The Installer whose certificate has been withdrawn may appeal for renewal of the certificate after one year from the certificate withdrawal date.

4.11. Factors affecting work productivity

The photovoltaic system constitutes a series of elements in which energy transformations occur. In photovoltaic cells, there occurs conversion of photon energy to electrical energy, in voltage regulators electrical energy of voltage and direct current of different parameters, while in the inverter there occurs transformation of electrical energy from direct current and voltage to alternate current and voltage, while in batteries electrical energy is converted to chemical energy, and vice versa.

Every electrical energy converter is characterised with some efficiency – less than one. General efficiency for the entire photovoltaic system is a product of efficiencies of particular system elements. In order to obtain as high energy efficiency of the photovoltaic system as possible, system components should be properly selected so that they work mostly in a range of the highest efficiencies.

An analysis of changes in efficiency of particular system elements in the load function and presentation of criteria for selection of system components shall allow for obtaining energy efficient configurations of photovoltaic systems.

Efficiency of photovoltaic modules

Depending on the applied type of photovoltaic modules, their efficiency shall be different. Moreover, impact of temperature on cell operation shall be different for every module type, which may also affect its efficiency in specific operating conditions. Therefore, while planning the photovoltaic system, proper selection of a module type for specific operating conditions should also be considered.

In most cases, photovoltaic installations are made from modules performed in silicic technologies (mono- and polycrystalline). Their efficiency fluctuates between 17 and 21%.

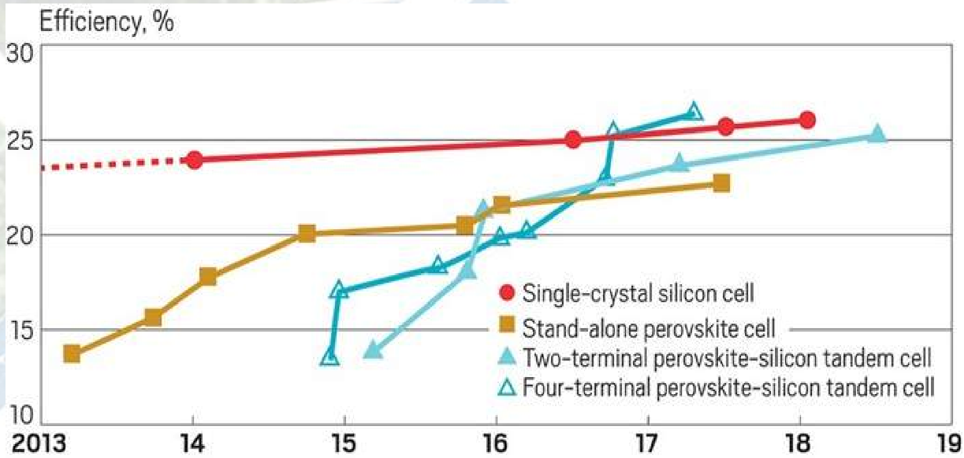


Fig. 1. Efficiency of PV modules for different technologies

Source: https://cen.acs.org/energy/solar-power/Perovskite-progress-pushes-tandem-solar/96/i24 [access: 20 June 2018]

Efficiency of photovoltaic inverters

Maximum efficiency of photovoltaic inverters is high and reaches values from 96 to 98.5%. Nevertheless, due to fluctuations of DC input voltages, operation with maximum efficiency happens rarely. Therefore, to ensure operation with as high efficiency as possible, there should be carefully conducted the process of DC voltage adjustment between the PV module and the inverter MPPT input.

Working range of the inverter is between Ustart and Umax, while its efficiency depending on the input voltage value is variable.

When voltage on the DC side reaches the value Vstart, the inverter switches on and starts searching for the maximum power point. If this point is between Vmin and Vstart, the inverter switches on and starts operation. It operates with incomplete power unless voltage exceeds the minimal value of the MPPT scope. The inverter has the highest efficiency at voltage Vnom.

Therefore, configuration of PV panel chains should provide with voltage close to Vnom of the inverter.

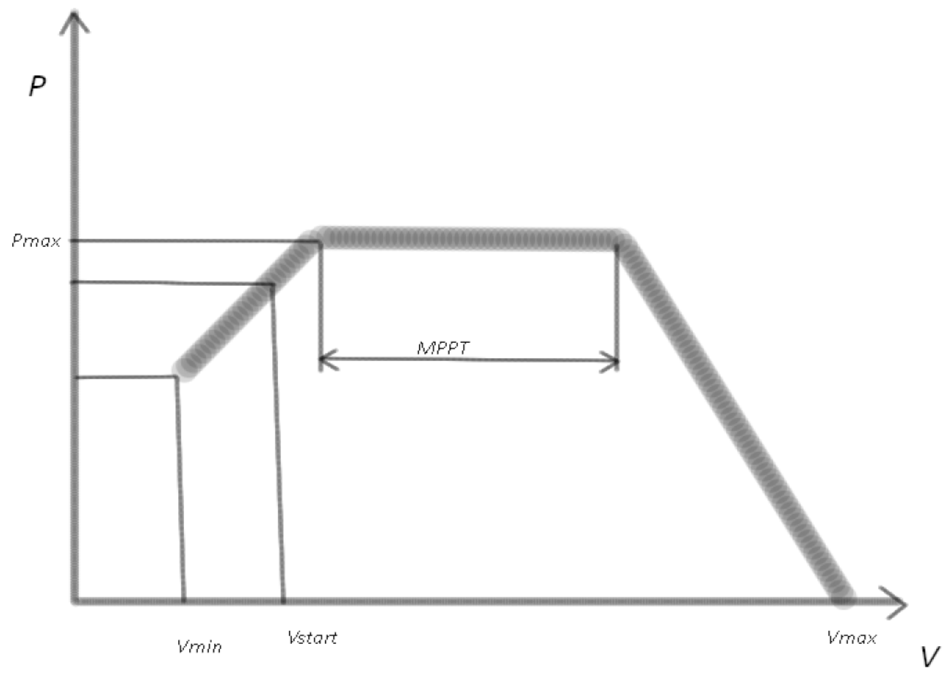


Fig. 2. Power available from the inverter depending on the input voltage

Adjustment of modules to the inverter

Every inverter has two usable powers in its safety data sheet:

- power rating of direct current DC,
- nominal power of alternate current AC.

Nominal power of alternate current AC for the inverter is the power that it may supply continuously in an ambient temperature of 25° ± 2°C.

Power rating of direct current DC for the inverter ($P_{INV\ DC}$) is approx. 5% higher than its nominal power AC.

At the inverter selection, power range may be specified as follows:

$$0.8\ P_{PV} < P_{INV\ DC} < 1.2\ P_{PV}$$

Where: P_{PV} – power of a set of PV modules [Wp].

Dependency between power of installed PV modules and maximum power of the inverter is expressed with the inverter dimensioning coefficient C_{INV} and can be calculated with use of the following formula:

$$C_{INV} = \frac{P_{PV}}{P_{INV\ AC}}$$

Where:

P_{PV} – power of installed PV modules,

$P_{INV\ AC}$: nominal AC power of the inverter.

Typical value C_{INV} is within the range of $0.83 < C_{INV} < 1.25$, but from an economic point of view it is better if $C_{INV} > 1$.

Appropriate selection of length and cross-sections of DC and AC cables

The main purpose for selection of an appropriate cross-section of wires is obtaining as low losses of voltage transmission/drops as possible.

