Chapter 3

Photovoltaic conversion of solar energy

3.1. Brief history of photovoltaic technologies

The term “photovoltaic” is derived from the combination of the Greek word “photos” - meaning light, and the name of the electromotive force unit - volt. Thus, photovoltaic technology (PV) describes the generation of electricity using light. In 1839, during the industrial revolution, Alexander Edmond Becquerel, the father of Nobel laureate Henri Becquerel, discovered the photovoltaic effect, which explains how electricity can be generated from sunlight. He concluded that "illumination of an electrode immersed in a conductive solution would create an electric current”.

Despite extensive research, after this discovery, photovoltaic conversion continues to be ineffective. Photovoltaic cells were used mainly for measuring of light intensity proposals. The first report on photovoltaic or photoelectric effect, as it was called at that time, was done by Cambridge scientists W. Adams and R. Day in 1877. The report described changes that occurred in light-exposed selenium plate. In his experience, Heinrich Hertz noticed in 1887 that a zinc plate is loaded with positive charge when exposed to ultraviolet radiation. The phenomenon is due to the same photoelectric effect: the action of ultraviolet rays separates electrons from metal, as a result the metal is positively charged.

The first PV cell was built by an American electrician, Charles Fritts, in 1883 using selenium. Construction of the cell was patented in 1884 [1]. It should be noted that the construction of the cell was very similar to today's cells. However, cell efficiency was less than one percent and the industrial use has not been realized.

After about a century since the first discovery of the effect, Albert Einstein in 1921 received the Nobel Prize in physics for explaining the photoelectric effect that allowed the practical use of photovoltaic cells. In 1946, Russell Ohl invented the solar cell [2], followed by the invention of the transistor in 1947.

In the middle of XXth century scientists and engineers returned to the study of the photovoltaic effect, occurring in semiconductors. In 1953, a Telephone Laboratories (Bell Labs) team of engineers, D. Chapin, C. Fuller and G. Pearson, creates the silicon PV cell with a much higher efficiency than the selenium cell. The following year, the same team built a silicon cell with 6 % efficiency. At the same time, first consumers of photovoltaic energy - artificial satellites, have appeared. In 1957, PV cells were installed on the first artificial satellite of the earth "Sputnik 3", and in 1958 PV cells were installed aboard the U.S. satellite Vanguard 1 and served to power a radio transmitter. Until these days PV cells are the most suitable energy sources for space machinery. Competition between the USA and the former USSR in the ‘60s of last century in the field of sources for electricity supply of the satellites led to a spectacular development of PV technology and caused a breach in the rigid dependence of decentralized power from traditional sources: generator units, storage batteries or dry cell batteries. A new competition started - to bring PV generator back to earth. Governments of industrialized countries and many private companies have invested billions of dollars in the development of PV technology.

By using the photovoltaic effect direct conversion of sunlight into electricity occurs. Direct conversion technology excludes intermediate transformations: solar radiation to heat, heat to mechanical energy, and mechanical energy into AC power. Direct conversion is performed using semiconductor materials and the photovoltaic effect. Photovoltaic generator, the so-called photovoltaic cell, unlike the electromechanical generator produces DC electricity. Elimination of intermediate processing from the technological chain, lack of motion, noise and vibration, modular construction, a service life of over 25 years, are arguments in asserting that the future of decentralized energy shall belong to photovoltaic technology. Not accidentally, on 31 August 1991 The Economist magazine mentioned the following about the photovoltaic solar energy conversion: *"Of all alternative energy sources - wind, sea wave, tidal, geothermal - perhaps the most promising solar energy conversion into electricity is photovoltaic one".*

3.2. Photovoltaic cell and module technology

PV cells are generally made either from crystalline silicon, sliced from ingots or castings, from grown ribbons or thin film, deposited in thin layers on a low-cost backing. The performance of a solar cell is measured in terms of its efficiency at turning sunlight into electricity. A typical commercial solar cell has an efficiency of 15 % about one-sixth of the sunlight striking the cell generates electricity. Improving solar cell efficiencies while holding down the cost per cell is an important goal of the PV industry.

Crystalline silicon technology. Crystalline silicon cells are made from thin slices cut from a single crystal of silicon (monocrystalline) or from a block of silicon crystals (polycrystalline). The efficiencies of different PV technologies are presented in the table 3.1. This is the most common technology representing about 90 % of the market today. The

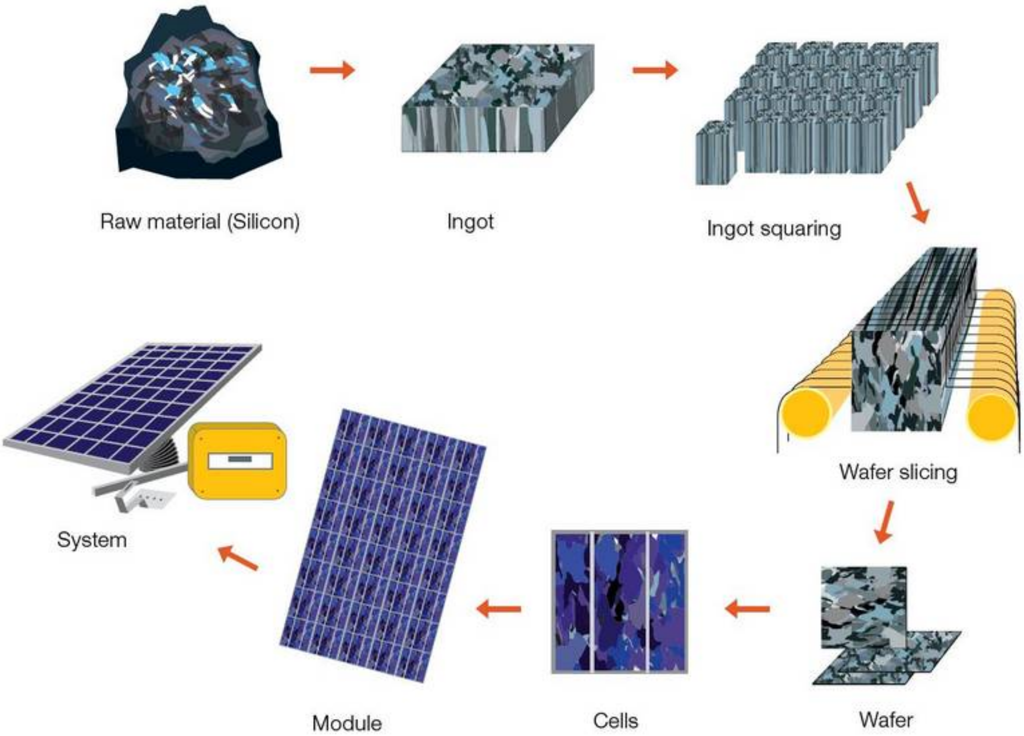


Fig. 3.1. PV sells and modules technological chain

technological chain of production of PV cells and modules from crystalline silicon is shown in fig. 3.1 [3]. Three main types of crystalline cells can be distinguished:

- Monocristalline (Mono c-Si) ;
- Polycristalline (multi c-Si) ;
- Ribbon sheets (ribbon-sheet c-Si).

Thin Film technology. Thin film modules are constructed by depositing extremely thin layers of photosensitive materials onto a low-cost backing such as glass, stainless steel or

Table 3.1. Commercial PV module efficiency [4]

Commercial module efficiency							
Technology	First generation: Crystalline silicon		Second generation: Thin film				Third generation: Concentrated PV
	Mono	Multi	a-Si	CdTe	GIS	a-Si/m-Si	CPV
Cell efficiency, %	16-22	14-18	5,4-7,7	9-12,5	7,3-12,5	7,5-9,8	30-38
Module efficiency, %	13-19,7	11-15					25
Area needed, m^2/kW	7,0	8,0	15,0	10,0	10,0	12,0	

plastic. Thin Film manufacturing processes result in lower production costs compared to the more material-intensive crystalline technology, a price advantage which is counterbalanced by lower efficiency rates (from 4% to 11%). However, this is an average value and all Thin Film technologies do not have the same efficiency. Four types of thin film modules (depending on the active material used) are commercially available at the moment:

- Amorphous silicon (a-Si);
- Cadmium telluride (CdTe);
- Copper Indium/gallium Diselenide/disulphide (CIS, CIGS);
- Multi junction cells (a-Si/m-Si).

Other cell types. There are several other types of photovoltaic technologies developed today starting to be commercialized or still at the research level, the main ones are:

1. Concentrated photovoltaic (CPV): some solar cells are designed to operate with concentrated sunlight. These cells are built into concentrating collectors that use a lens to focus the sunlight onto the cells. The main idea is to use very little of the expensive semiconducting PV material while collecting as much sunlight as possible. Efficiences are in the range of 20 to 30 %.

2. Flexible cells: Based on a similar production process to thin film cells, when the active material is deposited in a thin plastic, the cell can be flexible. This opens the range of applications, especially for building integration and end-consumer applications.

