

Study on the possibility of use of photovoltaic cells for the supply of electrolysers

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Abstract Photovoltaic cells have been used for a long time to supply the electrical devices of small power in areas without access to the electricity networks (or other sources of electric energy). The ecological aspect of the use of the renewable energy sources, together with the technology development and increasingly lower costs of production the photovoltaic cells, cause the increase of their application. The solar power plants are built in several places in the world, not necessarily in the areas of high light intensity. Nowadays, such developments mostly depend on the wealth of a particular country. The largest photovoltaic power stations have power of a several dozen of MW. The major disadvantage of the photovoltaic cells is that the energy production is possible only during the day. This causes a necessity of energy accumulation in large photovoltaic systems. One possibility of storing large amounts of energy gives a hydrogen fuel, generated in the electrolysers powered directly from photovoltaic cells. Hydrogen, stored in pressure tanks or in tanks with synthetic porous materials, can be again used to produce electricity in fuel cells. This paper introduces selected issues and test results associated with the use of photovoltaic cells to power the hydrogen generators. The possible connections of photovoltaic modules integrated with electrolysers were analyzed. In this article the results of the electricity daily production by polycrystalline photovoltaic cells, collected in the course of the entire year were also presented.

Keywords: Solar energy; Photovoltaic cell; Electrolyser

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1 Introduction

Production of the photovoltaic cells and number of energy installations based on various types of photovoltaic cells is increasing every year. In last years the increase of production is estimated to be more than 100%. Nowadays, the greatest competitors in the photovoltaic industry are China (more than half of the world's production), Taiwan, Germany and Japan. On the other hand majority of photovoltaic installations are built in the European Union (about 80% of the world's production) and USA. Such state has been continuing at the same level for a few years – data from 2010, basing on the European Photovoltaic Industry Association (EPIA). Silicon cells are most frequently used in these type of installations, but more frequently are built a very technologically advanced systems. The leader in this sector is Germany (almost 7 GW installed capacity added in 2010 – growth of the power of photovoltaic installations is greater than the installed power in the wind energy sector). Also important partners are Italy (3 GW), Czech Republic (1.3 GW), Japan (1 GW) and USA (0.8 GW). The photovoltaic installations built in the world until 2010 have a total capacity of 40 GW. This result is considerable but for the rational use of solar energy, the effective energy storage systems are required, because during higher electricity demand (evenings and winters) there is not enough electricity from photovoltaics. One of the technologies for storing large amounts of energy is the production of hydrogen in electrolyzers, and then use of hydrogen fuel in polymer electrolyte membrane (PEM) type fuel cells – also called proton exchange membrane fuel cells. Hydrogen can be stored in large quantities in pressure tanks or in liquid form in properly insulated containers. This technology is not yet finalized due to the high costs and limited lifetime of PEM fuel cells. Additionally, at present it is not possible to obtain the high power output from PEM fuel cells.

The use of photovoltaic installations is mainly dependent on the amount of solar radiation that reaches the earth's surface. Based on the meteorological data collected over the period of 30 years by the Institute of Meteorology and Water Management (IMGW), it is possible to estimate the total average annual amount of the solar radiation on south oriented surfaces and with the inclination 30° for the city of Katowice (geographical position 50.23° N, 19.03° E) is about 1100 kWh/m^2 . Changing the orientation of the surface to the south-east or south-west, and its inclination to 60 degrees does not cause significant changes in the total amount of solar radiation. These data also show that over 60% of radiation intensity on a horizontal surface is

due to diffuse radiation. Therefore, in order to obtain more electricity from the sunlight, the photovoltaic cells more sensitive to the diffuse radiation than to direct solar radiation should be used. Assuming the efficiency of commercially available silicon cells reaching 14–17%, in Poland it can be obtained annually no more than 150 kWh from 1 m² of the panel, when the solar tracer is used [1]. It causes, that in order to use photovoltaic panels for energy (industrial) purposes a large amount of panels on a large surface area is required. Currently, photovoltaic cells are not used in Poland on a larger scale. They are used, first of all, in road signs and lighting in gardens. Probably the greatest working installation is the installation built in Wierzchosławice. It is a brand new installation consisting of 4445 photovoltaic panels and with the peak power 1 MW_p. In Bydgoszcz on the roofs of a cold store of the Frosta company, panels of the total area of 600 m² and the peak power 80 kW_p are situated. Energy from the cells is used, among others, to supply refrigerating units. This solution is justified because of the increased electricity demand of cold store during sunny days. Another new photovoltaic installation is the installation consisting of 312 photovoltaic panels, with the area of 500 m², built on the roof of Sanctuary of the Holy Lady in Jaworzno. The peak power of installation is 72 kW_p and it works on-grid. Most installations built in Poland do not exceed 10 kW and generally they are small private installations [2].

2 Characterization of photovoltaic cells

Photovoltaic cells are direct conversion devices which convert energy of the solar radiation into electric energy. These devices are characterized by: a lack of moving parts, stability of work, minimum range of maintenance work, high reliability and low operating costs. Moreover, the operation of photovoltaic cells does not cause pollution of the environment, cells are reliable and ideal for places where it is difficult to provide a fuel, such as cosmic space or mountain areas. Unfortunately, despite the presence of the know-how of the production technology, manufacturing process of photovoltaic cells is very expensive, due to the use of expensive crystalline silicon or the rare elements (such as indium or tellurium) in thin film photovoltaic (PV) solar cells. Moreover, the installations which are built, require the use of additional electrical equipment with high-capacity batteries, that significantly increase the price of power station based on photovoltaic cells. The vast majority of produced and used (approximately 80%) photovoltaic cells

are cells based on the silicon semiconductor p - n junction.