It is recommended that voltage drop in the circuit of direct current DC amounts to less than 1% of rated voltage of the PV system in STC, in order to limit power losses on all DC cables to the level lower than 1% in STC. Losses at this level can be maintained with use of standard cross-sections of cables for PV systems with inverters operating on higher input DC voltages ($V_{MPP} > 120V$). (DGS, 2008)

In order to select appropriate cross-section of wires with maintenance of voltage drop below 1% (in STC), the equation below shall be applied to calculate the cable cross-section surface:

$$A_M = \frac{2 \cdot L_M \cdot I_{SC}}{1\% \cdot V_{MPP} \cdot \kappa}$$

Where:

L_M: length of module/chain cabling wires [m],

I_{SC}: chain current [A],

V_{MPP}: chain voltage [V],

κ : conductivity [m/Ω mm^2, for cuprum $\kappa_{Cu} = 56$, for aluminium $\kappa_{Al} = 34$].

The obtained value should be rounded up to the nearest standard wire cross-section.

The next equation defines total power losses (W) in module/chain cabling for the selected wire cross-section:

$$P_M = \frac{2 \cdot n \cdot L_M \cdot I_{SC}^2}{A_M \cdot \kappa}$$

Where:

n: number of chains of PV modules.

When various lengths of wires for chains are applied, the equation below should be applied:

$$P_M = \frac{2 \cdot I_{SC}^2}{\kappa} \cdot \left(\frac{L_1}{A_1} + \frac{L_2}{A_2} + \frac{L_3}{A_3} + \cdots\right)$$

Main DC cable and DC rail cables for PV module subsets must be capable of transmission of maximum current that may be produced by these modules. For the main DC cable, maximum current with the value 1.25 times larger than maximum short-circuit current of the entire set of PV modules for the STC conditions should be adopted.

$$I_{max} = 1.25\ I_{SC\ PV}$$

Cable cross-section must be selected according to the allowed maximum current of the cable. Again, there is assumed 1% decrease in reference to the nominal power of a set of PV modules.

DC cable cross-section is defined by the dependency:

$$A_{DCcable} = \frac{2 \cdot L_{DCcable} \cdot I_n^2}{(v \cdot P_{PV} - P_M) \cdot \kappa}$$

Where:

$L_{DC\ Cable}$: length of module/chain cabling wires [m],
I_n: nominal current of the PV module [A],
P_{PV}: nominal power of the PV module [W_P],
P_M: power loss on the line of the DC main [W],
K: conductivity,
v: coefficient of losses v=1% or v=2% for a low-voltage solution.

The obtained value should be rounded up to the nearest standard wire cross-section.
The next equation defines total power losses (W) in module/chain cabling for the selected wire cross-section:

$$P_M = \frac{2 \cdot L_{DCcable} \cdot I_n^2}{A_{DCcable} \cdot \kappa}$$

Calculation of the wire cross-section for the alternate current AC connection is conducted with assumption of a 3% voltage drop in reference to the nominal network voltage. Cable cross-section $A_{AC\ cable}$ is calculated with use of the formula:

$$A_{ACcable} = \frac{2 \cdot L_{ACcable} \cdot I_{nAC} \cdot \cos\varphi}{3\% \cdot V_n \cdot \kappa}$$

For one-phase solution:

$L_{AC\ cable}$: length of AC connecting cable [m],
$I_{n\ AC}$: nominal voltage of the inverter alternate current AC [A],
cosφ: power coefficient (between 0.8 and 1.0),
V_n: nominal network voltage, one-phase: 230 V.

In case of three-phase connection:

$$A_{ACcable} = \frac{\sqrt{2} \cdot L_{ACcable} \cdot I_{nAC} \cdot \cos\varphi}{3\% \cdot V_n \cdot \kappa}$$

V_n: nominal network voltage, three-phase: 400 V.

Loss on the cable $P_{AC\ cable}$ for the selected cable cross-section is defined with use of the formula:

for one phase:

$$P_{ACcable} = \frac{2 \cdot L_{ACcable} \cdot I_{nAC}^2 \cdot \cos\varphi}{A_{ACcable} \cdot \kappa}$$

for three phases:

$$P_{ACcable} = \frac{3 \cdot L_{ACcable} \cdot I_{nAC}^2}{A_{ACcable} \cdot \kappa}$$

Selection of a tilt angle of PV modules

Benefits from PV systems depend largely on the orientation and tilt of modules. They are related to the orientation and tilt of roofs and facades:

- Optimal orientation = southern;
- Optimal tilt = latitude (°) - 10° (over 30° in Europe).

Modules mounted on facades are 30% more efficient that the roof ones.
The table below presents coefficients to calculate losses in performance of PV systems depending on the orientation and tilt of modules.

ROOF ANGLE	WEST						SOUTH						EAST
	90°	**75°**	**60°**	**45°**	**30°**	**15°**	**0°**	**15°**	**30°**	**45°**	**60°**	**75°**	**90°**
90°	56	60	64	67	69	71	71	71	71	69	65	62	58
80°	63	68	72	75	77	79	80	80	79	77	74	69	65
70°	69	74	78	82	85	86	87	87	86	84	80	76	70
60°	74	79	84	87	90	91	93	93	92	89	86	81	76
50°	78	84	88	92	95	96	97	97	96	93	89	85	80
40°	82	86	90	95	97	99	100	99	98	96	92	88	84
30°	86	89	93	96	98	99	100	100	98	96	94	90	86
20°	87	90	93	96	97	98	98	98	97	96	94	91	88
10°	89	91	92	94	95	95	96	95	95	94	93	91	90
0°	90	90	90	90	90	90	90	90	90	90	90	90	90

Fig. 3. Installation efficiency depending on the orientation and tilt angle
Source: http://www.freesolarpanelsuk.co.uk/the-best-angle-and-orientation-for-solar-panels-in-the-uk.php [access: 20 June 2018]

Field conditions – possible overshadowing

Even if the best orientation and tilt angle of modules is planned, the system may be inefficient if overshadowing was not considered.

There are two types of overshadowing:

- overshadowing caused by neighbouring buildings, trees, topography,
- self-overshadowing.

The first type of overshadowing should be regarded with consideration of:

- winter period, morning and evening hours,
- tree growth,
- newly planned buildings in the area.

In order to prevent these issues, bypass systems and module dummies in shaded places should be planned. Caution is advised, as the light scattered by obstacles throwing a shadow may significantly affect the PV installation performance.

In order to avoid self-overshadowing, attention should be paid to the building geometry and such elements as:

- satellite dishes,
- chimneys and ventilation,
- skylights and other protruding elements,
- hanging elements.

In places being subject to over-shadowing, module dummies or bypass systems should be installed.

Fig. 4. Overshadowing by trees

Source: https://news.energysage.com/solar-panels-work-shade/ [access: 20 June 2018]

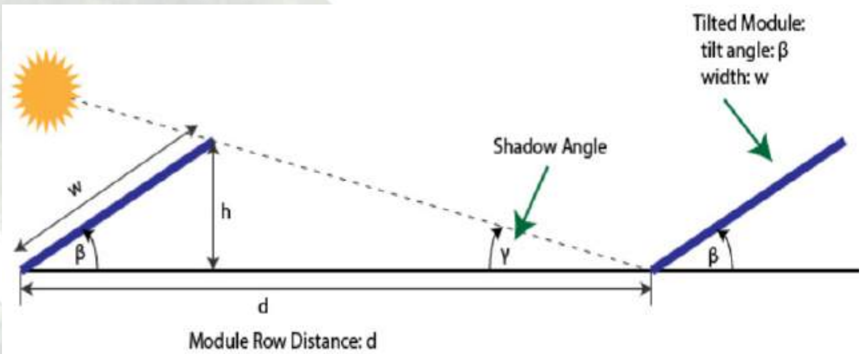


Fig. 5. Selection of distance between rows

Source: http://www.greenrhinoenergy.com/solar/performance/shading.php [access: 20 June 2018]

Selection of energy storage

Natural operation of the photovoltaic system is that the peak of production of electrical energy falls in afternoon hours. In most cases of household installations and in a significant part of industrial installations, it does not correspond with maximum load, which would naturally use the produced energy in the same time. Therefore, for these cases it is justified to consider the use of energy storage adjusted to our load profile (demand for electrical energy). Selection of a proper technology of accumulator and its capacity shall allow for the storage of energy overproduction, its keeping and use whenever it is convenient for the user. Depending on energy price rates in particular countries, this process is less or more profitable, nevertheless there is noticed a general trend of an increase in share of energy storage in PV installations.