3.3. Photovoltaic cell: characteristics and technical parameters

Construction and operating principle. Fig. 3.2 shows a schematic diagram of the simplified design of PV cell, based on *p*-type semiconductor material. Consider the phenomena that occur when PV cell is exposed to incident radiation. This radiation can be

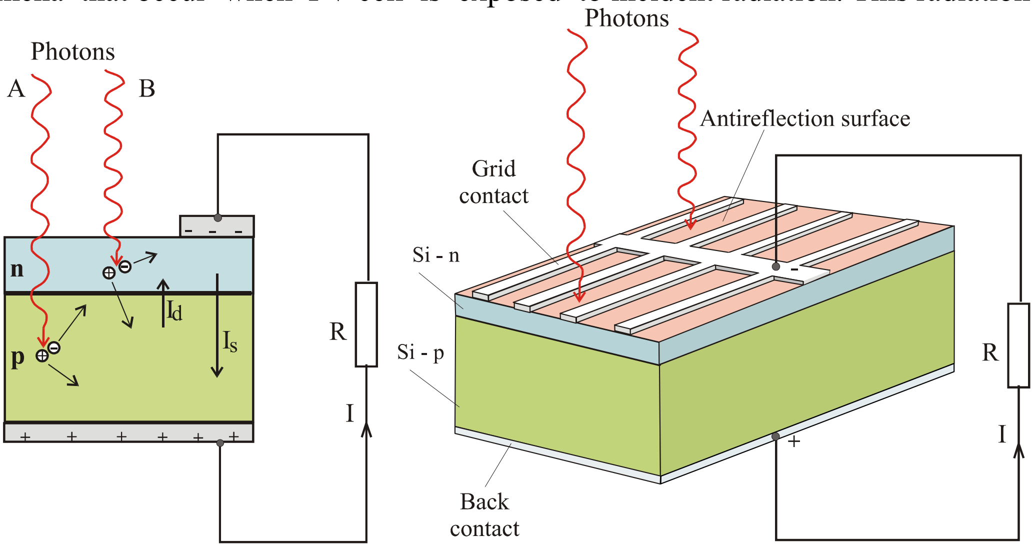


Fig. 3.2. Design diagram of photovoltaic cell.

equalized with a flux of photons, which have energy $E = hv$, where h is Planck's constant and v is photon frequency. If the photon energy is bigger than the energy of the semiconductor power forbidden band, then, from the photon interaction with an atom, the electron from the valence-bond band will pass into the conduction band, becoming free, and generating also in a gap in the valence-bond band. Thus, under the action of photons, generation of hole-electron pairs occurs. This is called internal photovoltaic effect. In fig. 3.2 on the left, the photon A has a lower frequency and therefore a lower energy, and photon B has a higher frequency and, correspondingly, a higher energy (low-frequency electromagnetic wave penetrates to large depths of the material and vice versa). Free charge carriers are separated from the electric field of the *p-n* junction, characterized by the barrier potential U_0 and which, depending on the type of semiconductor used, is about 0,2 - 0,7 V. Here, the electric field will serve as free load break switch – hole-electron pairs. The electrons will be directed to the n zones, the holes - to the cell p zone. This is why, under the influence of light, p zone is positively charged and zone n - negatively charged, which leads to an electric current through the external circuit, caused by photovoltaic conversion of solar radiation. This current (fig. 3.2 on the left), leads to a voltage drop U in the external load R connected to the rear contacts and to the front-grid contact (fig. 3.2 on the right). Voltage U compared to *p-n* junction acts against the direct sense and, in its turn, will determine via the junction the diode I_d current against the inverse direction of photovoltaic current I_s which is determined from the known expression:

$$I_d = I_0\left[exp\left(\frac{eU}{kT}\right) - 1\right], \tag{4.1}$$

where: I_0 is the saturation current strength; k – is Boltzmann's constant; T – absolute temperature; e – is the electron charge.

Photovoltaic cell characteristics. The main characteristics of PV cells are as follows: ampere-volt *I(U)* or volt–ampere *U(I)* characteristic and power characteristic *P(U)*. The current in the external circuit I is determined by the difference between photovoltaic current I_s and the diode current I_d [5-7]:

$$I = I_s - I_d = I_s - I_o\left[exp\left(\frac{eU}{kT}\right) - 1\right], \tag{4.2}$$

The simplified equivalent circuit of PV cell, shown in fig. 3.3 a, corresponds to equation (4.2). If we take into account the leak resistance R_i of the PV cell *p-n* junction and the cell base-spreading resistance R_s, a complete equivalent scheme of PV cell can be produced (fig. 3.3, b). Modern technologies help to obtain cells with $R_i = \infty$ and $R_s = 0$, so that the simplified equivalent circuit is satisfactory. Electrical power transferred to load R of a PV cell is:

$$P=UI=U\left\{I_s - I_o\left[exp\left(\frac{eU}{kT}\right)\right] - 1\right\}. \tag{4.3}$$

Maximum value of power is obtained at point M of the current-voltage characteristic, which coordinates are derived from the condition $dP/dU=0$:

$$U_M = U_0 - U_T\, ln\left(1 + \frac{U_M}{U_T}\right),$$
$$I_M = I_s\left(1 + \frac{I_0}{I_s}\right)\frac{U_M}{U_M + U_T}, \tag{4.4}$$

where $U_T = kT/e$.

For a passive load, the optimum value of load resistance is:

$$R_M = \frac{U_M}{I_M}. \tag{4.5}$$

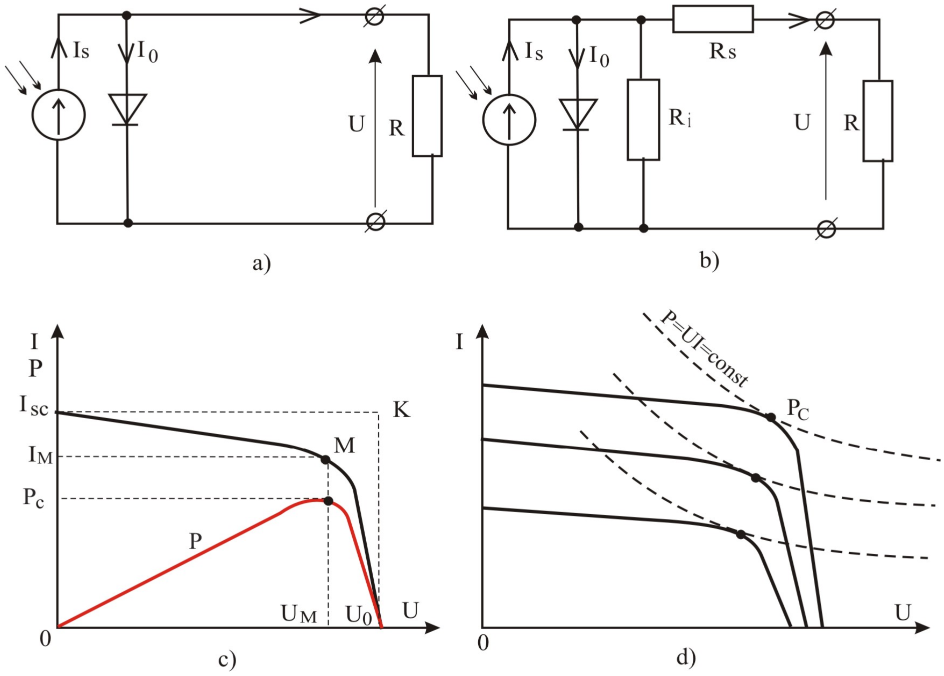


Fig. 3.3. Equivalent diagrams of PV cell: a – simplified; b – complete; c, d – cell characteristics

PV cells and modules parameters. Manufacturers of PV cells and modules show in the technical sheet of the product the technical parameters for standard conditions:

- Global solar radiation on the cell surface, G=1000 W/m^2;
- Cell temperature, T_C= 25^{0}C;
- Conventional air mass, AM=1,5.

It is compulsory that the technical sheet lists the following information: short circuit current, I_{sc}, Open circuit voltage, U_0, maximum or critical power, P_c, voltage and current in the critical point, U_M and I_M. Besides these parameters, additional indicators may be: the Fill Factor, FF, efficiency of PV cell or module, normal operating cell temperature NOCT, coefficients of variation of no-load voltage and short circuit current with the temperature.

Short circuit current. It occurs at shorting of load R terminals as shown in Fig. 3.3. On the I-U caracteristic this is the point with coordinates $U = 0$, $I = I_{sc}$. From the expression (4.2) for $U = 0$, we obtain $I_{sc} = I_s$. The output power is zero.

Open circuit voltage. Corresponds to the point on I-U characteristic with coordinates $I = 0$, $U = U_0$. The output power in this point is equal to zero. No-load voltage can be determined from (4.2) for $I = 0$:

$$U_0 = \frac{kT}{e} ln \frac{I_s + I_0}{I_0} \approx \frac{kT}{e} ln \frac{I_s}{I_0}. \tag{4.6}$$

For silicon cell the ratio I_s/I_0 is about 10^{10}, factor kT/e, called thermal voltage, is equal to 26 mV. Thus, U_0= 0,6 V.

Critical or maximum power. It is the product of current and voltage in point M of I-V characteristic. This parameter is called the peak power and is noted by P_C .

$$P_C = U_M \cdot I_M . \tag{4.7}$$

Geometrically, critical power P_C meets the tangent points of hyperbolas $P = UI$ = const. for the ampere – volt I-U characteristics (see fig. 3.3, d).

Fill Factor is determined as the report between the surfaces of rectangles OU_MMI_M and OU_0KI_{sc} (fig. 3.3, c) or

$$FF = \frac{U_M I_M}{U_0 I_{sc}}, \quad (4.8)$$

and critical power is

$$P_C = FF \cdot U_0 \cdot I_{sc}. \quad (4.9)$$

Fill factor is the measure of the PV cell quality. The lower internal resistance R_s of PV cell the bigger *FF*. Usually *FF* > 0,7.

Efficiency of PV cell or module is determined with the ratio between the generated power of the PV cell or module in the optimum operating point *M* for a specified temperature and the solar radiation power

$$\eta = \frac{P_C}{A \cdot G}, \quad (4.10)$$

where P_C is the delivered power in W; *A* is the surface of cell or module in m^2; *G* – global radiation incident on the cell or module surface in W/m^2. A PV module with an efficiency of 14 % and with the surface area of 1 m^2, exposed to solar radiation equal to 1000 W/m^2 will produce approximately 140 W.