2.1 The principle of operation of photovoltaic cells

Operation of silicon cells is based on the semiconductor p - n junction. At the junction of two semiconductors there is the barrier of potential, negative, in the p region and positive in the n region. If the cell (junction) is not illuminated by the sunlight, the very low current is flowing in it (reverse diffusion current). The cell is becoming a source of energy when it is illuminated (in the p - n junction photons must strike with an appropriate, well-defined energy, which allows electrons from the semiconductor valence shell defeat energy gap). The generated pair of electron ($-$) and hole ($+$) creates an electric field (polarization of p - n junction) which is moving carriers of different signs in the opposite directions. The electrons migrate to the n region, and the hole to the p region which gives rise to the potential difference across the joint. Closing the circuit by the external load causes the flow of photoelectric current [3].

Depending on the materials used in photovoltaic cells the photoelectric effect occurs for different wavelengths and with different intensity. Simultaneously, in a particular wavelength range for each cell, the conversion of sunlight into electrical energy is never 100%. This causes a change of the value of the solar cells efficiency and the change of a quantity of electricity obtainable within the year. Depending on the climate zones the spectrum of radiation for which the photoelectric effect occurs is changing. In order to maximize the production of electricity, the type of photovoltaic cell should be selected depending on the specific climate zones. In the places where there is high solar radiation (more direct solar radiation), the photovoltaic cells that effectively absorb the energy of visible light and ultraviolet should be used. While, in the places where there is frequent cloud cover (in the absence of direct solar radiation) more efficient will be the cells that absorb the energy within a range of visible light and infrared. The theoretical maximum efficiency of a silicon solar cell using a p - n junction to collect power (photovoltaic effect) does not exceed 33.7% – “the Shockley-Queisser limit” or “a detailed balance limit” [4].

There are several types of photovoltaic cells available on the market today. The most commonly used photovoltaic solar cells are: monocrystalline silicon, polycrystalline silicon, amorphous silicon, CIGS (copper, indium, gallium, selenium), CdTe (cadmium telluride), DSSC (dye-sensitized solar cell). Each of them works in a different wavelength range radiation, in which

the maximum photovoltaic effect is obtained.

2.2 First-generation solar cells — silicon cells

The most popular photovoltaic cells are composed of a semiconductor p - n junction made of very pure crystals of silicon (purity 99.99999%). They are characterized by relatively high efficiency (even above 20%) but also high cost of production. Due to the manufacturing process, they can be divided into: monocrystalline, polycrystalline, multicrystalline. Silicon solar cells have a different semiconductor band gap and therefore they react differently to visible light and ultraviolet or infrared. Besides different production costs they are also characterized by a different efficiency [4].

2.3 Second-generation solar cells — thin film solar cell

The construction of the cells is also based on the properties of p - n junctions, but made of: cadmium telluride (CdTe) or compound of copper, indium, gallium and selenium (CIGS) or amorphous silicon (a-Si). They are characterized by a lower efficiency but also lower costs of production, resulting from much lower demand for semiconductor material used to build p - n junctions (semiconductor layer is even up to 100 times thinner than in the typical silicon junction) and a simple and cheap technology. For example, CdTe cells do not require high temperature processes such as silicon cells. Thin film solar cell represent less than 20% market share of photovoltaic cells nowadays. They can be mounted on curved or even flexible substrates.

2.4 Third-generation solar cells — „low cost, clean power generation,,

Cells in which there is no classical p - n junction. The research are carried out on many technologies including: dye-sensitized solar cell (DSSC – the most advanced) and organic/polymer solar cells. They are characterized by much lower production costs compared to the silicon cells and the simplicity of the production. Moreover, energy consumption in the technological process is very small and energy payback time, i.e. the time in which a solar panel will produce that same amount of energy that was used to make the panel, may be only about a month. Unfortunately, low efficiencies obtained currently, oscillating around a few percent, effectively limits their use on a large scale. Cells of this generation can be mounted on surface of any shape and have little weight.

DSSC cells are the most developed among the third generation cells. Except those mentioned advantages the production process is characterized by a small effect on the environment. These cells absorb radiation in the near infrared band. They can produce electricity for the whole day and are characterized by low sensitivity to the angle of incidence of the sunlight. Their efficiency are the highest among the third generation solar cells and reach a value around 10%.

Trends in the development of photovoltaic cells based on the National Renewable Energy Laboratory (NREL) in Colorado, USA, are shown in Fig. 1. Currently, the intensive works are carried out on the new solutions of photovoltaic cells which allow to use a much wider spectrum of solar radiation. These cells (called multijunction photovoltaic cell) consist of many layers responsive to different wavelengths. This should lead to a significant increase of the cell efficiency. The theoretical efficiency of such a solution can reach 86%, assuming an infinite number of layers and the highly concentrated sunlight [5]. The latest solutions allow to achieve the efficiency of over 40%. It has been obtained on the three-junction cell. Such technologies are still too expensive to be used on a large scale, mainly due to the fact that they need additional optical elements for focusing the solar radiation.