Regular maintenance, clearing photovoltaic modules

Effectiveness of the photovoltaic installation may be improved also by remembering about and performing regular system maintenance. Starting from regular washing of modules, their inspection with regard to damage, through the review of proper location of cables and connections, to the control of ventilation near the inverter and of DC and AC protections. It is worth to entrust these works to an installing company within the framework of maintenance services. Such a procedure may save us from longer system failures, during which energy production shall be decidedly lower or none.

Fig. 8. Washing of the PV installation
Source: http://gramwzielone.pl/energia-sloneczna/17916/czyszczenie-instalacji-fotowoltaicznej-zwiekszy-jej-wydajnosc [access: 20 June 2018]

4.12. Cooperation of the photovoltaic installation with alternative energy sources

Types and specificity of alternative energy sources

A photovoltaic power plant is one of many alternative energy sources. Taking a look at its nature, it can be said that it is an unstable source, as it is not able to ensure production continuity during the day. Wind power plant is the second source of this type, which cannot operate 24/7.

Two other power supply sources of alternative power plants, i.e. biomass and biofuel, shall work as stable sources, as their operation is based on the combustion process which can be effectively controlled by human being.

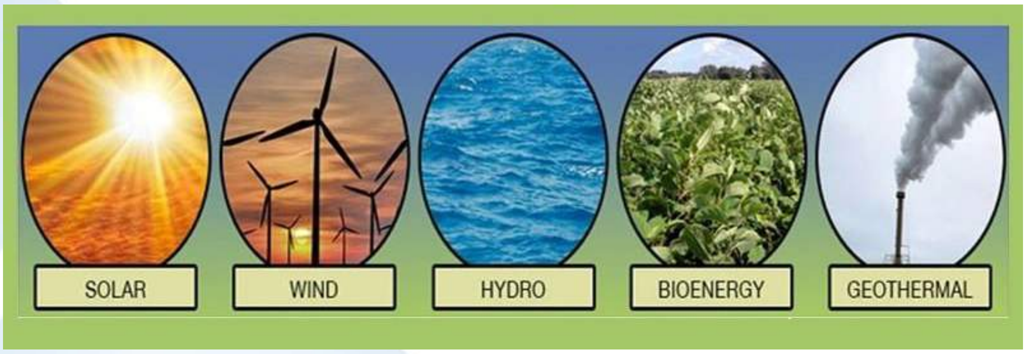


Fig. 1. Renewable energy sources
Source: http://www.studymumbai.com/renewable-energy-resources.html [access: 20 June 2018]

Photovoltaic systems cooperating with alternative energy sources

The photovoltaic system may effectively cooperate with every source of the three above-described.
In case of connection of a wind power plant with a photovoltaic power plant, systems complete each other, as basically if winds are blowing and energy from windmills is produced, we have to do with nebulosity that minimise the PV energy production. And vice versa – in periods of a high amount of sunshine, production of energy from the Sun is maximised, while production of wind power plants is practically minimal, as wind is relatively light.

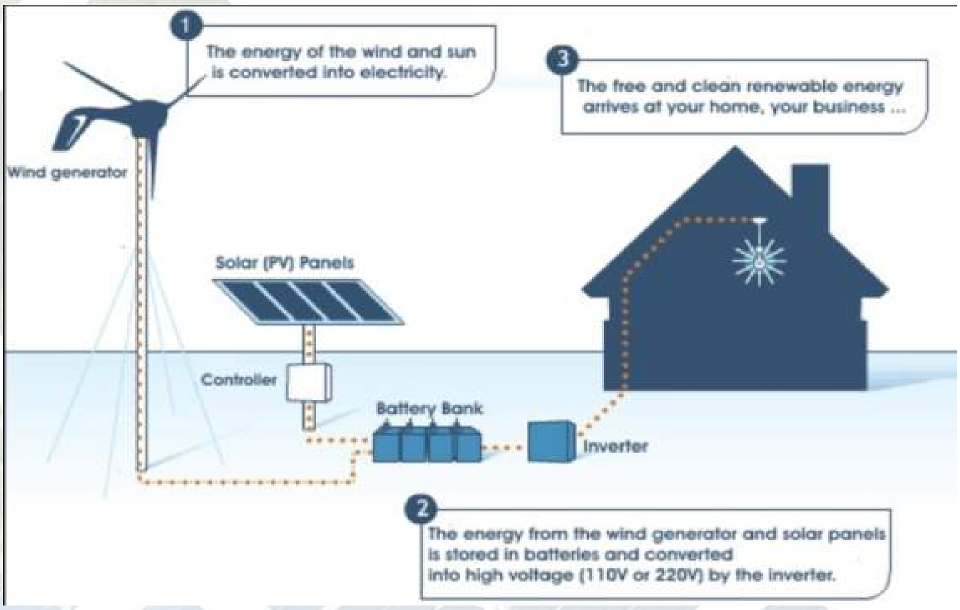


Fig. 2. Photovoltaic installation with the wind generator

In case of biofuels and biomass, these sources shall constitute an element stabilising production of such a hybrid source of production. Due to their character, we can select their size and management method in such a way that energy production is stable from the client's point of view.

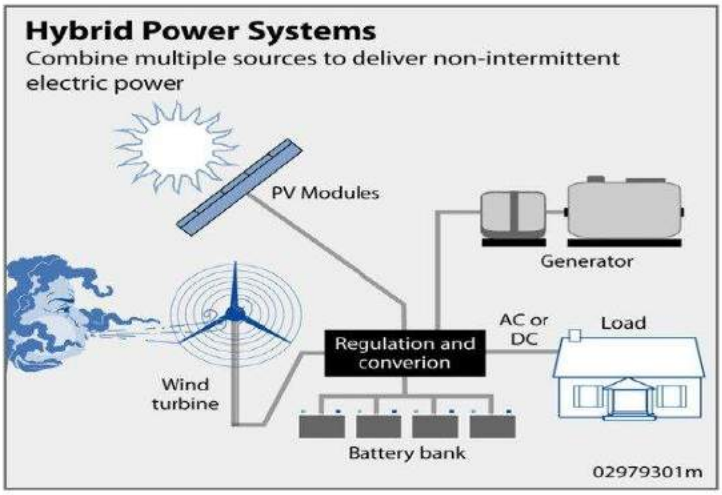


Fig. 3. Photovoltaic installation with the wind generator and biofuel-supplied generator
Source: https://www.energy.gov/energysaver/buying-and-making-electricity/hybrid-wind-and-solar-electric-systems [access: 20 June 2018]

Role of energy storage in systems with many alternative energy sources

In each of the above-mentioned cases of operation of PV systems with alternative energy sources, it is required to use power retention in the system. Its function shall consist in energy receipt in periods of increased production, at simultaneous lack of possibility of energy receipt and deliver when the client's energy demands are larger than the possibility of its production. PV and wind power plant is the most critical connection here, as it may happen that one source completes the other. Then, the storage role cannot be underestimated. When we have to do with PV installations associated with biofuels or biomass, energy storage shall be used to collect surpluses from the PV installation, while in case of no production from the Sun, the client will have provided energy from biofuels and the one collected in the storage.