Normal operating cell temperature corresponds to the temperature of PV cell in no-load operation conditions at the environment temperature of 20 ^{0}C, global radiation of 800 W/m^2 and wind speed smaller that 1 m/s. For usual cells *NOCT* parameter is between 42 and 46^{0}C. If *NOCT* parameter is known, it is possible to determine the cell temperature T_C for other operating conditions characterized by the environment temperature T_A and global radiation *G* [7]:

$$T_C = T_A + \left(\frac{NOCT - 20}{0{,}8} \right) \cdot G. \quad (4.11)$$

3.4. The influence of solar radiation and temperature on the characteristics of PV cells and modules

PV cell characteristic for different solar radiation values are presented in fig. 3.4, a. It is noted that the short circuit current is directly proportional to solar radiation and no-load

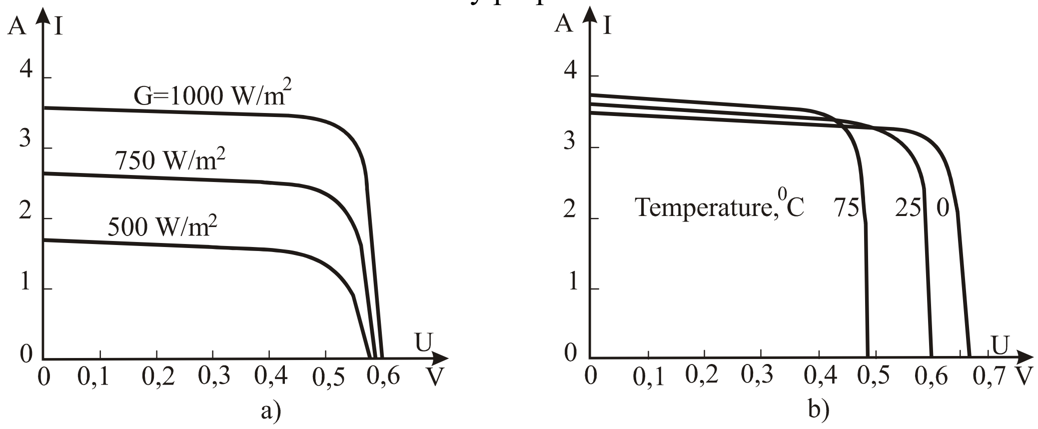


Fig. 3.4. PV cell characteristics at variation of solar radiation (a) and temperature (b).

voltage is varying a little, since according to (4.6), voltage U_0 depends logarithmically on solar radiation and often in practical calculations this variation is neglected. Short-circuit current, for different values of solar radiation G, can be determined with a satisfactory approximation of the formula:

$$I_{sc} = \frac{G}{G_{st}} \cdot I_{scst}, \quad (4.12)$$

where I_{scst} is the cell short circuit current corresponding to the standard radiation G_{st}=1000 W/m^2. PV cell temperature significantly influences the open circuit voltage and less - short-circuit current (see fig. 3.4, b). With increasing temperature, open circuit voltage decreases. For silicon cells the voltage variation coefficient of temperature K_T is equal to 3,6 mV/^{0}C [6]. Thus, the parameter U_0 for the temperature different from the standard is calculated by following equation:

$$U_0 = U_{025} - K_T(t - 25), \qquad (4.13)$$

where U_{025} is the PV cell open circuit voltage corresponding to the standard temperature; t – temperature of the cell, ^{0}C. In the design calculations variation of short circuit current and of the filling factor *FF* depending on the temperature is neglected.

3.5. Photovoltaic modules

Modern photovoltaic cells produce electrical energy which does not exceed 1,5 to 3 W power at voltages from 0,5 to 0,6 V. To obtain voltage and power necessary for the consumer, PV cells are connected in series and/or parallel. The smallest photoelectric generator, consisting of PV cells connected in series and / or parallel and encapsulated to obtain greater strength and protect cells from environmental action, is called photovoltaic module. A number of PV modules assembled mechanically as one larger unit and electrically connected is called panel or field of modules. In accordance with the standards of the International Electrotechnical Commission (IEC) the term “array” is used, which means system or network. The terms “photovoltaic module”, “photovoltaic panel” or “field of modules” very often have the same meaning. When designing PV modules take into account the frequent use of PV modules for charging electric batteries, whose voltage is 12 to 12,5 V. Thus, in standard radiation conditions, voltage U_M must be 16 to 18 V, and open circuit voltage - 20 to 22,5 V. A single cell generates in open circuit approximately 0,6 V and it is necessary to connect 33-36 cells in series to obtain the necessary voltage. PV module construction (fig. 3.5, a is usually rectangular. The support is made of anodized aluminum and separated from the cell laminated structure by lining that prevents moisture intrusion. PV cells are protected from unfavorable conditions impact that may occur during operation: rain, hail, snow, dust, etc.., by a system which consists of a layer of glass and at least two layers (front and rear) of ethylene vinyl acetate EVA or PVB Polyvinyl butyral (fig. 3.5, b).

Fig. 3.6 shows PV modules of various powers, manufactured by Kyocera Company, and in table 3.2 – their basic characteristics [8].

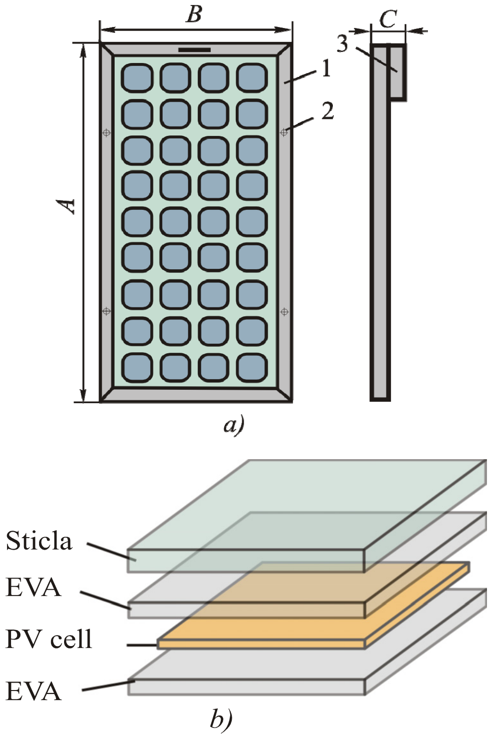


Fig. 3.5. Design of PV module (a) and PV cell package (b): 1 – support; 2 – panel assembly holes; 3 – terminal box.

To obtain the necessary voltage and power for the consumer of electrical energy, PV modules can be connected in series, parallel or in series-parallel (see fig. 3.7 a, b, c). At series connection of two identical PV modules the current delivered to the consumer remains the same, and voltage increases twice. In fig. 3.7 a, *PV1* and *PV2* modules connected in series charge *GB* storage battery. Operating point of the system “PV modules-GB” is the point of

Fig. 3.6. PV module manufactured by Kyocera, Japan [8].

Table 3.2. Electrical performance at 1000 W/m^2 [8]

PV module type	KD140GH	KD240GH	KD320GH
Maximum power, W	140	240	320
Maximum power voltage, V	17,7	29,8	40,1
Maximum power current, A	7,91	8,06	7,99
Open circuit voltage, V	22,1	36,9	49,5
Short circuit Current, A	8,68	8,59	8,60
Efficiency, %	13,9	14,5	14,5

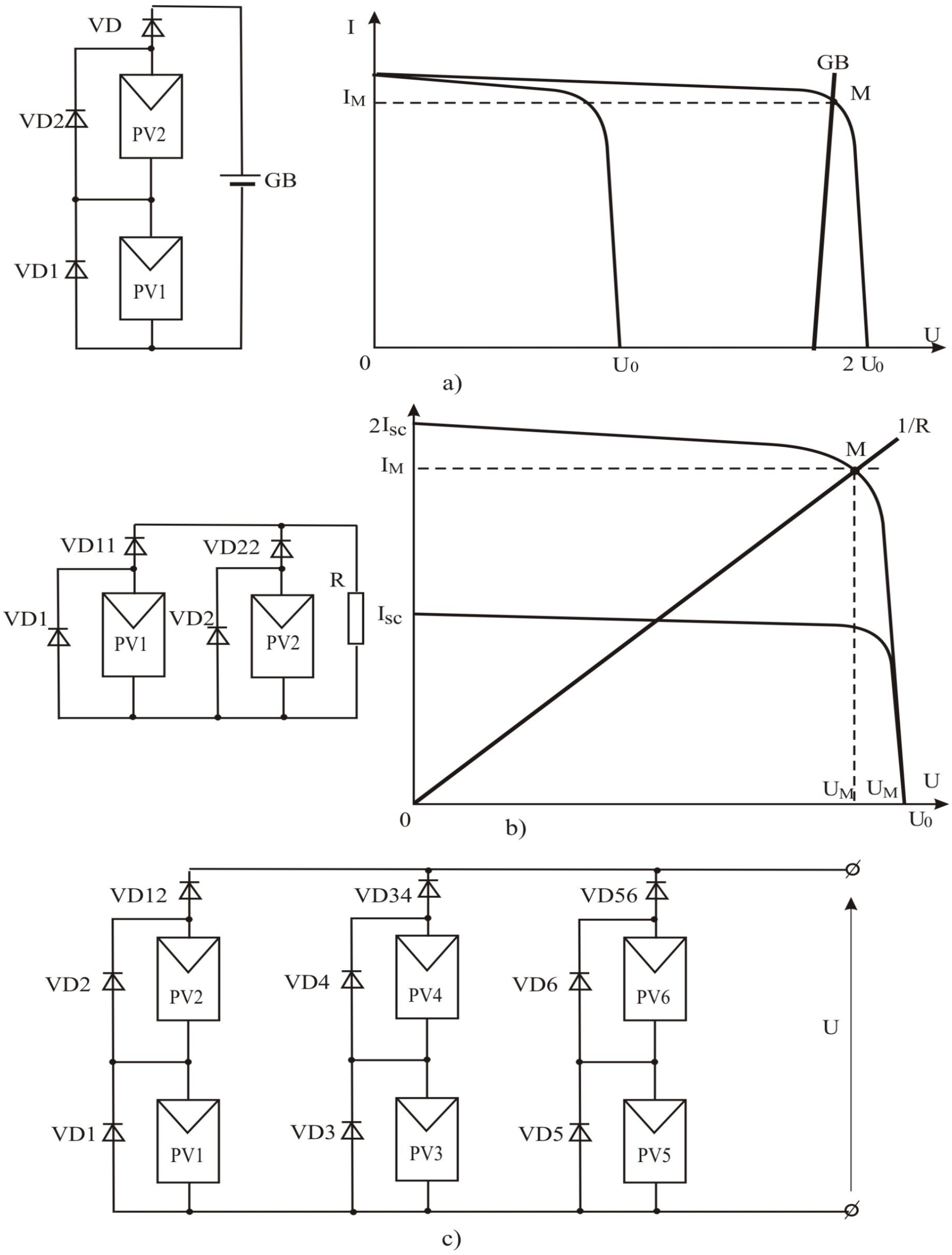


Fig. 3.7. PV modules interconnection: a – in series; b – in parallel; c – in series–parallel.

intersection *M* of these characteristics: two modules connected in series and a storage battery. Diodes *VD1* and *VD2*, called bypass diodes or bypass connects in parallel with each module or group of modules connected in parallel (see fig. 3.7, a). Bypass diode limits the reverse voltage, if a circuit module in a row is less efficient or is shaded and avoids thermal overstress. In normal operating mode diodes *VD1* and *VD2* do not consume energy. Diode *VD*, called anti-return, is connected in series with the load. This diode prevents the situation when the PV module can become energy consumer, if the generated voltage will be less than the battery voltage. It is obvious that it introduces a voltage drop of about 0,5 V and, accordingly, loss of energy. fig. 3.7, b shows a parallel connection of two identical modules. The voltage output remains the same and the current increases twice. Operating point of the system "PV modules - resistance *R*" is the point of intersection *M* of the volt-ampere characteristics of the module and consumer – $I = (1/R)\cdot U$. Anti-return diodes *VD11* and *VD12* do not allow a module or a group of modules connected in parallel to pass under the consumer regime, when they are not identical or when they are shaded.