3 Energy storage

The use of renewable energy sources (RES) such as wind or solar radiation requires the use of efficient systems of storing large amounts of energy. Due to the unpredictable amount of energy obtained from these sources, it is necessary to use accumulators that store energy in the periods of increased production and release it in the energy demand peaks. This seems to be a more rational solution than building additional gas or water peak power stations. Output of that power plant is comparable with the total power capacity of RES. One of the most effective installations for storing energy is the pumped-storage hydro power plants. Storage of electricity in conventional electrochemical cells is too expensive to be used on an industrial scale, despite high efficiency of charging and small energy losses during storage. At the current pace of development of batteries, it will soon be possible to use them in small power plants. Unfortunately, the materials used in their production process that have a seriously negative effect on the environment and hence they limit their application for large power stations.

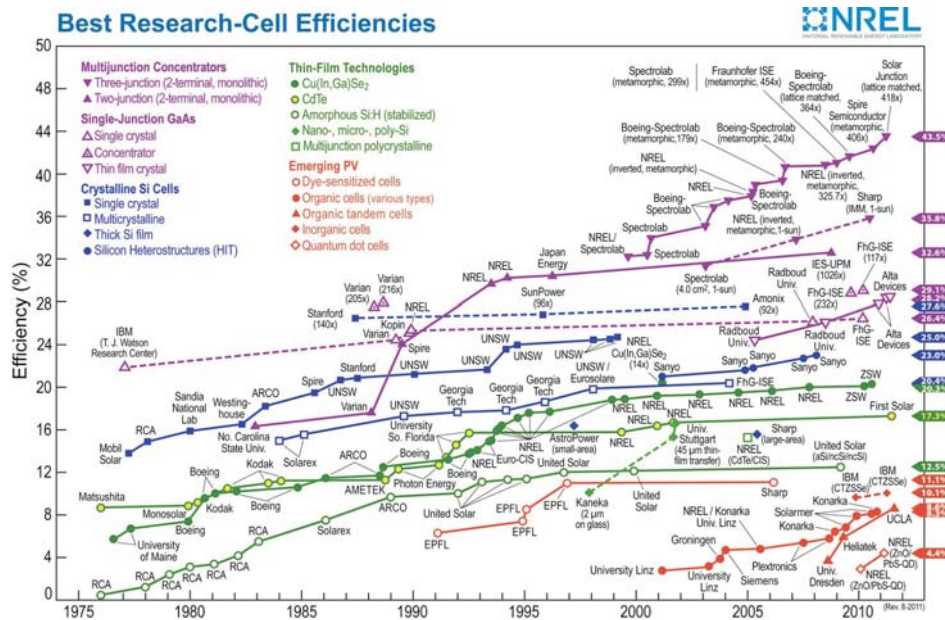


Figure 1. Trends in the development of photovoltaic cells (from NREL).

Today large hopes are connected with the vanadium redox battery (VRB). It is an electrochemical energy storage system, which consists of placing two electrolytes, obtained on the basis of vanadium and having the different values of redox potential, in separate tanks. In order to obtain electricity, liquids from storage tanks must be pumped through a membrane element, where potential difference is created on the electrodes. This process is characterized by: high efficiency (60–75%), long life cycle, easy extension of the system, the possibility of re-charging and discharging (even 10^5 cycles), the possibility of rapid voltage changes and negligible impact on the environment [7]. Several of these installations with hundreds of kW power capacity is already operating in the United States and Ireland.

Theoretically, large possibilities of energy storage from solar radiation give hydrogen technologies [8,9]. Hydrogen produced on a large scale in hydrogen production plant, which has a direct access to energy and water, could be than stored in tanks and during higher electricity demand would be used as hydrogen fuel in PEM type fuel cells. However, the storage and transport of large quantities of hydrogen and the production of cheap, long-life fuel cells are still a significant problem. Currently, there are already widely known the safe hydrogen tanks, but unfortunately they have

a relatively small capacity [10]. The hydrogen could be produced using solar electric energy from solar panels for the electrolysis of deionised water. This method is well known and allows direct coupling of an electrolyser to a photovoltaic cells [11–13,19]. This solution is very simple and beneficial because it eliminates a number of devices and processes, causing additional energy losses. Additionally, electrolytic method allows to obtain hydrogen of high purity (above 99.9%), which is necessary for PEM type fuel cell. Electrolysis process is rather simple and relatively inexpensive to conduct, but actually in practice is characterized by a low efficiency (24–35%), despite the high value of the theoretically possible efficiency (80%) [14]. Despite that fact, this method of hydrogen production is very often preferable, for both the small and large scale, and the theoretical possibility of electrolysers and photovoltaic cells, allow to look with optimism at the future development of this technology. Installations using water electrolysis to obtain hydrogen, are characterized by a quick start-up and simplicity of operation (possible automation of the process). However, this technology is too expensive at the moment, thus it cannot be widely used.

Another method to generate hydrogen using solar radiation is the technology of photoelectrochemical (photolysis) or photocatalysis decomposition of water. These methods consist of the direct decomposition of water into hydrogen and oxygen when exposed to sunlight. Despite not high efficiency of these methods (estimated from 8 to 20%) and the high cost of hydrogen generating devices, it is believed that in the future, together with fuel cells and photovoltaic cells, they can create a comprehensive system for production of electricity and hydrogen fuel from solar energy [15].