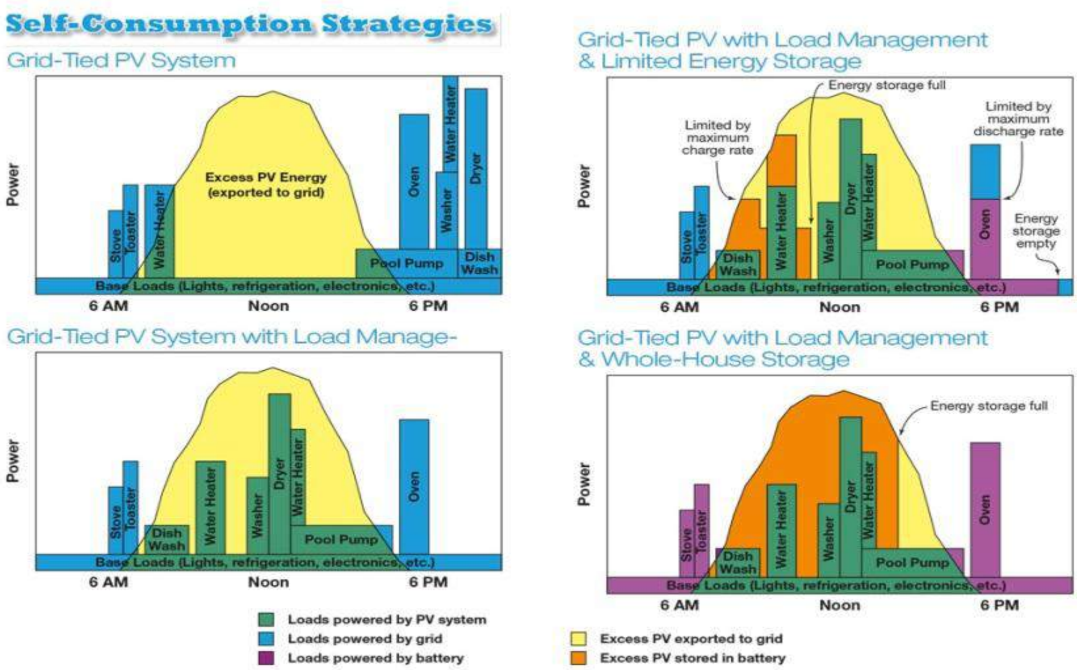


Fig. 4. Impact of energy storage on its effective consumption
Source: https://www.homepower.com/articles/solar-electricity/design-installation/maximizing-solar-self-consumption [access: 20 June 2018]

Role of advanced control systems and software for cooperation with alternative energy sources

In all hybrid solutions of this type, where we have to do with cooperation of several production sources, advanced software is a key. It may be located directly in the inverter in an independent, dedicated driver, which shall manage the operation of alternative sources, energy storage and receivers. Thanks to remote communication and information exchange with database weather systems, management software shall be able to effectively manage the energy flow between PV sources and other alternative sources and the receipt system, network and associated energy storage. Effectiveness of such a system depends on two basic factors: properly selected places to read data and properly implemented algorithms. For the user, transparent and simple user interface shall be very important.

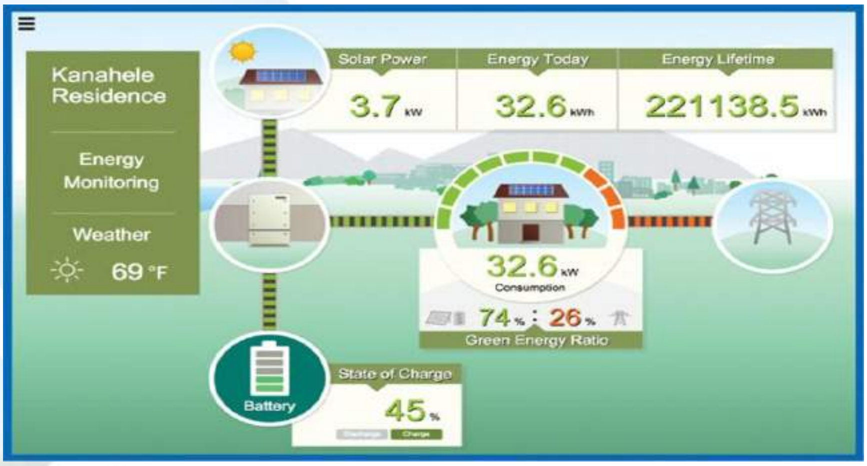


Fig. 5. Exemplary user interface
Source: http://www.laplacesolar.com/photovoltaic-products/solar-link-monitoring-solutions/ [access: 20 June 2018]

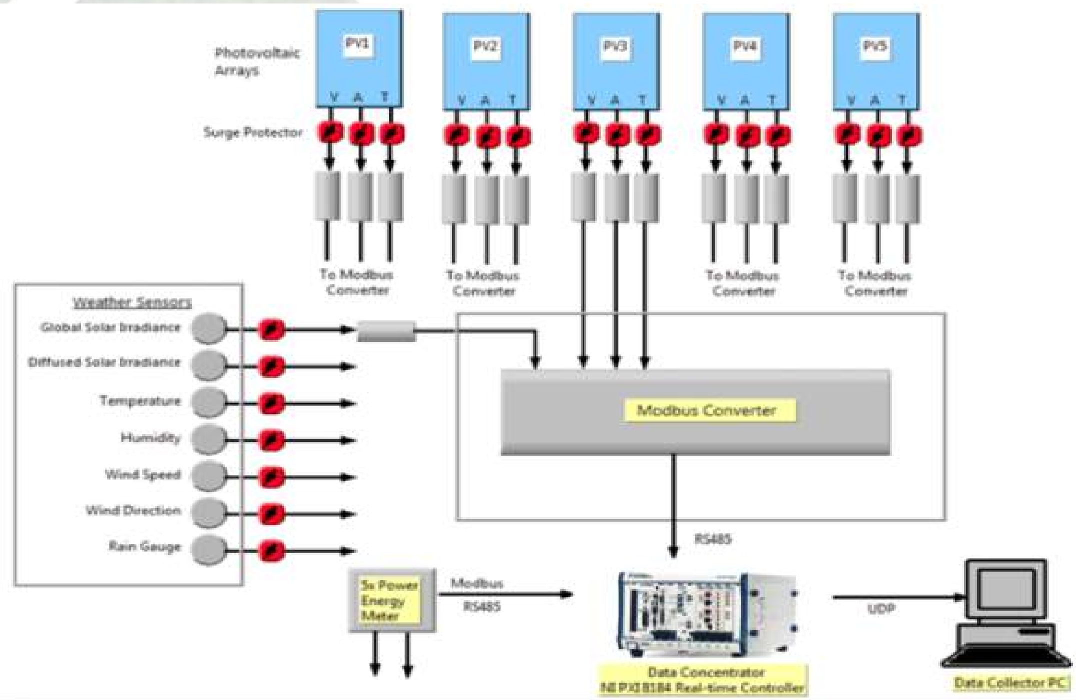


Fig. 6. Scheme of the installation parameter monitoring system
Source: http://sine.ni.com/cs/app/doc/p/id/cs-12744 [access: 20 June 2018]