In fig. 3.7, c modules *PV1-PV2, PV3-PV4* and *PV5-PV6* are joined in series, but between them - in parallel. Thus, we obtain a double increase of the voltage and a triple increase of the current. Obviously, the unit power increases six times. *VD1-VD6* are bypass diodes and *VD12, VD34, VD56* – are anti-return diodes. The parameters of a PV module are determined by the cell parameters.

Further analysis will determine a numerical example for PV module parameters, operating in specified weather conditions

Numerical example. Determine the parameters of PV module consisting of 36 cells. The module operates under the following conditions: global radiation G = 800 W/m^2, environment temperature T_a = 20 ^{0}C. Manufacturer of PV module guarantees the following parameters in the standard test conditions:

- short-circuit current, I_{scst} = 8,68 A;
- open circuit voltage, U_{0st} = 22,1 V;
- Maximum power voltage, U_M = 17,7 V;
- Maximum power current, I_M = 7,91 A
- critical (maximal) power, P_{Cst} = 140 W;
- normal operating cell temperature, NOCT = 45 ^{0}C;
- temperature coefficient of U_{0st}=0,0036 V/^{0}C;
- cell number, N_C=36.

Solution:

1. Short-circuit current: According to (4.12)

$$I_{sc}(G) = (G/G_{st})\cdot I_{scst} = (800/1000)\cdot 8{,}68 = 6{,}94 \text{ A}.$$

2. Cell temperature. According to (4.11):

$$T_C = T_A + \left(\frac{NOCT - 20}{0{,}8}\right)\cdot G = 20 + 25 = 45\ ^0\text{C}.$$

3. Open circuit voltage. The (4.13) is applied:

$$U_0(55\ ^0C) = U_{0st} – 0{,}0036\cdot N_C\cdot(T_C\text{-}25) = 22{,}1 – 0{,}0036\cdot 36\cdot 20 = 19{,}5 \text{ V}.$$

4. Fill factor. According to (4.8):

$$FF = \frac{P_C}{U_{0st} I_{scst}} = \frac{140}{22{,}1 \cdot 8{,}68} = 0{,}73.$$

5. Maximal power. Determined if the *FF* factor does not depend on solar radiation and PV cell temperature:

$$P_C = FF \cdot U_0(55\ ^0C) \cdot I_{sc}(G) = 0{,}73 \cdot 19{,}5 \cdot 6{,}94 = 98{,}8 \text{ W}.$$

3.6. Photovoltaic systems

The structure of a photovoltaic system. PV modules are not the only components of a PV system. To provide continuously electricity to the consumer, PV systems include storage batteries. PV module is a direct current (DC) generator, but often the load is an alternative current (AC) consumer. PV electricity has a variable character. The alternating day / night process and clear / overcast sky causes a wide variation in the energy flux and voltage generated by the PV module. Thus, there is need for conditioning the power flux using electronic converters: DC/DC, which also has monitoring function of the charge / discharge process of the battery, DC/AC – to transform DC into AC. To avoid over sizing of the photovoltaic system, an auxiliary power source often is used: a generator or a wind generator or even public electricity network.

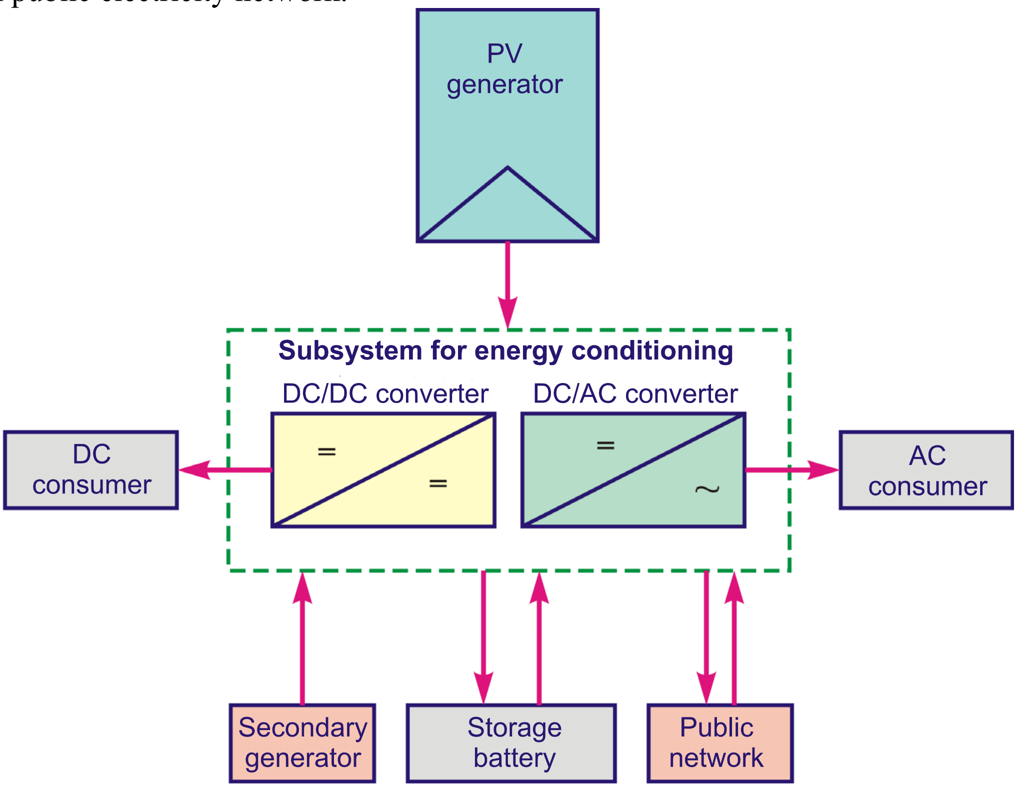


Fig. 3.8. Photovoltaic system structure

All these components must be interconnected, designed and specified to operate in a single system, the so-called photovoltaic system. Fig. 3.8 shows the structure of a PV system. Its main components are:

- module, panel, module field or otherwise said photovoltaic generator.
- storage battery;

- subsystem for electrical energy conditioning including measuring, monitoring, protection, etc;
- auxiliary energy source, for example, a generator unit, that works on gasoline or diesel. In this case, the PV system is called hybrid photovoltaic system.

PV systems are divided into two main categories: connected to the grid (grid-connected) or operating in parallel with the public electricity grid and autonomous PV systems (stand - alone PV system). The simplest system is the PV system for pumping water, the DC pump motor being used. This system does not contain storage batteries (water tank serves as storage) and AC or DC converters.

Grid-connected PV systems can be divided into: PV systems, in which the public electricity network serves as a secondary source of energy (grid back - up); PV systems, in which the excess PV energy is supplied to the network (grid interactive PV system) and PV power plant (multi-MW PV system), which provides all the energy produced in the network.

PV module - load system operation. In paragraph 4.5 it was noted that PV cell, the PV module respectively, has the best performance at point *M* (see fig. 3.3, c), and where the load delivered power is maximum. However, variation of overall radiation and temperature cause changes of PV module I-V characteristics. Also, different consumers have different *I-V* characteristics. As a result, the operating point of PV module - load system (the intersection of *I-V* characteristics of the module and load) will not coincide with the point *M*. In Fig. 3.9,

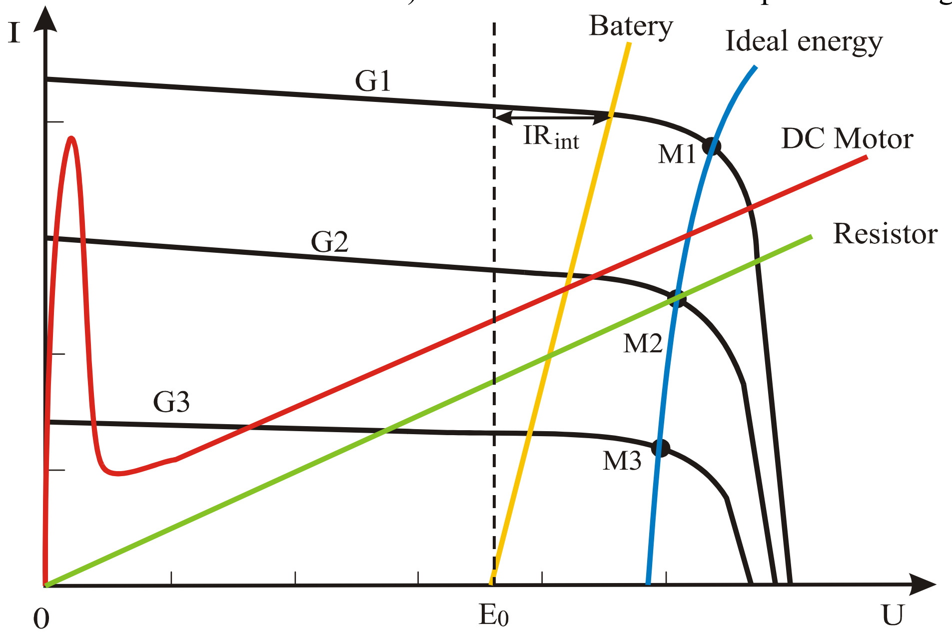


Fig. 3.9. PV module and different loads *I-V* characteristics

I-V characteristics of three of the most widespread loads are presented: resistor, DC motor with permanent magnet and a battery. The properties of an ideal consumer are presented for which the point of operation coincides with the optimal point *M*. *I-V* characteristics are described with the following analytical expressions:

- resistor $$I = \frac{1}{R}U; \tag{4.14}$$
- DC motor $$I = \frac{U - E}{R_i} = \frac{U - k\Omega\Phi}{R_i}; \tag{4.15}$$

- battery $$I = \frac{U - E_0}{R_{int}},\qquad (4.16)$$

where U is PV module voltage; k – motor constant; Φ –excitation flux; Ω – rotational speed; R_i – armature resistance; E_0 –battery open circuit voltage; R_{int} – internal resistance of battery. When starting the DC motor, the input current drawn from the module is up and is close to the short circuit. Although the induced voltage is minimal its starting occurs due to the product created $k\Phi I_{sc}$. If $U = E_0$, the battery is charged and will not consume power, otherwise charging current will increase with increasing global radiation, and with the voltage respectively. Voltage drop IR_{int} increases with increasing load current.