4 Measuring system

4.1 Description of the photovoltaic installation

The constructed test stand for examining the possibility of using the photovoltaic cells for the supply of electrolysers, consists of: four polycrystalline photovoltaic panels IBC-225TE, two hydrogen generators TsvetChrom-60 and measuring system allowing to measure current, voltage and the flow of the produced hydrogen. Each of the photovoltaic panels consists of 60 cells with a total area of 1.46 m². Technical parameters specified by the manufacturer differ slightly from each other, despite the same type of panels. Parameters of the panels, marked as FOTO1 and FOTO2 (previously ordered) are: nominal power (P_{max}) 225 W, nominal voltage (U_{mpp}) 30.3 V,

nominal current (I_{mpp}) 7.44 A, open-circuit voltage (U_{oc}) 36.7 V and short-circuit current (I_{sc}) 8.13 A; whereas panels FOTO3 and FOTO4 (Fig. 2) are respectively: $P_{max} = 225$ W, $U_{mpp} = 29.3$ V, $I_{mpp} = 7.69$ A, $U_{oc} = 36.5$ V, $I_{sc} = 8.23$ A. Electrical specifications are based on measurements performed at standard test conditions (STC) of 1000 W/m² irradiance, air mass 1.5, and cell temperature of 25 °C after stabilization. These panels are generally designed for parallel operation. Their main task is to power the electrolysers located in hydrogen generators [17].



Figure 2. The photovoltaic panels IBC-225TE.

The photovoltaic panels are mounted on the roof of a building. Photovoltaic panels were set at about 30° to the southeast because of the technical possibilities of installation, which resulted in the fact, that the maximum of direct sunlight was at about 11:00 am. Due to the work during the whole year, the cell is inclined at an angle of 50° to the horizontal plane.

The built system has the possibility of independent measurement of the power load of each panels and the use of DC/DC converters, that match the photovoltaic cells voltages levels to the receivers. Solar panels were chosen in such a way, that the maximum power from a single panel corresponds to the power needed to supply a single electrolyser. Protection systems, cooling fans and control of hydrogen generators are powered from the electricity grid. Each hydrogen generator has 2 electrolysers, which at total

current supply 26 A and voltage 14 V generates about 1 l/min of hydrogen. While the DC/DC converter was selected in terms of matching electrolyzers supply voltage. When determining the current-voltage characteristics and long-term measurements of photovoltaic panels, they were charged by laboratory variable resistor (rheostat).

In order to determine the co-operation point of photovoltaic cells and electrolyzers, it was necessary to determine the current-voltage characteristics of photovoltaic panels. It was realized by changing the load of photovoltaic cells at a constant value of solar radiation. Due to the conduction of measurements in real conditions, it was not possible to keep the temperature stability of photovoltaic cells. The real data were obtained for different values of solar radiation, and allow to designate current-voltage characteristics – Fig. 3. Currently, the measuring system is not equipped with pyranometer and temperature sensors, therefore obtained characteristics should be regarded as possible to obtain in existing installation.

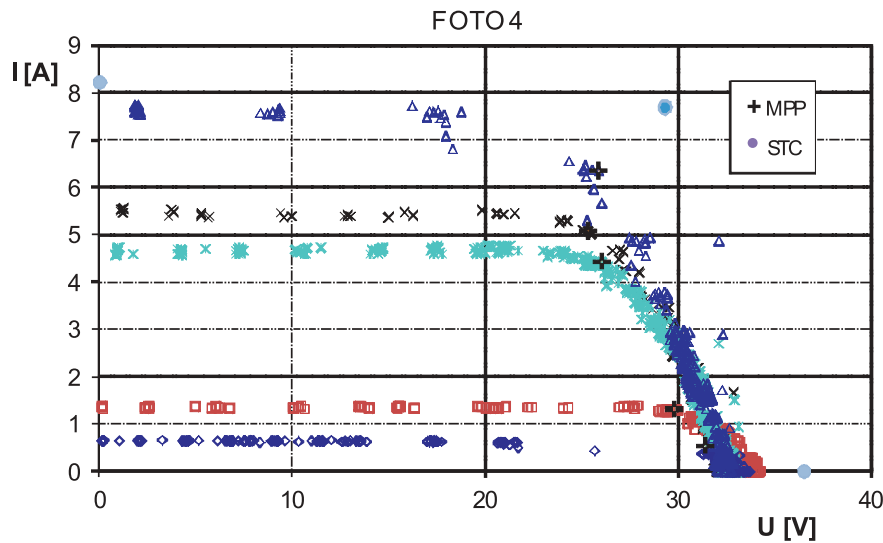


Figure 3. The current-voltage characteristics of photovoltaic panel IBC-225TE (MPP – maximum power points, STC – standard test conditions).

The measurements, performed for higher values of solar radiation, were also held at higher photovoltaic cells temperatures. This caused lowering of the open-circuit voltage [3] with respect to the rated data. Based on measurements, the power curve was determined. The shape of the char-

acteristics indicate that with increasing temperature there is a shift of the maximum power points towards the lower voltages – Fig. 4.