5. EXERCISES

5.1. General issues. Basis for the use of photovoltaic systems – exercises

Exercise 1. *(to the topic 4.1)*
Tick the correct answer:
History of photovoltaics started in:
a) 1905
b) 1798
c) 1839
d) 1918

Exercise 2. *(to the topic 4.1)*
Assign a historical event to the date:

No.	Historical event		Date
1.	The first solar cell was built in Bell Laboratories in Murray Hill, USA, by researchers Chapin, Fuller and Pearson	a)	1976
2.	The first 108 cells were installed on the Vanguard satellite.	b)	1954
3.	The first solar cell was made from amorphous silicon by David Carlson and Chris Wronski.	c)	1958

Exercise 3. *(to the topic 4.1)*
Arrange countries according to the total installed PV power in 2017, decreasingly:
a) Japan
b) USA
c) China
d) Germany

No.	*Historical event*		*Date*
1.	*The first solar cell was built in Bell Laboratories in Murray Hill, USA, by researchers Chapin, Fuller and Pearson*	*a)*	*1958*
2.	*The first 108 cells were installed on the Vanguard satellite.*	*b)*	*1976*
3.	*The first solar cell was made from amorphous silicon by David Carlson and Chris Wronski.*	*c)*	*1954*

5.2. Photovoltaic cell – structure and operating principle – exercises

Exercise 1. *(to the topic 4.2)*
Connect symbols and definitions of PV parameters measured and calculated.

Power of PV modules measured in standard conditions (STC)	NOCT
Intensity of solar radiation (global) measured in the plane of PV generator modules	P_{MSTC}
Nominal operating temperature of modules	T_{amb}
Ambient (air) temperature	G_{POA}

Exercise 2. *(to the topic 4.2)*
Connect typical defects of the PV system with the method of their diagnosis.

Excessive heating up of PV modules, hot spots	DC power, AC power, internal inverter data logger
Breaks in DC chains (burnt fuses in DC boxes, damaged wires, connections, junction boxes of PV modules)	Visual inspection, thermal camera
Internal inverter failure (electronics, switches, firmware)	DC current in the chain (as compared to other chains)

5.3. Types of photovoltaic cells and modules – exercises

Exercise 1. *(to the topic 4.3)*
PV cell produces voltage of 0.5 V. Calculate voltage of four cells connected in series and tick the correct answer:

a) 2.0 V
b) 0.5 V
c) 2.5 V
d) 1.0 V

Exercise 2. *(to the topic 4.3)*
PV cell produces current of 0.6 A. Three cells were connected in parallel, calculate current flowing through load and tick the correct answer:

a) 2.0 A
b) 0.6 A
c) 1.8 A
d) 1.0 A

5.4. Types of photovoltaic systems – exercises

Exercise 1. *(to the topic 4.4)*
Connect beginnings and ends of sentences so that they are true

On-grid photovoltaic systems	are systems containing an additional source of energy allowing for generation of electrical energy when the PV source does not work
Off-grid photovoltaic systems	allow for the use of produced electrical energy to periodic power of the investor's receiving installation
PV systems equipped with batteries	are systems intended for cooperation with the electrical grid
Hybrid PV systems	are systems allowing for electrical energy storage
PV systems partially satisfying one's own requirements	are systems allowing for autonomous power of receivers

Exercise 2. *(to the topic 4.4)*

Complete sentences with words from the frame.

1. .... are installations assembled on existing building elements, such as roofs, skylights, facades, balconies, shelters, etc.
2. .... systems consist in the replacement of standard building materials such as roof tiles, windows, balcony barriers, skylights, with properly prepared photovoltaic modules.

HDMI	BAPV	SEE	BIPV

Exercise 3. *(to the topic 4.4)*

From the group of parameters, select four describing energy storages

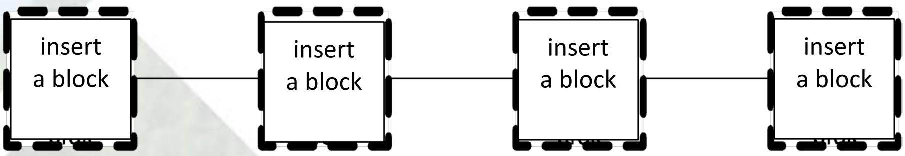
Energy storage should be characterised with the following parameters:

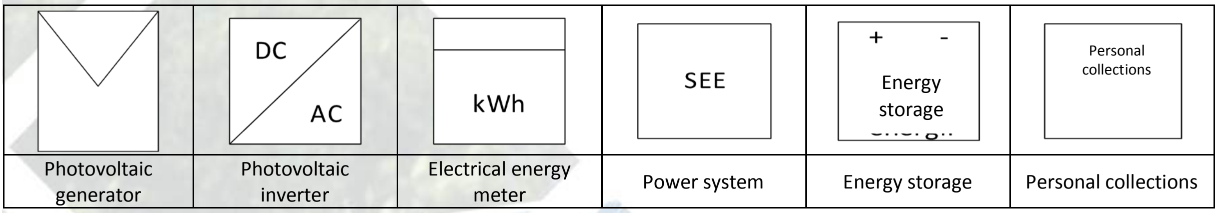
1. ....
2. ....
3. ....
4. ....

galvanic isolation	capacity	voltage frequency	absorptivity
maximum output current	lifetime	rated voltage	short-circuit current

Exercise 4. *(to the topic 4.4)*

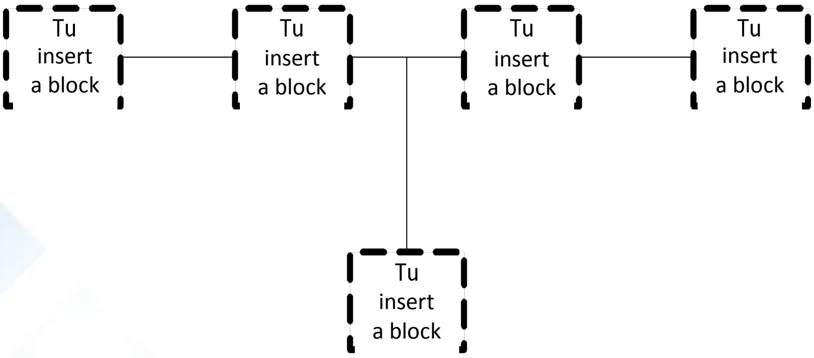
Draw a block diagram of a simple photovoltaic system connected to the electrical grid and operating only on the electrical grid.





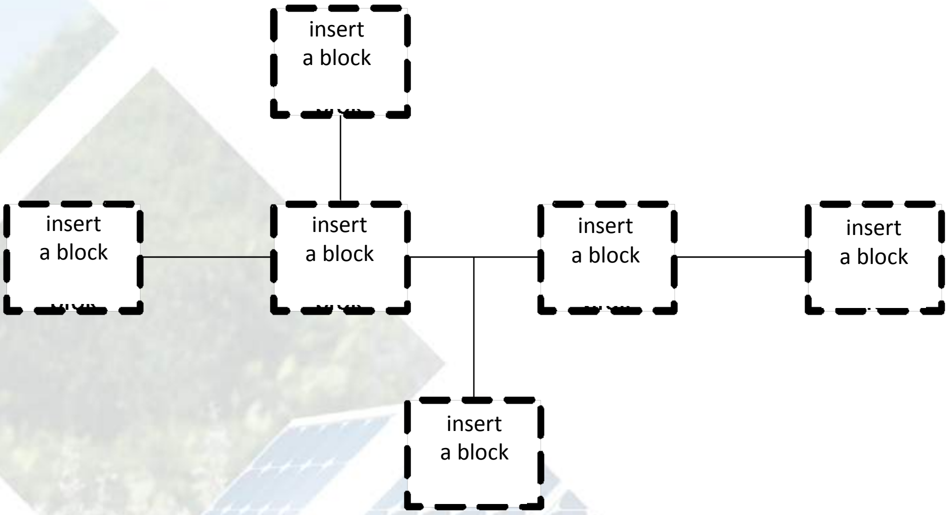
Exercise 5. *(to the topic 4.4)*

Draw a block diagram of a photovoltaic system connected to the electrical grid allowing for partial satisfaction of one's own requirements.