Fig. 3.9 shows that resistor type load or DC motor will not operate in the optimum point of changing radiation. You will need to change *I-V* characteristics of PV module or of the load to track the optimal operating point. To this end, they use DC / DC electronic converters called MPPT (Maximum Power Point Tracker).

MPPT is connected between the PV module and the load to change the output voltage so as to ensure optimum operating point tracking. Fig. 3.10 demonstrates two cases of the maximum point tracking - using MPPT technology (fig. 3.10, a) and by changing the load (fig. 3.10, b). In the first case, we have two loads with different *I-V* characteristics, which, for simplicity, linear allowed. For both loads we find an essential deviation of operating points *A*, *B* and *D*, *C* from the optimal points *M1* and *M2*. Hyperbolas $I = P_{max.1}/U$ and $I = P_{max.2}/U$ are drawn in the same coordinates. At any point of mentioned hyperbolas, power $P_{max.1}$ or $P_{max.2}$ are constant sizes and respectively equal to the maximum power in point *M1* or *M2*.

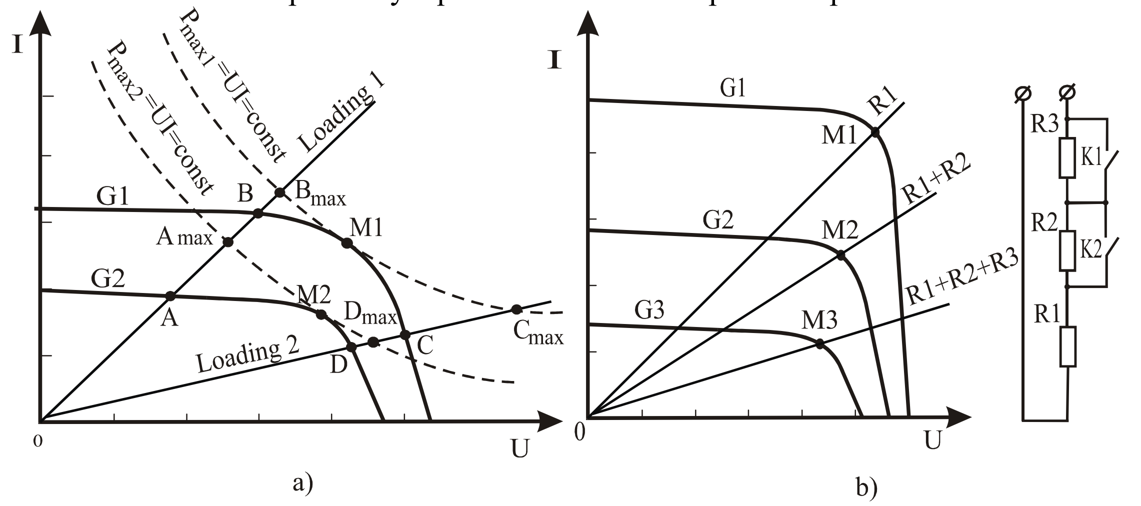


Fig. 3.10. Maximum output diagram: a) – employing MPPT technology; b) – by modifying load characteristics.

It is considered that the subsystem PV module - load 1 operates in point *B* in conditions of global radiation equal to *G1*. To get the maximum power from the module load *I-V* characteristics should be modified, so as to cross in point *M1*. The same result can be achieved if the voltage decreases and current increases in comparison with *M1* point, moving on the hyperbola in B_{max} point, similarly if radiation reduces from *G1* to *G2*. For load 2, to track the maximum point it is necessary to do the opposite - to increase the voltage and to decrease the current (C_{max} will be compared to *C* or D_{max} with *D*). Electronic converter MPPT should vary the voltage and current so that their product at outlet to be constant and equal to the maximum power generated by PV module exposed to global radiation *G*. In some specific cases, the maximum power point tracking can be achieved by changing the load *I-V* characteristics, as shown in fig. 3.10, b. For maximum solar radiation, equal to *G1*, the subsystem PV module-load *R1* will operate at the point *M1*; in which case contacts *K1* and *K2* are closed. Contact *K2* opens at the average value of solar radiation equal to *G2*, the load *I-V* characteristics changes and the subsystem will operate at point *M2*. If solar radiation continues to decrease, contact *K1* opens and the subsystem will operate at point *M3*.

Designer's decision to use or not use MPPT technology will be taken as a result of economic estimation. The following should be taken into account: MPPT converter cost, energy losses in MPPT (modern DC / DC converters efficiency is 90-95%) and power gain under optimal MPPT operation subsystem. According to available data [6], the maximum power point tracking in pumping PV systems increases the rated output by at least 20 %.

Inverter is part of the power conditioning subsystem of PV system (see fig. 3.8) and is the main component of the converter DC / AC. Inverter converts DC energy generated by PV modules or stored in the batteries into AC energy of predetermined frequency. Converters have been already designed which provide power quality parameters at the same level as public networks: steady frequency and voltage, sinusoidal form of the voltage wave and current. Depending on load requirements on the voltage waveform, overload factor, efficiency, different types of inverters are available, which parameters are presented in table 3.3.

Table 3.3. Performance parameters of main types of invertors [6].

Parameters	Rectangular voltage	Quasi – sinusoidal	PWM technology
Rated output, kW	Up to 1000	Up to 2,5	Up to 20,0
Overload factor	Up to 20	Up to 4	Up to 2,5
Efficiency, %	70 – 98	>90	>90
Harmonic (wave form) distortion, %	Up to 40	>5	<5

Indicated efficiency corresponds to inverter's operation at a load of 75-100 % of rated output. When choosing the inverter it is important to know the characteristic of efficiency as a function of load. Motors require a starting current much higher than the nominal one. It is important that the inverter's overload factor meets this requirement.

Rectangular wave inverter has the simplest scheme, a relatively good efficiency, is the cheapest, but it causes the highest harmonic distortion, which causes motor overheating. This type of inverter is recommended for use in low power PV systems for lighting, heating at other than DC voltages, also in the composition of DC/DC converters, electromagnetic drives. Quasi-sinusoidal wave inverter is more complicated, but relatively efficient. The pulse width modulation (PWM) technology is newer. Inverter control scheme is much more complicated, the cost of the inverter is higher, but also ensures high efficiency and minimum harmonic distortion.

3.7. Photovoltaic system design

The general principle underlying the PV system designing is to always respect the balance between the energy produced by PV generator and the consumed energy. This balance is achieved for a defined period, usually a day or a month. Presence of the storage battery allows compensation of the shortfall between the produced and consumed energy, which may be due to cloudy weather or overloading on behalf of the consumer.

Sizing a PV system requires the following basic steps (fig. 3.11):

1. Calculation of available solar radiation on the surface of PV module;
2. Daily electricity consumption calculation – E_c;

3. Calculating the amount of power needed to be produced by PV module – E_p;
4. Calculation of critical power of PV module – Pc and its choice;
5. Calculation of battery capacity – *C* and choice of batteries;
6. Checking balance generation -consumption.

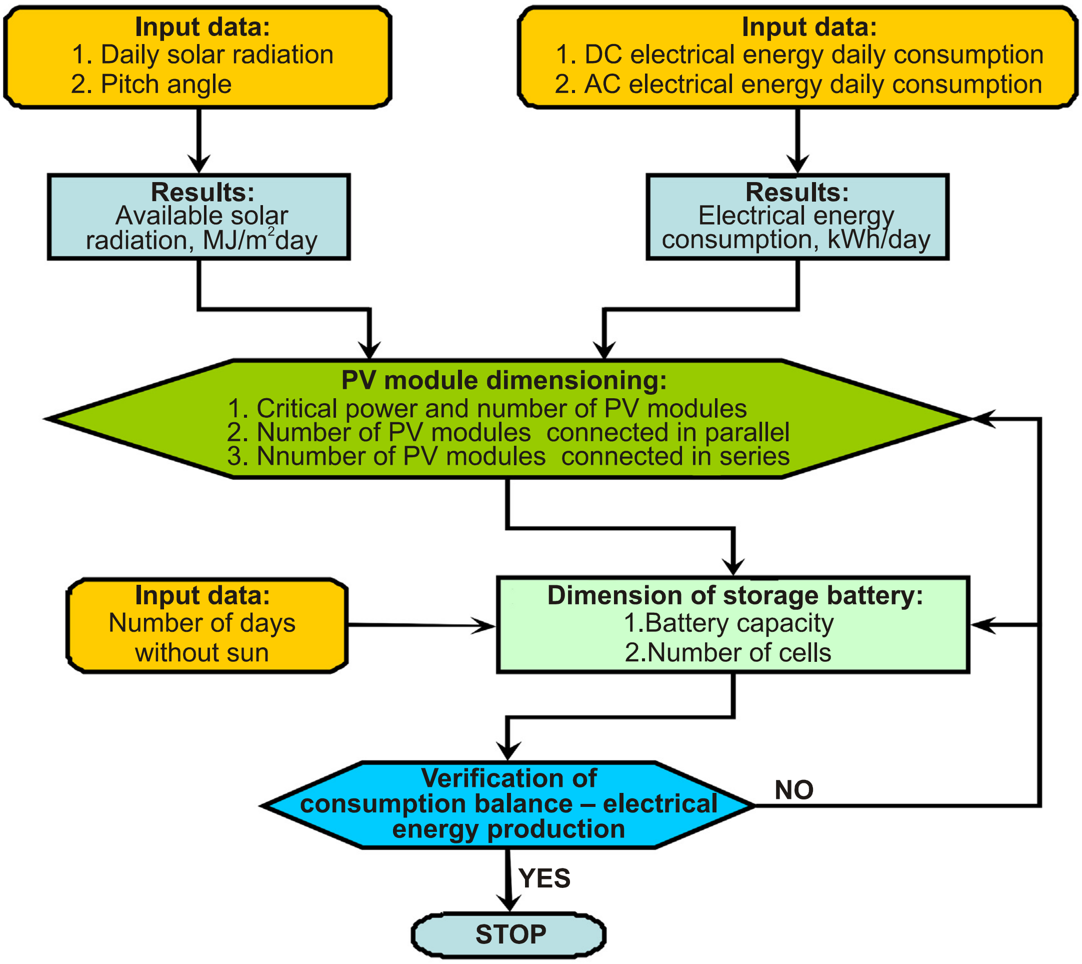


Fig. 3.11. Photovoltaic system design procedure

Calculation of available solar radiation on the surface of PV module is made in accordance with the method described in paragraph 2.6.2. PV module slope angle to the horizon β is determined from the condition ensuring the equilibrium "consumption – electrical energy production" in the months with the lowest solar radiation.