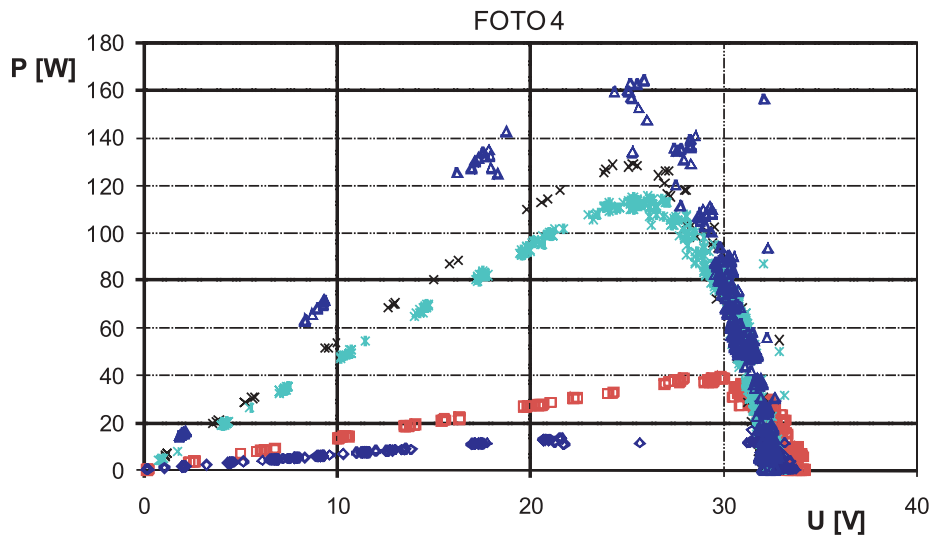


Figure 4. The power curve of photovoltaic panel IBC-225TE.

The rated values of currents, voltages and power were not obtained, because of too low value of the total solar radiation (deviates from standard test conditions).

4.2 The daily production of electric energy from the solar panels

In order to determine the daily production of electricity from a 1 m^2 of photovoltaic panel, current and voltage measurements were carried out separately on each (out of four) panels, throughout the day with a constant load. Measurements were repeated every day for over a year. The following figures present the results of measurements obtained on sunny days, so that they can be compared with the maximum power generated from the individual photovoltaic panels. The current value was measured at constant load (where current-voltage characteristic is flat), which corresponds to the electrolyser current in that case.

Because of the existing differences in rated data of individual panels (another series of production), there are small deviations in the values of

maximum currents obtained for described panels – Fig. 5. Due to the almost identical shape of characteristic of the panels FOTO1 and FOTO2, as well as FOTO3 and FOTO4, only one of them was selected in order to make the figure more clear. At the lower intensity of solar radiation (it corresponds to a lower current value) there are no clear differences between the shapes of the characteristics of individual panels. This means that the examined polycrystalline cells are more sensitive to the direct solar radiation. The scattered radiation does not substantially affect the operation of cells (identical shape of characteristics with small deviations in the area of maximum currents).

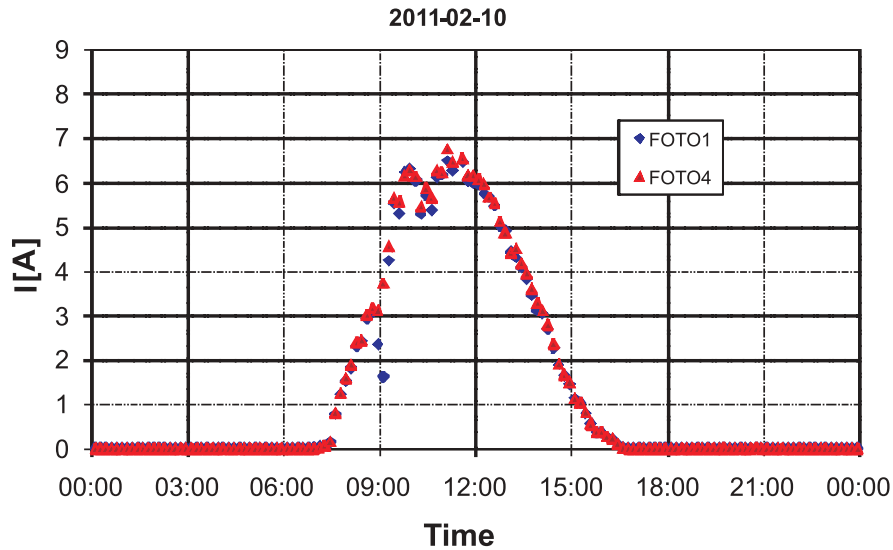


Figure 5. Daily profile of photovoltaic panel IBC-225TE.

For example, the daily production of electricity on February 10th 2011 (sunny day with small clouds) from panels FOTO1 and FOTO2 amounted to about 445 Wh/m^2 (the daily average energy yield in kilowatt-hours per installed kilowatt-peak – 2.89 kWh/kW_p) whereas from panels FOTO3 and FOTO4 to about 458 Wh/m^2 (2.97 kWh/kW_p). That values were calculated with the assumption, that photovoltaic cell works in this range of current-voltage characteristic where current is independent from load. It was assumed that the load characteristic always cross the current-voltage characteristic of the panel IBC-225TE for voltage equal 20 V . This assumption was used because of the different voltage values at which the maximum

power points (MPP) are obtained. Exceeding the MPP voltage might cause a sudden drop in output power – Fig. 4. The daily production of electricity on May 10th 2011 (sunny day without clouds) from panels FOTO1 and FOTO2 amounted to about 794 Wh/m^2 (5.15 kWh/kW_p) whereas from panels FOTO3 and FOTO4 to about 780 Wh/m^2 (5.06 kWh/kW_p). It is close to the maximum value of energy which can be received from this type of photovoltaic panels.