	DC AC	kWh	SEE	+ - Energy storage	Personal collections
Photovoltaic generator	Photovoltaic inverter	Electrical energy meter	Power system	Energy storage	Personal collections

Exercise 6. *(to the topic 4.4)*
Draw a block diagram of a photovoltaic system connected to the electrical grid allowing for partial satisfaction of one's own requirements, equipped with electrical energy storage.



	DC AC	kWh	SEE	+ - Energy storage	Personal collections
Photovoltaic generator	Photovoltaic inverter	Electrical energy meter	Power system	Energy storage	Personal collections

5.5. Elements and devices of photovoltaic installation – exercises

Exercise 1. *(to the topic 4.5)*
Connect names of elements of the photovoltaic system with a correct description.

Basic element of the PV system that produces electrical energy in the conditions of exposure to light such as solar radiation	PV chain
The smallest, fully protected against environmental impact set of interconnected PV cells	PV cell
Circuit in which PV modules are connected in series in order to produce required output voltage	PV module
Mechanically and electrically integrated set of PV modules and other necessary elements that create a unit supplying with direct current	PV generator
Set of PV collectors	PV inverter
Device converting DC voltage and current to AC voltage and current	PV collector

Exercise 2. *(to the topic 4.5)*
Connect beginnings and ends of sentences so that they are true.

Grid inverter	allows for power supply of electrical receivers in places where the electrical grid is inaccessible grid.
Islanding inverter	may supply electrical receivers regardless of accessibility of the electrical grid and allows for cooperation with the electrical grid, if available.
Hybrid inverter	may be connected directly to the electrical.

Grid inverter	*may be connected directly to the electrical grid*
Islanding inverter	*allows for power supply of electrical receivers in places where the electrical grid is inaccessible*
Hybrid inverter	*may supply electrical receivers regardless of accessibility of the electrical grid and allows for cooperation with the electrical grid, if available.*

5.6. Selection of technical solutions – exercises

Exercise 1. *(to the topic 4.6)*
Complete sentence with word from the frame.
Still photovoltaic systems generate the highest energy yield when the photovoltaic generator is oriented towards ...

west	east	north	south

Exercise 2. *(to the topic 4.6)*
Complete sentence with word from the frame.
While planning the arrangement of photovoltaic modules, it should be kept in mind that overshadowing of a part of module or several modules .... of the photovoltaic installation.

does not affect performance	increases performance	reduces performance	improves operation

Exercise 3. *(to the topic 4.6)*
Complete sentence with word from the frame.
Power of the photovoltaic installation should be ... than connection power in the facility.

larger	smaller	much larger	does not matter

Exercise 4. *(to the topic 4.6)*
Cross out an item that does not suit the rest:
Division of assembly systems of photovoltaic modules:
- Roof assembly systems
- Assembly systems integrated with the building
- Hybrid photovoltaic systems
- Free-standing assembly systems
- Mobile assembly systems

Exercise 5. *(to the topic 4.6)*
Complete sentence with word from the frame.
Assembly systems of photovoltaic modules should ensure proper resistance to ...

operation of insects	tearing	operation of stray voltage	atmospheric conditions, in particular gusts of wind

5.7. Energy profile of consumers – exercises

Exercise 1. *(to the topic 4.7)*
Complete sentence with word from the frame.
The client's energy profile is .... in a given time.

power consumed by device	distribution of external temperatures	distribution of demand for electricity	power generated in the photovoltaic installation

Exercise 2. *(to the topic 4.7)*
Among the mentioned factors, select those that affect weekly variability of the client's demand for electricity.

	Factors affecting weekly variability of the client's demand for electricity
Working days	
Seasons of the year	
Cyclicality related to sunrise and sunset	
Days off – Saturday, Sunday	
Changing atmospheric conditions	

Exercise 3. *(to the topic 4.7)*
Cross out an item that does not suit the rest:
Among periods of variability of the demand for electricity, there may be distinguished:
- daily variability,
- weekly variability,
- annual variability,
- fixed variability.

5.8. PV system sizing – exercises

Exercise 1. *(to the topic 4.8)*
Complete sentence with word from the frame.
Voltage of the created photovoltaic chain should be ... maximum voltage of the MPPT system and simultaneously ... threshold voltage of the photovoltaic inverter.

calculated regardless of	higher than	equal to	lower than

Exercise 2. *(to the topic 4.8)*
Cross out an item that does not suit the rest:
The photovoltaic generator is composed of:
- photovoltaic modules,
- photovoltaic chains,
- photovoltaic collectors,
- photovoltaic inverters.

Exercise 3. *(to the topic 4.8)*
Complete sentence with word from the frame.
At the connection of photovoltaic modules in series, ... of the photovoltaic chain increases.

total voltage	total current	temperature	Risk of damage

Exercise 4. *(to the topic 4.8)*
Complete sentence with word from the frame.
At the parallel connection of photovoltaic modules, ... of the photovoltaic chain increases.

temperature	total voltage	total current	risk of damage

Exercise 5. *(to the topic 4.8)*
Calculate the maximum number of photovoltaic modules that may be connected to the photovoltaic inverter's input for the below data, with consideration of the module's lowest temperature at the level of -20°C.

Data of the photovoltaic module

Parameter	Value
Power rating	270 Wp
Short-circuit current	9.15 A
Voltage of an unloaded module	38.25 V
Rated current	8.65 A
Rated voltage	31.25 V
Temperature current coefficient	0.049 %/°C
Temperature voltage coefficient	-0.30 %/°C

Data of the photovoltaic inverter

Input data	
Maximum input current	16.0 A / 16.0 A
Maximum short-circuit current, module field	24.0 A / 24.0 A
Minimal input voltage	150 V
Work start voltage	200 V
Rated input voltage	595 V
Maximum input voltage	1000 V
Scope of MPP voltage	267-800 V

Exercise 6. *(to the topic 4.8)*
Calculate the minimal number of photovoltaic modules that may be connected to the photovoltaic inverter's input for the below data, with consideration of the module's highest temperature at the level of 70°C.

Data of the photovoltaic module

Parameter	Value
Power rating	270 Wp
Short-circuit current	9.15 A
Voltage of an unloaded module	38.25 V
Rated current	8.65 A
Rated voltage	31.25 V
Temperature current coefficient	0.049 %/°C
Temperature voltage coefficient	-0.30 %/°C

Data of the photovoltaic inverter

Input data	
Maximum input current	16.0 A / 16.0 A
Maximum short-circuit current, module field	24.0 A / 24.0 A
Minimal input voltage	150 V
Work start voltage	200 V
Rated input voltage	595 V
Maximum input voltage	1000 V
Scope of MPP voltage	267-800 V

Exercise 7. *(to the topic 4.8)*
Calculate the maximum number of photovoltaic chains that may be in parallel connected with the photovoltaic inverter's input for the below data, with consideration of the module's highest temperature at the level of 70°C.