Daily electricity consumption calculation. To this end, for every consumer of *DC* and *AC* rated power and hours of daily consumption are determined. Electrical energy consumption E_C is determined as the result of the multiplication of rated power to the number of hours:

$$E_C = \sum_{i=1}^{k} \frac{P_{ni}^{cc} \cdot t_i}{\eta_R \cdot \eta_{Ac}} + \sum_{j=1}^{m} \frac{P_{nj}^{ca} \cdot t_j}{\eta_{CF}}, \qquad (4.17)$$

where *k* is the number of *DC* consumers; *m* is the number of *AC* consumers; P_{ni}, P_{nj} is the rated power of *DC* and *AC* consumers; t_i, t_j – operating period of the given consumers; η_R, η_{CF}, η_{Ac} – efficiency of charge - discharge controller, frequency converter and batery. For preliminary calculations η_R = 0,95–0,98, η_{CF} = 0,85 – 0,95, η_{Ac} = 0,85–0,90,. Electrical equipment rated powers are specified in the technical sheet. However, they can be made available to the designer by the company producing these machines. The values of operating times per day of the equipment are obtained from the beneficiary's stated needs or are determined from statistical data. Further on, some technical data on the most usual estimates of household electricity consumers are presented in tables 3.4 and 3.5 [8,9].

Table 3.4. Lighting source.

Lighting source	Power, W	Efficiency, lm/W	Lifetime, h
Incandescent bulb	25	9,0	2500
Incandescent bulb	40	9,0	1000
Incandescent bulb	75	13,0	1000
Incandescent bulb	100	16,0	1000
Incandescent bulb (quartz))	50	19,0	2000
Compact fluorescent lamp (CFL)	4 8 13 18	45,0	6000-10 000
Fluorescent lamp T-8	n/a	75-100	12 000-24 000
Halogen lamp	n/a	80-115	10 000-20 000
Low pressure sodium lamp	35	128,0	5000
LED surface	3,6	130,0	>100 000
High pressure sodium lamp	n/d	90-140	10 000-24 000

Table 3.5. Estimative values of functioning period of power consumers for an isolated house

Consumer	Rated power, W	h/day		
		Months		
		XII,I,II	III,IV,V,IX,X,XI	VI,VII,VIII
Lighting kitchen	2x13 LFC	4,0	3,5	2,0
Lighting bedroom	3x9 LFC	1,0	1,0	1,0
Lighting living room	2x20 LFC	1,0	1,0	1,0
Lighting bathroom	1x18 LFC	1,0	1,0	1,0
Vacuum cleaner	1200	0,5	0,5	0,5
refrigerator	100	7,0	7,0	7,5
Colour TV, 54 cm	60	4,0	4,0	4,0
Stereo	60	2,0	2,0	2,0
Microwave oven	600	0,5	0,5	0,5
Water pump	200	1,0	1,0	1,0

Calculating the amount of electrical energy needed to be produced by PV module. Electrical energy to be produced by PV module:

$$E_P = \frac{E_C}{K}, \tag{4.18}$$

where K factor takes into account the uncertainty of weather data, the losses in cables, the deviation of functioning point of the subsystem "PV module – load" from the optimum one, etc. According to [9], the value of K factor for PV systems with storage batteries is between 0,75 and 0,85.

Critical power of PV module is determined from the relation:

$$P_C = \frac{E_P}{G_\beta} = \frac{E_C}{K \cdot G_\beta}, \tag{4.19}$$

where G_β shows the average global solar radiation during the period of interest in this locality for the slope angle β of the PV module. In (4.19) G_β is equal numerically to the number of hours per day of standard solar radiation, which is equal to 1000 W/m^2 and is noted by *HSR*.

Depending on power P_C, the power of PV module and the number of modules connected in series are selected:

$$N_S = \frac{U_{cc}}{U_m} , \tag{4.20}$$

where U_{cc} is the nominal voltage of DC consumers; U_m – nominal voltage of a PV module.

The number of PV modules connected in parallel is defined in the following way: the average current of load per day is estimated:

$$I_{med} = \frac{E_P}{24U_{cc}} . \tag{4.21}$$

At the same time, respecting the condition of energy balance it is possible to write:

$$24 \cdot I_{med} \cdot U_{cc} = HRS \cdot I_{PV} \cdot U_{cc} \quad \text{or} \quad I_{PV} = \frac{24 I_{med}}{HRS} , \tag{4.22}$$

where I_{PV} is PV module current.

The number of PV modules connected in parallel will be:

$$N_P = \frac{I_{PV}}{I_{sc}}, \tag{4.23}$$

where I_{sc} is the short circuit current of a PV module that is considered almost equal to the current in point M .

Calculation of battery capacity. It is determined from the relation:

$$C = \frac{n \cdot E_C}{K_D \cdot U_{cc}}, \tag{4.24}$$

where n is the number of days without solar radiation ; K_D – battery discharge rate (0,5 – 0,6 for Pb–acid and 1,0 for Ni–Cd).

The number of batteries connected in series:

$$N_{As} = \frac{U_{cc}}{U_A}, \tag{4.25}$$

where U_A is the battery nominal voltage.

Checking the balance of electrical energy consumption and generation. Verification is done by comparing the amount of electricity, E_i, that will be produced by the PV panel in a day for each month of the period of interest to the amount of electricity needed calculated as 4.18. Calculations made from the relationship:

$$E_i = HRS_i \cdot P_C \quad \text{and} \quad E_i \geq E_P \tag{4.26}$$

where HSR_i is the number of hours per day of standard solar radiation equal to 1000 W/m^2 for the given month i.

3.8. PV resources and future prospects

There is more than enough solar irradiation available to satisfy the world's energy demands. On average, each square meter of land on Earth is exposed to enough sunlight to generate 1,700 kWh of energy every year using currently available technology. The total solar energy that reaches the Earth's surface could meet existing global energy needs 10,000 times over. European Photovoltaic Industry Association EPIA [11] has calculated that Europe's entire electricity consumption could be met if just 0,34% of the European land surface was covered with PV modules. International Energy Agency (IEA) calculations show that if 4 % of the world's very dry desert areas were used for PV installations, the world's total primary energy demand could be met [11].

Theoretical solar energy potential of the Republic of Moldova is 1700 times higher than total energy consumption in 2010. Technical potential of solar energy, thermal and PV, is estimated of 50,4 PJ [12].

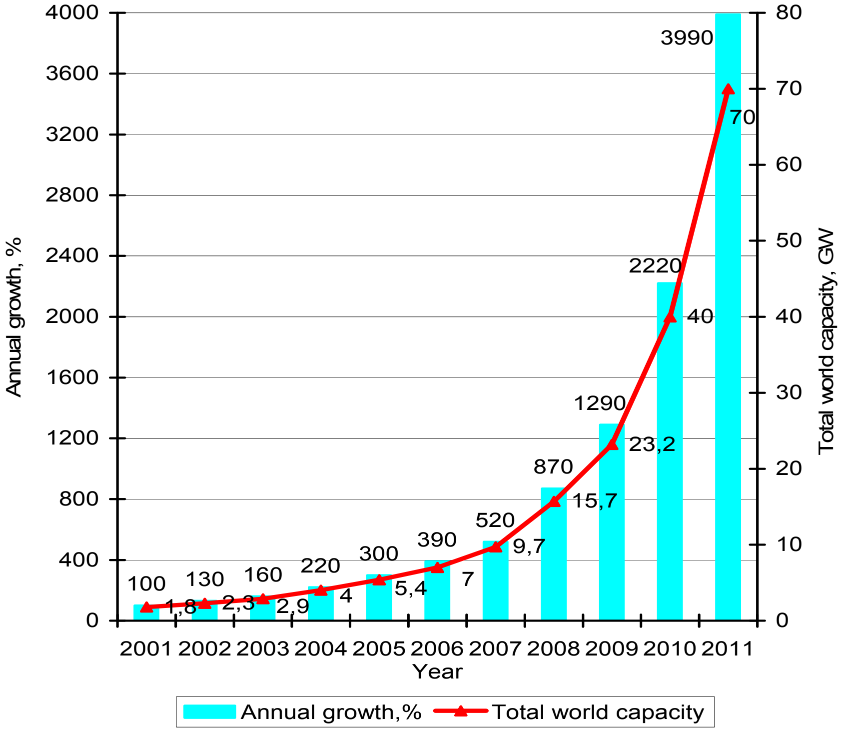


Fig. 3.12. Solar PV total world installed capacity, 2001-2012

Fig. 3.12 shows the evolution of global installed PV power in the period 2001-2011.