According to the Stoletov's law, photovoltaic cells start-up (the flow of current appears) takes place right after the sunrise and shut-down right after the sunset. Only when the sky was full of clouds, working time of the solar panel was shorter by maximum 2.5 h than duration of the day. The shortening of the working time is noticeable, especially from November to February. Complete cover of the panel, e.g. by linger snow, caused it shut-down (lack of the current). Thus, the photovoltaic panels should not be mounted in the places where it is impossible to remove snow because it could shut-down photovoltaic installation for a few months. Another important problem is partial shading of PV modules because they are very sensitive to shading. If even one full cell of photovoltaic module is shaded the power of that module drops rapidly, even to almost half of the nominal value [16]. From that reason PV modules should be mounted in the place where any element (such as: chimney, fence, tree, part of roof, pole etc.) could obstruct the sun. The start-up of the solar cell does not mean that it produces energy on a reasonable for the practical use value. With assumption of the minimal usefulness current value equal to 1 A from one panel, the effective working time of the installation is shorten by two hours in reference to duration of the day (calculated from sunrise to sunset). This assumption caused that effective working time of photovoltaic panels amount to half of the total duration of the days in the year.

The assumption of minimal current value of photovoltaic cells is necessary when they power the electrolyzers. Too small current value passed through electrolyser, which generate hydrogen, can be insufficient to cover hydrogen losses to the surroundings (these losses always occur in hydrogen installation). Thus, there is some minimal critical current value, above which starting of the installation is justified. In the presented installation, this value is equal to 4 A for each electrolyser.

4.3 Influence of inclination on energy production in photovoltaic panels

Within the framework of the experiment, during collecting of the measurements data, inclination of two out of four panels was changed (β – angle between horizontal surface and panel surface). New inclination of photovoltaic panel FOTO2 is 41° , and FOTO4 is 33° . The rest of photovoltaic panels (FOTO1 and FOTO3) stay in unchangeable inclination (angle $\beta = 50^\circ$).

The change of inclination angle influenced the daily profile of the panels IBC-225TE. It was wider and maximum current value grew in case of the panel FOTO2. However, a change of inclination did not influence the total daily amount of energy obtained from photovoltaic panel. It is caused by shortened the working time of solar panels to the current below 2 A (Fig. 6). Main reason of that is the construction of the place on which the photovoltaic panels are mounted (shorter working time due to the shading). The measurement data presented in Fig. 6 concern May 26th 2011.

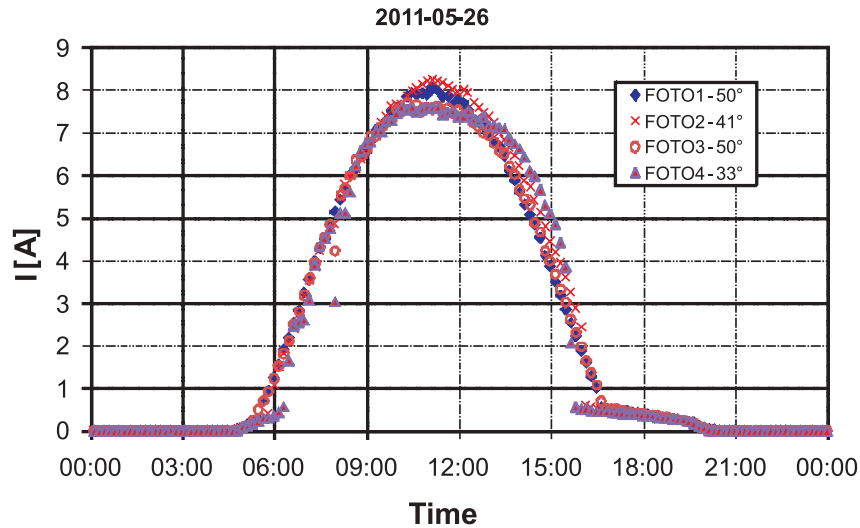


Figure 6. The influence of photovoltaic panels inclination on daily characteristics

It results from experimental data collected in the period 11.05–24.07.2011, that the decrease of the angle β below 50° caused increase of the total amount of produced energy. This increase is not big and it achieves at maximum 5%. In particular this applies to the panel FOTO2, which are set at an angle of $\beta = 41^\circ$. It is important that the obtained results relate

to the longest days in the year, when the Sun at noon is at the highest position above the horizon. Based on the meteorological data from IMGW for Katowice, the change of the surface inclination in the range between 30–60°, does not significantly affects the total solar radiation during the year (value varies by no more than 5%).

5 The total quantity of energy

The measurement data were collected for over one year and allowed to describe the quantity of energy which can be obtained from polycrystalline photovoltaic cells within the year. The data were collected for the whole day with interval of 10 min. Currents and voltages of each panel separately were measured. The measurements were made at a constant value of termination resistance. For the analysis a period between March 25th 2010 and March 24th 2011 was selected. In the mentioned period there were some breaks caused by maintenance works and voltage decay of the network supplying measurement apparatus.

Due to the electrolyser operation procedure (linear dependence of hydrogen flow on the current) in this analysis maximal current value from photovoltaic cell was taken into consideration. The photovoltaic panels applied in the experiment are the constant current source for voltage level 20–25 V, in constant solar radiation. It was assumed, that solar cells are the ideal current source, i.e. load change has no impact on the value of current. Due to the limitations of the measurement system, the total electricity production from 1 m² of photovoltaic panel was calculated with the assumption that the operating voltage is $U = 20$ V DC (in accordance with the characteristics shown in – Fig. 3). Up to this voltage value, the panels operate as current sources with the current value dependent on solar radiation, which is a function of time (i.e. time of the day). The maximum energy that can be achieved during a day was calculated from the formula:

$$E = U \int I(t) dt , \quad (1)$$

where U is the voltage, I the current, and t the time. The quantity of the energy was referred to the surface of photovoltaic panels and was shown in Fig. 7. It can be observed, that the production of electricity was significantly changing for each day. This is due to the changes in weather conditions (rain, temperature, clouds, etc.).