Data of the photovoltaic module

Parameter	Value
Power rating	270 Wp
Short-circuit current	9.15 A
Voltage of an unloaded module	38.25 V
Rated current	8.65 A
Rated voltage	31.25 V
Temperature current coefficient	0.049 %/°C
Temperature voltage coefficient	-0.30 %/°C

Data of the photovoltaic inverter

Input data	
Maximum input current	16.0 A / 16.0 A
Maximum short-circuit current, module field	24.0 A / 24.0 A
Minimal input voltage	150 V
Work start voltage	200 V
Rated input voltage	595 V
Maximum input voltage	1000 V
Scope of MPP voltage	267-800 V

5.9. PV system – connection to the grid – exercises

Exercise 1. *(to the topic 4.9)*
Complete sentence with word from the frame.
Photovoltaic installation is equipped with the inverter without a transformer. What type of residual current circuit breaker should be applied?

A	AC	B	D

Exercise 2. *(to the topic 4.9)*
Cross out an item that does not suit the rest:
Protection of the photovoltaic installation on the AC side consists in the selection of the following protection types:
– Residual current circuit breaker,
– Surge protection,
– Overcurrent protection,
– Undervoltage protection.

Exercise 3. *(to the topic 4.9)*

In the photovoltaic generator, 4 identical photovoltaic chains are connected in parallel. Using the provided range of overcurrent links with the gPV description, select an appropriate protective link to the photovoltaic chain, which maximum short-circuit current $_{SC}$=10.62 A, and maximum chain voltage U_{DCmax}=650V.

Range of protective links

Answer	Rated current of the protective link I_{zabDC} [A]	Operating voltage of the protective link [V]
1	6	700
2	8	700
3	10	700
4	12	700
5	16	700
6	20	700
7	25	700
8	6	900
9	8	900
10	10	900
11	12	900
12	16	900
13	20	900
14	25	900

5.10. Standards and technical specifications connected with a thematic group – exercises

Exercise 1. *(to the topic 4.10)*

Select proper sentence end from the table:

Microinstallation is:

a renewable energy source of total installed electrical power not exceeding 10 kW, connected to the electrical grid of rated voltage lower than 6 kV or with total installed thermal power not exceeding 12 kW
a renewable energy source of total installed electrical power not exceeding 50 kW, connected to the electrical grid of rated voltage lower than 110 kV or with total installed thermal power not exceeding 120 kW
a renewable energy source of total installed electrical power not exceeding 100 kW, connected to the electrical grid of rated voltage lower than 110 kV or with total installed thermal power not exceeding 120 kW

Exercise 2. *(to the topic 4.10)*

Cross out an item that does not suit the rest:

President of the Energy Regulatory Authority withdraws an issued certificate of the RES installation installer:

a) if the Installer uses the certificate contrary to its scope.
b) if there is proven evidence that a microinstallation or small installation is assembled contrary to valid regulations.
c) if the company in which the certified installer works did not discharged its contract with the investor within the scope of construction of the photovoltaic installation.

4.11. Factors affecting work productivity – exercises

Exercise 1. *(to the topic 4.11)*
Among the mentioned factors, select those that affect weekly energy efficiency of the photovoltaic installation.

	Factors affecting weekly energy efficiency of the photovoltaic installation
Good technical condition of electrical loads	
Efficiency of photovoltaic inverters	
Rate for produced kWh	
Losses on DC cables	
Arrangement of photovoltaic modules	
Regular maintenance of the photovoltaic installation	
Losses on AC cables	
Provisions of an agreement with the distribution network's operator	
Efficiency of photovoltaic modules	

Exercise 2. *(to the topic 4.11)*
Cross out an item that does not suit the rest:
Activities constituting the maintenance of photovoltaic systems include:
- regular clearing of photovoltaic modules.
- proper selection of photovoltaic modules to the photovoltaic inverter.
- control of the condition of the photovoltaic inverter's ventilation system.
- control of the condition of cables included in the photovoltaic installation.

4.12. Cooperation of the photovoltaic installation with alternative energy sources – exercises

Exercise 1. *(to the topic 4.12)*
Complete sentence with word from the frame.
In case of connection of a wind power plant and a photovoltaic power plant, there is developed the ... system.

uneconomic	complementary	reducing availability of electrical energy	preventing from cooperation of electrical energy sources

Exercise 2. *(to the topic 4.12)*
Cross out an item that does not suit the rest:
Cooperation of two or more types of electrical energy sources:
- is possible,
- increases availability of electrical energy for the end user,
- increases stability of electrical energy supplies,
- is illegitimate.

Exercise 3. *(to the topic 4.12)*
Complete sentence with word from the frame.
Management and control of operation of many energy sources in the RES system is allowed by ...

dedicated control and management system	appropriate selection of a number of PV modules to the PV inverter power	application of a wind power plant	hiring at least five employees

6. PROGRESS TEST

Can you:	Yes	No
1) Explain the concept of carbon footprint?		
2) List at least six advantages of photovoltaics?		
3) Describe the history of photovoltaics?		
4) Discuss the perspectives of photovoltaics?		
5) Explain the concept of qualitative factor of the PV system?		
6) List at least six measured parameters of the PV system?		
7) Discuss the quality of electrical energy released to the network?		
8) Discuss the validity of measurement of module temperature?		
9) Explain the concept of "hot spots"?		
10) List phases of the production process of the crystalline photovoltaic photocell?		
11) Discuss the photovoltaic module's cross-section?		
12) Discuss connection of modules in series?		
13) List basic elements of the islanding photovoltaic system?		
14) List basic elements of the hybrid photovoltaic system?		
15) List basic elements of the grid photovoltaic system?		
16) Discuss functions that should be performed by the photovoltaic inverter?		
17) Indicate differences between the islanding and grid inverter?		
18) Explain a difference between the photovoltaic system ON-GRID and OFF-GRID?		
19) List types of photovoltaic systems?		
20) Discuss the principle of operation of the photovoltaic system cooperating with the electrical grid?		
21) Discuss the principle of operation of the autonomous photovoltaic system?		
22) Indicate main elements of the OFF-GRID system?		
23) List basic elements of the islanding photovoltaic system?		
24) List basic elements of the hybrid photovoltaic system?		
25) List basic elements of the grid photovoltaic system?		
26) Discuss functions that should be performed by the photovoltaic inverter?		
27) Indicate differences between the islanding and grid inverter?		
28) Explain the need for avoidance of overshadowing at planning of arrangement of photovoltaic modules?		
29) List types of assembly systems?		
30) Discuss basic types of assembly systems applied for the installation of photovoltaic modules?		
31) Discuss the principles of arrangement of photovoltaic modules?		
32) Indicate issues that should be considered at planning of arrangement of photovoltaic modules?		
33) Explain what daily load variability consists in?		
34) List types of variability of the demand for electricity due to the analysed period?		
35) Discuss indicators characterising variability of the client's load?		
36) Discuss energy profiles of selected receivers?		
37) Indicate factors affecting formation of weekly demand for electricity?		