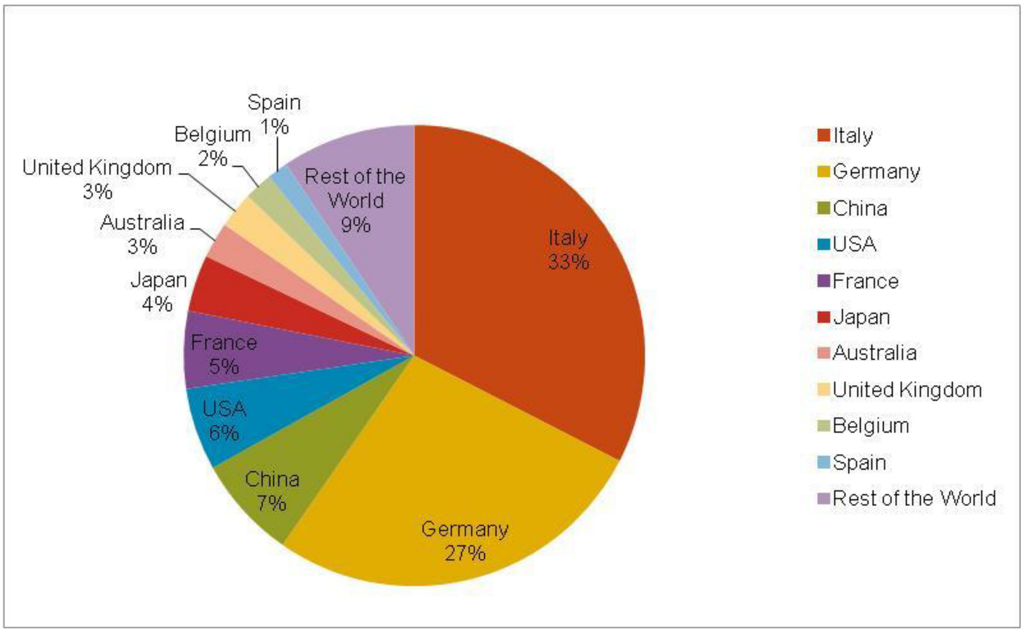


Fig. 3.13. The market share of the world's top 10 PV markets

After 2005 there is an extraordinary increase in worldwide installed capacity. In the years 2008 - 2011, growth compared with the previous year was equal to 47,7, 72,4 and 75,0 %. Over a period of last 10 years, global installed PV capacity has increased about 39 times.

The market share of the world's top 10 markets is highlighted in the fig. 3.13. These top 10 markets make up over 90 % of the entire PV growth world-wide.

PV is now a significant part of Europe's electricity mix, producing 2 % of the demand in the EU and roughly 4 % of peak demand. In Italy, PV covers 5 % of the electricity demand, and more than 10 % of peak demand [13]. In EU countries the cumulative PV capacity in 2011 was 74 % of worldwide power, fig. 3.14

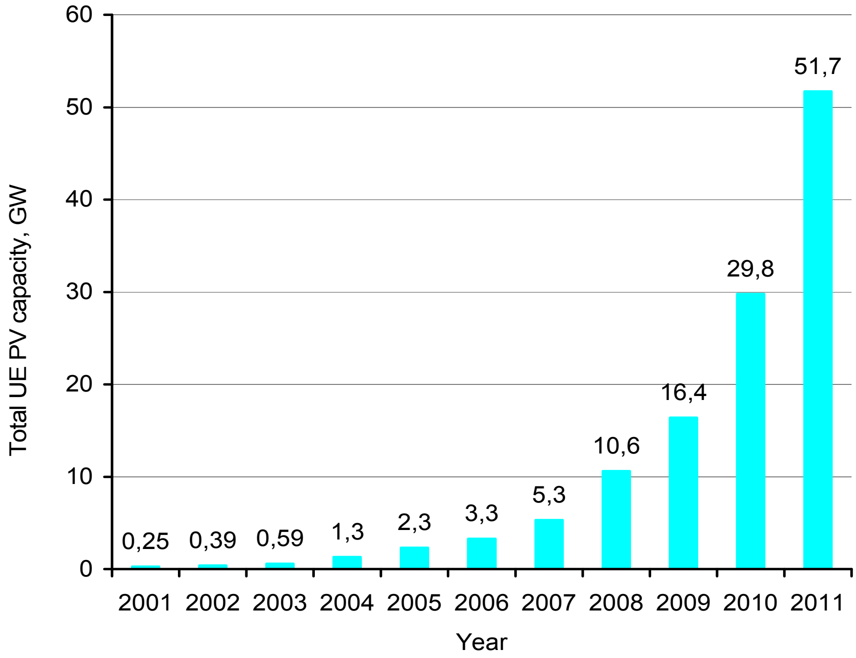
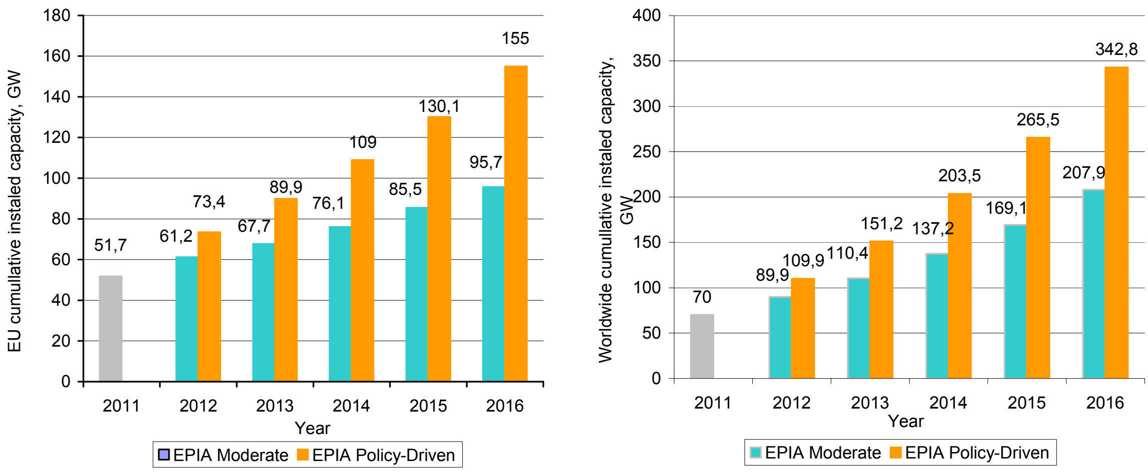


Fig. 3.14. Evolution of European cumulative installed capacity, 2001-2011

EPIA estimates for the period 2012-2016 a considerable increase in installed PV power at European and global level, fig. 3.15. Were analyzed two scenarios [13]:

1. **The Moderate scenario** assumes rather pessimistic market behavior with no major reinforcement of existing support mechanisms, or strong decrease/limitation of existing support schemes. In countries close to transition, customers are not reacting well to a PV market without feed-in tariffs (FiT).
2. **The Policy-Driven scenario** assumes the continuation or introduction of adequate support mechanisms, accompanied by a strong political will to consider PV as a major power source in the coming years. This also requires removing unnecessary administrative barriers and streamlining grid connection procedures.



a b

Fig. 3.15. PV forecasts until 2016: a - EU level; b – global level

At the European level, EPIA estimates an increase of 85 %, according to the first scenario and 200 % under scenario 2. At the worldwide level – respectively 197 and 390 %. The fastest PV growth is expected to be in China and India, followed by Southeast Asia, Latin America and the Middle East and North African countries.

The table 3.6 compares the cumulative installed capacity at the end of 2011 in most EU markets, the official National Renewable Energy Action Plan (NREAP) targets for PV by 2020 and the necessary yearly market to reach this 2020 target (linear projection).

Table 3.6. NREAPS vs. reality of UE 27 PV markets [13]

Country	Cumulative installed capacity in 2011	NREAP target for 2020	Necessary market until 2020	NREAP target reached in ...
Austria	176	322	16,2	2012-2014
Belgium	2018	1340	N/A	2011
Bulgaria	135	303	18,7	2012-2013
Czech Republic	1959	1695	N/A	2010
Denmark	16	6	N/A	2010
France	2659	4860	24,.6	2013-2015
Germany	24678	51753	3008,3	2016-2020
Greece	631	2200	174,4	2014-2016
Hungary	4	63	6,6	2013-2015
Italy	12754	8000	N/A	2011
Netherlands	103	722	68,7	2015-2018
Poland	3	3	N/A	2012
Portugal	183	1,000	90,7	2016-2020
Romania	3	260	28,5	2013-2016
Slovakia	468	300	N/A	2011
Slovenia	81	139	6,4	2012-2014
Spain	4400	8367	440,8	2016-2020
Sweden	15	8	N/A	2011
United Kingdom	875	2680	200,6	2013-2015
Rest of EU 27*	55	360	34	2016-2020
Total EU 27	51216	84381	3685	2013-2015

* Rest of EU includes Cyprus, Estonia, Finland, Latvia, Lithuania, Luxembourg, Malta and Ireland.

Target already reached in 2011-2012: Country has significantly underestimated PV's potential.
Target to be reached by 2012-2015: Country has underestimated PV's potential.
Target to be reached by 2016-2020: Country has either properly estimated PV's potential (Germany) or has set measures constraining the market to meet the set target not earlier than 2020 (Netherlands, Portugal, Spain).

3.9. Costs of electricity from PV

3.9.1. Introduction

As with any energy source, the costs per kWh of energy from PV modules consist essentially of a combination of the investment cost (IC) and operate and maintenance (O&M) cost. The capital cost of a PV energy conversion system includes not only the cost of the PV modules themselves, but also the so-called "balance of system" (BOS) costs: the costs of the interconnection of modules to form arrays, the array support structure, land and foundations, if the array is not roof mounted, the cost of cabling, charge controllers, switching, inverters and metering, plus the cost of either storage batteries or connection to the grid.

Although the initial capital costs of PV systems are currently high, their O&M costs are extremely low in comparison with those of other renewable or non-renewable energy systems. A PV system connected to the grid not require any fuel, it has no moving parts and should require far less maintenance than, say, a wind turbine.

Two prestigious professional associations have recently analyzed the cost of electricity produced by PV systems and future trends:

1. First is 6th edition of the report "Solar Generation: Solar Photovoltaic Electricity Empowering the World" conducted by the European Photovoltaic Industry Association and Greenpeace International [11].
2. Second is "Solar Photovoltaics Competing in the Energy Sector – On the road to competitiveness" [14] is the comprehensive study conducted by the European Photovoltaic Industry Association with the support of the strategic consulting firm A.T. Kearney, analyzing how Photovoltaics will become a mainstream player in the energy sector and how PV industry progresses toward competitiveness with conventional energy sources.

In the following sections we present the main results obtained in these studies, emphasis on the cost of PV energy.

3.9.2. PV generation costs

The generation cost refers to the price of a single unit of electricity – normally expressed as one kilowatt hour (kWh). The concept of Levelised Cost of Electricity (LCOE) allows to calculate the real cost of PV electricity and to compare this with the cost of other sources of electricity. The formula for LCOE calculation [14]:

$$LCOE = \frac{IC + OM_{NPV}}{EP_{NPV}}, \tag{4.27}$$

where IC- the investment cost; OM_{NPV} – net present value of operate and maintenance cost: EP_{NPV} - net present value of electricity production, kWh.