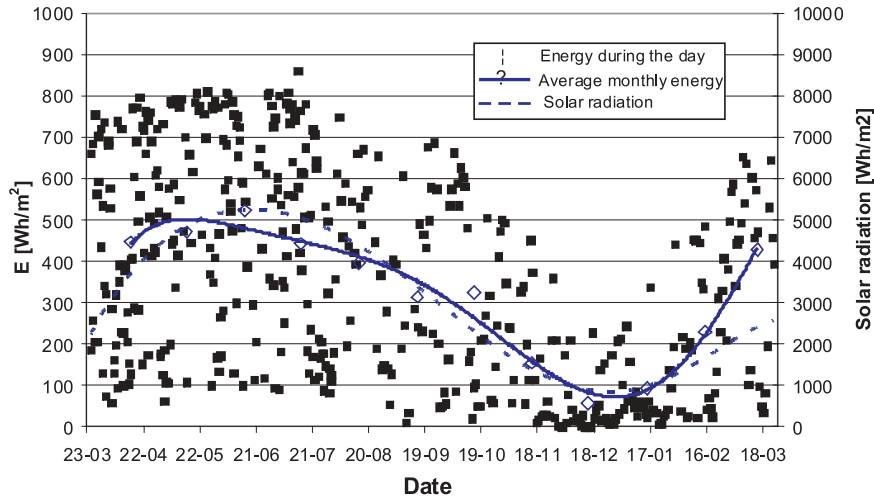


Figure 7. Annual average electricity production from 1 m² of photovoltaic panel IBC-225TE.

During the analyzed period the daily average of about 300 Wh/m² was achieved. Annually, it gives less than 110 kWh/m², which is the realistic value for the climate zone where the research was conducted. This is not a large amount of energy, [20]. Taking into account that the maximum values reach 860 Wh/m² during the day, the technological potential is large. Additionally, matching a system of photovoltaic cells to the charge of electrolyzers, allows to get power close to the maximum power point (Fig. 4). The lowest level of energy from the Sun was obtained during the months from November to January. It is associated with a shorter day, larger cloudiness and snowfalls. All the fluctuations, both during the day and year, require use of the energy storage system, which will adjust the amount of generated electricity to the demand.

The curves shown in Fig. 7 indicate a broad convergence of data obtained from measurements and the data resulting from meteorological observations (average data from IMGW for the years 1971–2000 for Katowice). In this case the energy obtained from the cells will be stored in the hydrogen fuel produced by electrolysis. Due to the electrolyser rated currents of around 13 A, on one electrolyser two photovoltaic panels are required, which are parallel connected. Characteristics of hydrogen generators and the electrolyzers were described in details in [18].

5.1 Coupling of the electrolyser to a solar panel

Due to the linear dependence of the amount of hydrogen produced on the electrolyser current, the most important is a way of coupling of photovoltaic panels and electrolysers allowing to obtain appropriate values of electrolyser current. The tests carried out during a sunny day allowed to obtain a set of points corresponding to the work of the system in different sunlight conditions, at the combination of two photovoltaic panels with two electrolysers. On the basis of measurement data, the graph was obtained, presenting the changes of hydrogen flow (produced by the hydrogen generator), as a function of current – Fig. 8. The current value the abscissa is the sum of currents flowing through the two solar panels, which are connected in parallel. The resulting relationship is similar to the characteristics obtained for the electrolyser powered from the stabilized source in the laboratory conditions. Due to the current limitations of photovoltaic panels (Fig. 3) usually it is

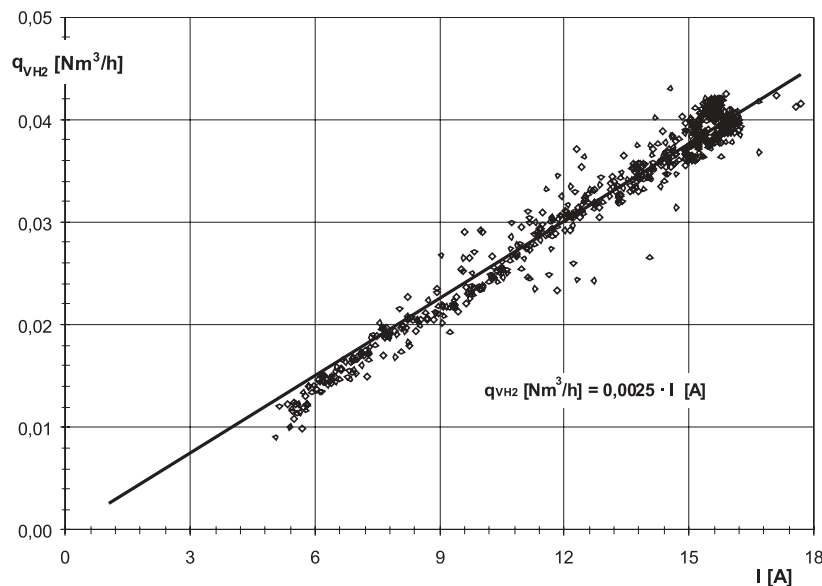


Figure 8. The relationship of hydrogen flow produced in the generator and current.

required to use several panels connected in parallel, to ensure a sufficiently high value of current which supplies the electrolyser.