38) Explain the principle of selection of the photovoltaic installation protections?		
39) List types of protections applied in photovoltaic installations?		
40) Discuss the method of selection of surge protections?		
41) Discuss the method of selection of overcurrent protections on the AC and DC side?		
42) Indicate security functions in grid inverters?		
43) Discuss the information obligations of OSD to the President of the Energy Regulatory Authority?		
44) List reasons for withdrawal of the Installer's certificate?		
45) Discuss the support system for RES energy producers?		
46) Discuss the method of selection of overcurrent protections on the AC and DC side?		
47) Define a small installation?		
48) Define typical values of efficiency of photovoltaic inverters?		
49) List factors affecting performance of the photovoltaic installation?		
50) Discuss the selection of a tilt angle of photovoltaic modules?		
51) Discuss the selection of energy storage to the photovoltaic installation?		
52) Indicate activities related to the maintenance of photovoltaic modules?		
53) Explain the principle of cooperation of two sources of electrical energy?		
54) List sources of electrical energy that may cooperate with the photovoltaic installation?		
55) Discuss the role of control systems applied in installations of renewable energy sources?		
56) Discuss the impact of energy storage in installations containing two or more sources of electrical energy?		
57) Indicate advantages and disadvantages of cooperation of two sources of electrical energy?		

If you selected the answer "NO", we propose you returning to the teaching material and its repeated analysis in order to achieve intended learning outcomes (knowledge, skills).
If necessary, use additional source of information prepared to each topic.

7. GLOSSARY

English
Amorphous semiconductor
Array
Azimuth
Balance-of-system (BOS)
Battery
BIPV (Building Integrated Photovoltaics)
Blocking Diode
Bypass diode
Conversion Efficiency
Crystalline silicon cells
Current-voltage
Depth of discharge
Diffuse Irradiance
Energy Pay-Back Time
Equivalent carbon dioxide
Feasibility Study
Feed-in-Tariff
Filling Factor
Gallium Arsenide (GaAs)
Global Horizontal Irradiance
Global In-Plane Irradiance
Grid-connected system
Hot spot
Hybrid System
Ingot
Internal Rate of Return
Inverter

English
Irradiance
Junction Box
Learning Curve
Life Cycle Analysis
Mismatch losses
MPP Regulator
Open circuit voltage
Peak (Maximum) Power Point (MPP)
Peak Sun hours
Performance ratio
PV effect
PV Module
Pyrometer
Quality management system
Semiconductor
Silicon
Solar spectrum
Stand-alone PV system
Standard test conditions (STC)
String
Tracking system
Voltage
Wafer

8. LITERATURE

1. Goetzberger A., Voß B., Knobloch J.: *Sonnenenergie: Photovoltaik*. Teubner Studienbücher, Stuttgart, Germany, 1994.
2. Goetzberger A., Wittwer V.: *Sonnenenergie – Physikalische Grundlagen und thermische Anwendungen.* Teubner Studienbücher, Stuttgart, Germany, 1996.
3. Benz J., Ortiz B., Roth W., Sauer D.U., Steinhüser A.: *Fuel Cells in Photovoltaik Hybrid Systems for Stand-Alone Power Supplies*. Proceedings 2nd European PV-Hybrid and Mini-Grid Conference, Kassel, Germany, 2003.
4. Roth W., Schmidt H., Schulz W., Steinhüser A.: *Photovoltaic Power Supply for Telecommunication Network Components in Remote Areas*. Proceeedings TELESCON 2000, Dresden, Germany, 2000.
5. Palz W.: *Power for the world – a global photovoltaic action plan*. Solar Europe Newsletter, Kommission der Europäischen Gemeinschaften, DG XII, 1993.
6. Schweizer P., Shresta J.N.: *What can solar electricity provide for the Himalayan society? The case of Nepal.* 13th European Photovoltaic Solar Energy Conference, Nice, France, 1995.
7. *Successful User Schemes for Photovoltaic Stand-Alone Systems*. European Commision DG XVII, 2000.
8. *EPIA Global Market Outlook for Photovoltaics 2014-2018 (June 2014).*
9. *PVPS Report Snapshot of Global PV 1992–2013. Report IEA-PVPS T1-24:2014.*

Electronic sources

1. http://aberdeensolar.com/solar-pv/home-suitable
2. http://alternateenergycompany.com/how-solar-pv-panels-works-with-the-grid
3. http://energyinformative.org/wp-content/uploads/2012/05/off-grid-solar-system.png
4. http://gramwzielone.pl/energia-sloneczna/17916/czyszczenie-instalacji-fotowoltaicznej-zwiekszy-jej-wydajnosc
5. http://sine.ni.com/cs/app/doc/p/id/cs-12744
6. http://thatpowerguy.nz/solar/solar-power-system-size
7. http://www.alternative-energy-tutorials.com/solar-power/pv-panel.html
8. http://www.freesolarpanelsuk.co.uk/the-best-angle-and-orientation-for-solar-panels-in-the-uk.php
9. http://www.greenrhinoenergy.com/solar/performance/shading.php
10. http://www.instsani.pl/519/system-montazu-dla-dachu-pokrytego-dachowka-ceramiczna
11. http://www.iparu.com/dual-axis-tracker-pst-2a
12. http://www.laplacesolar.com/photovoltaic-products/solar-link-monitoring-solutions/
13. http://www.nuvisionenergy.co.uk/
14. http://www.photon-solar.eu/
15. http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0365-05962015000300297
16. http://www.studymumbai.com/renewable-energy-resources.html
17. http://www.thesolarplanner.com/array_plaement.html
18. http://www.twojaenergia.pl/poradnik
19. https://ars.els-cdn.com/content/image/1-s2.0-S2214398X14000120-gr1.jpg
20. https://cen.acs.org/energy/solar-power/Perovskite-progress-pushes-tandem-solar/96/i24

21. https://energymag.net/daily-energy-demand-curve
22. https://greenpowerworksinc.com/energy-efficiency-for-residential
23. https://news.energysage.com/is-my-roof-even-suitable-for-solar
24. https://news.energysage.com/solar-panels-work-shade/
25. https://pveducation.org/pvcdrom/manufacturing/single-crystalline-silicon
26. https://solarips.com/2016/02/like-a-sunflower-solar-pv-panels-track-the-sun/
27. https://www.ecosoch.com/types-of-solar-on-grid-inverters-micro-string-central-2/
28. https://www.e-education.psu.edu/eme812/node/738
29. https://www.energy.gov/energysaver/buying-and-making-electricity/hybrid-wind-and-solar-electric-systems
30. https://www.homepower.com/articles/solar-electricity/design-installation/maximizing-solar-self-consumption
31. https://www.homepower.com/articles/solar-electricity/design-installation/energy-basics-shading-and-solar-electric-systems
32. https://www.indiamart.com/proddetail/aluminium-solar-mounting-structure-10795911762.html
33. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf
34. https://www.leoni-solar-windpower.com/en/products-services/generator-combiner-boxes/general-information/
35. https://www.met.hu/en/eghajlat/magyarorszag_eghajlata/altalanos_eghajlati_jellemzes/sugarzas
36. https://www.powersystemsdesign.com/articles/the-promise-of-solar-technology/28/6289
37. https://www.quora.com/How-does-off-grid-solar-plant-work
38. https://www.quora.com/Why-do-solar-panels-face-south
39. https://www.researchgate.net/figure/Mean-weekly-profile_fig1_313453567
40. https://www.sciencedirect.com/science/article/pii/S0378778814001224#fig0025
41. https://www.semanticscholar.org/paper/Design%2C-implementation-and-performance-analysis-of-Munna-Bhuyan/d143c1d713073ec0ada345f7b28ebdc7428b7c71/figure/0
42. https://www.semanticscholar.org/paper/Maximum-power-point-tracking-controller-using-P-and-Singh-Sarkar/89cc1255f020c31698fc6c90bc6d0872b523b39b/figure/1
43. https://www.solarpowerworldonline.com/2014/12/quick-run-bipv
44. https://www.solarquotes.com.au/blog/an-eastwest-spit-of-solar-panels-on-a-single-string-can-work-well/