LCOE represents the cost per kWh and covers all investment and operational costs over the system lifetime (usually 25 years). Using LCOE makes it possible to compare a PV installation with any kind of power plant. For each system the LCOE calculation takes into account:

- The lifetime of the plant;
- Investment costs (IC);
- Operational and maintenance costs (OM);
- The discount factor (expressed as the Weighted Average Cost of Capital or WACC):
- The location of the plant, which for PV is essential to consider the difference in solar exposure.

3.9.3. Components of current and future prices of PV systems

Total installed PV system prices. The starting bases for the calculation are the total installed PV system prices (also referred to as capital cost). The price of a PV system is split into the following:

- PV modules;
- Inverter (enables connection of the system to the electricity grid);

- Structural components (for mounting and connecting the modules);
- The cost of installation (including the following costs: project development, administrative requirements, grid connection, planning, engineering and project management, construction and margins of the installers).

The module price reflected around 45-60% of the total installed system price in 2010, depending on the segment and the technology. Therefore, it is still the most important cost driver.

Total system lifecycle cost. When calculating the generation cost, the total system lifecycle cost has to be considered, including all costs made over the entire lifecycle of the PV system. Therefore, some additional cost drivers need to be taken into account:

- Price for operation and maintenance services;
- Cost of one inverter replacement for each inverter (because the lifetime of inverters is shorter than that of PV modules);
- Land cost (for large-scale ground-mounted systems only);
- Cost of take-back and recycling the PV system at the end of the lifetime.

Discount factor. All costs and revenues that are not paid up-front have to be discounted in order to come up with a present value. The discount factor used is differentiated across the market segments and the countries. A country-specific risk has been taken into account based on the differences in long-term government bond yields between the five countries assessed. Moreover, a differentiation has been made between private PV owners and business investors.

Table 3.7. Discount factor or WACC in different EU countries, %

Country	Residential PV systems	Other segments
France	4,6	6,8
Germany	4,4	6,5
Italy	5,5	7,6
Spain	6,1	8,2
United Kingdom	4,6	6,8
Average	**5,04**	**7,18**

Assumptions on the evolution of future system prices. Determining PV's generation cost in 2, 5 or 10 years requires an assessment of how PV system component prices could go down in the future. For PV modules: an initial learning factor of 20 % has been assumed. For every doubling of the cumulative volume sold, the price will decrease by 20 %. Whereas for Thin Film PV modules the learning rate is assumed to remain 20 % until 2020, this rate could decrease towards 15 % for Crystalline Silicon modules in 2020. For inverters: a learning factor of 20 % has been assumed for small-scale inverters (used in residential systems) and of 10 % for large centralized inverters (used in all other market segments). The learning factors are based on the realized price reductions in the PV industry since the 1980s-1990s. For structural components: the evolution of the cost of some components, such as cables and mounting structures, depends on the evolution of raw material prices, scale and learning effects. However, a significant part of their costs are influenced by PV module efficiency: the higher the efficiency, the fewer structural components are required. Therefore, the efficiency evolution of the modules has been taken into account. The installation cost: the parameters that have been taken into account are similar to the ones that determine the evolution in the price of the structural components. The increase in labour cost is taken into account as well.

3.9.4. A huge potential for cost reduction

PV module prices: a 20% learning factor. The cost of PV systems has been going down for decades and is now approaching competitiveness. The figures below illustrate that remarkable price decline: over the last 20 years, PV has already shown impressive price reductions, with the price of PV modules decreasing by over 20 % every time the cumulative sold volume of PV modules has doubled (learning factor). The average price of a PV module in Europe in July 2011 reached around 1,2 €/W (Fig. 3.17). This is about 70 % lower than 10 years ago.

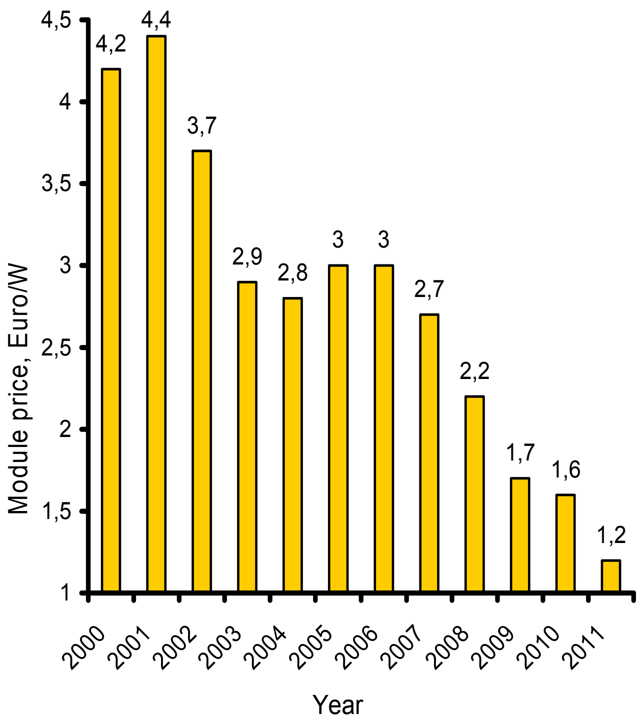


Fig. 3.17. Evolution of the average PV module price in Europe

System prices could go down by 36-51% by 2020. The cost of an investment in a PV system is driven mostly by the initial up-front investment or capital expenditure. Additional costs encountered during a system's lifetime are comparatively low. Therefore, it is useful to assess the evolution of the capital costs over time. System prices have declined rapidly, during the last 5 years a price decrease of 50 % has been realized in Europe (Fig. 3.18). Over the next 10 years, system prices could decline by about 0,83-1,59 €/W_C.

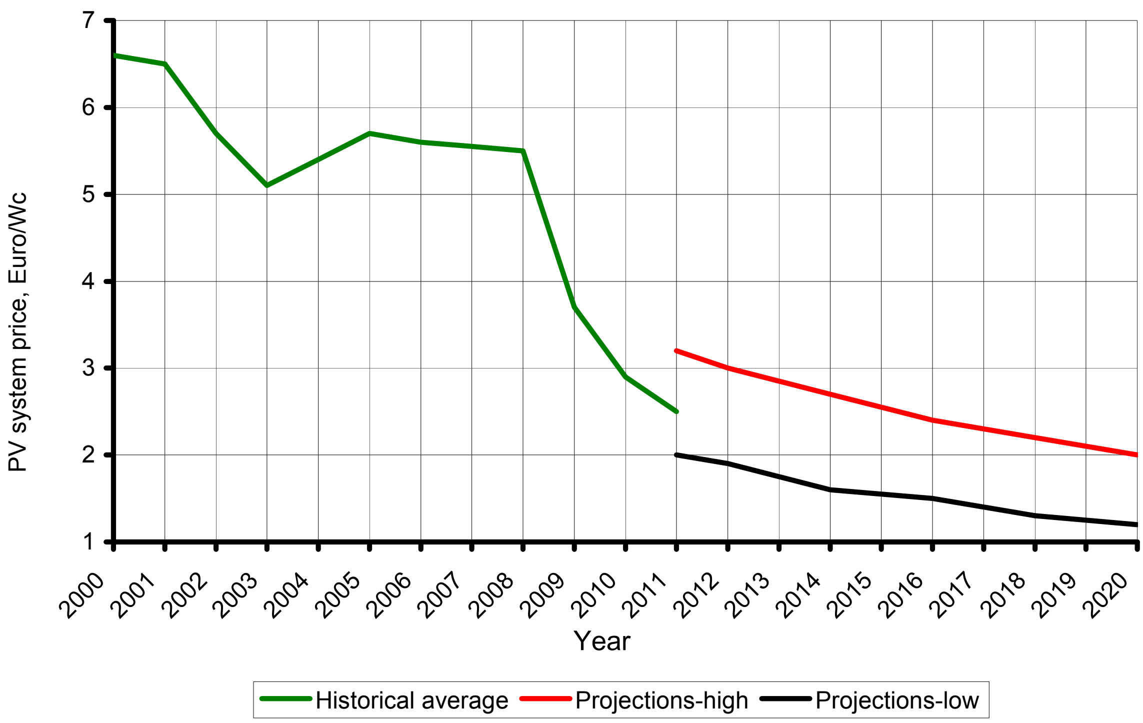


Fig. 3.18. Evolution of the PV system price in Europe

Generation cost could decline by 50% until 2020. The results shown in fig. 3.19 indicate a wide range for PV's generation cost in Europe as well as a huge potential for cost decline: around 50 % until 2020. This wide range is due to the large set of differing parameters taken into account:

- 2 different sets of technologies- Crystalline Silicon and Thin Film;
- National differences among the 5 countries (see table 3.7) studied with respect to irradiance levels, financial conditions (including VAT for the residential segment), total installed PV system prices and operation and maintenance costs;
- 4 different market segments.

The study assumes competitive cross-European hardware prices (modules, inverters, structural components) as well as competitive development prices. The range below therefore reflects the generation cost assuming mature market prices. Accordingly, the average European LCOE for 2010 was 0,239 €/kWh and for the first half of 2011 – 0,203 €/kWh. This calculation considers the real market volumes and market segmentation in Europe.

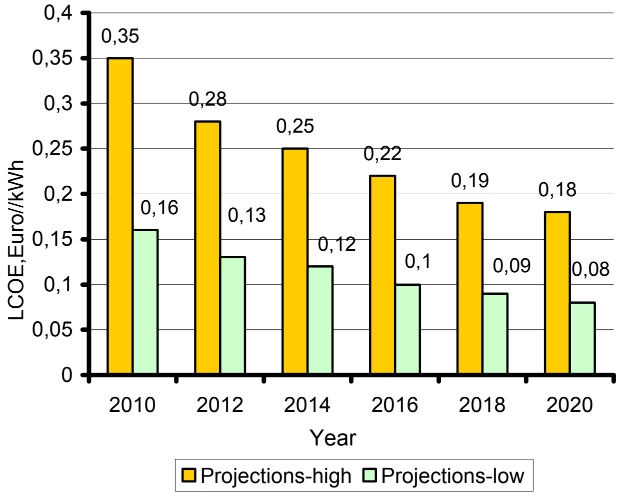


Fig. 3.19. European PV LCOE range projection 2010-2020

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