The current-voltage characteristics of electrolysers are not linear. That gives possibility of connection electrolysers with photovoltaic panels in such

way at which these devices will operate close to the maximum power points [19]. This allows for the optimal use of solar panels and also the direct coupling of hydrogen electrolyzers to solar panels, without a DC/DC converter, which changes the voltage levels influencing the whole system efficiency. In the case of the analyzed devices, the optimal solution will be a combination system (series-parallel connection) illustrated in Fig. 9. In order to supply the electrolyzers with a nominal current, it is necessary to connect five photovoltaic panels in parallel.

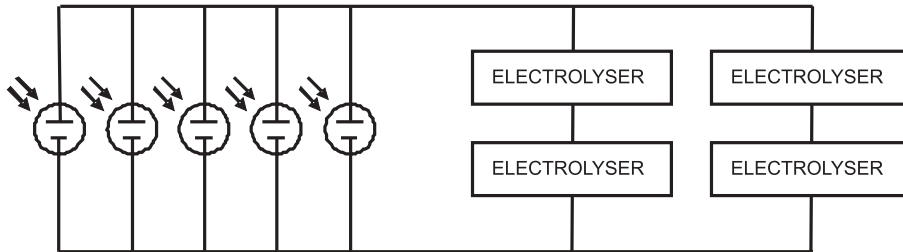


Figure 9. Diagram of connection between electrolyzers and photovoltaic panels.

The characteristics in Fig. 10 show that two well-illuminated photovoltaic panels will be able to provide a current value of approximately 11 A, when they will be connected in parallel and loaded by a conductance of two series-connected electrolyzers at a voltage of about 26 V (13 V for each). This will provide power of about 145 W to a single electrolyser. Five photovoltaic panels connected in parallel, loaded by the conductance of four electrolyzers (connected in series-parallel) can give current about 26 A (with a voltage of about 26 V), which will provide about 175 W to a single electrolyser.

A larger number of cells will provide a better “energetic comfort” of electrolyzers (combined within a single hydrogen generator in series). The current-voltage characteristics of electrolyzers and the photovoltaic cells should intercept in a point where the power of solar cell corresponds to the nominal power of the electrolyser (about 180 W per unit).

6 Summary

The installed power of the solar photovoltaic power plant increased in the recent years to the level having a real significance in the global energy sector, and the dynamics of the development of the photovoltaic market is currently

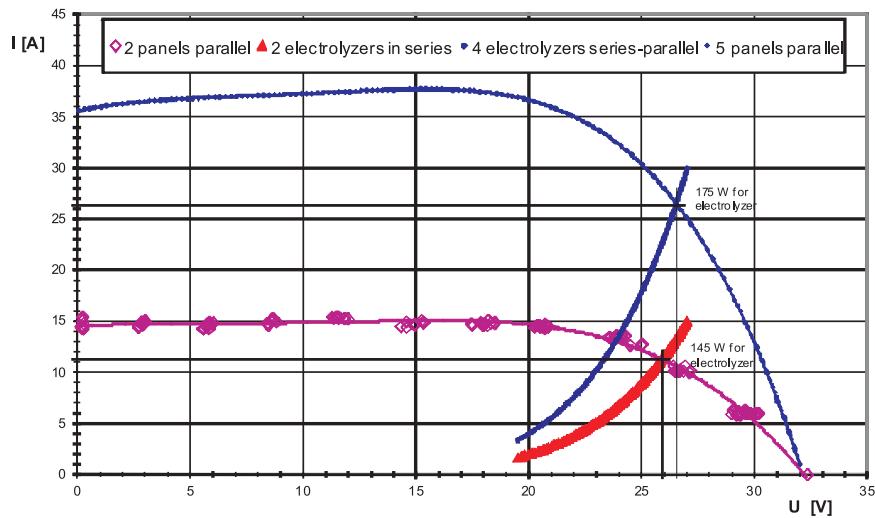


Figure 10. Scheme of the optimal combination of electrolyzers with photovoltaic panels.

the largest. It is particularly noticeable in the European Union. With current trends, the installed capacity in solar power plants may be greater than in wind turbines in a short time. Unfortunately, the photovoltaic cells do not ensure the stability of electricity supply, like most renewable energy sources. This results in a need to develop a reserve of peak power station or storage a large amount of energy from RES in order to use it during the increased demand. Such activities appear to be rational. One of the possible technologies to match production to the demand of electricity is production of hydrogen and its use as a fuel in fuel cells.

In the paper the results of research on polycrystalline photovoltaic cells and the possibility of using them to supply the electrolyzers producing hydrogen fuel were presented. Photovoltaic cells operating in the climate zone, in which the measurements were made, allowed to obtain about 110 kWh/m^2 in the year. When using mentioned above electrolyzers, obtained energy allows to produce approximately 13.5 Nm^3 of hydrogen from cells of 1 m^2 surface. The efficiency of the whole process is much smaller in comparison to the storage of electricity in rechargeable cells. However, the presented method allows to store much more energy. An important aspect of increasing the efficiency of energy conversion is to choose the proper type of photovoltaic cell to the climate conditions and the optimal combination of

the cells with electrolyzers. As shown in the presented research studies, the inclination of photovoltaic panels has no significant effect on the total amount of produced electricity. An increase in the use of the solar energy can be obtained when the tracking system, following the Sun, would be applied. About the use of motion tracking systems, the economic calculation will decide, which takes into consideration: the possibility of assembly of the installation, urban development of the area and the amount of direct solar radiation in the place where the solar power plant will be built.

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