IMPACT OF HIGH TEMPERATURE AND OTHER FACTORS ON PV MODULE EFFICIENCY ON SMALL FARMS IN LATVIA

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Abstract. Conversion of light into electricity is a relatively new invention. The use of solar energy has grown rapidly in the world. Advances in technology, climate change and price reduction have made PV systems very popular nowadays. However, despite the huge advances in technology, PV modules have relatively low efficiency. It is very important, because it shows how much solar energy PV modules can convert into electrical power. There are many factors that affect the efficiency of PV modules. One of them is temperature. It may seem a surprise for many people, but PV module performance is affected negatively by temperature increases. Therefore, it is important to examine the power losses of PV module overheating. The aim of this study is to determine and compare power losses from PV module overheating in several days with different weather conditions. Within this study 4 different days with various weather conditions were selected. For each day measurements of solar irradiance, solar elevation angle, solar azimuth angle, ambient temperature, PV module temperature and PV power from sunrise to sunset were obtained. The time of sunrise and sunset were different on each day. In order to achieve more objective results, the obtained data were analysed from 10:00 to 18:00. The ranges of average results in the given time period were determined and compared. The average solar irradiance ranged from 432.74 to 665.37 $W \cdot m^{-2}$, average ambient temperature from 13.50 to 25.35 ºC, average PV module temperature from 27.03 to 43.07 ºC, average PV power from 77.13 to 122.51 $W \cdot m^{-2}$, average power losses from PV module overheating from 0.81 to 7.23 % (from 1.25 to 7.98 $W \cdot m^{-2}$) and the average efficiency of PV modules ranged from 17.82 to 20.57 %. Power losses were up to 12.63 $W \cdot m^{-2}$, when the temperature of PV modules reached 53.5 ºC. The results show that high PV module temperature causes noticeable power loss.

Keywords: renewable energy, solar power, PV module, temperature, efficiency.

Introduction

Climate change is one of the most important topics in recent years. Our civilization relies heavily on fossil fuels, as about 80 % of primary energy comes from it [1; 2]. Many countries and organizations in the world are setting their targets to increase renewable energy to save fossil resources, secure global energy demand and reduce greenhouse gas emissions [3-5].

Solar energy has been researched and used for hundreds of years, but the studies on the use of solar energy for power generation have begun relatively recently [6]. The two most popular technologies using solar energy are solar heating and photovoltaics (PV). Solar collectors are mostly used for heat collection and drying processes and their efficiency mostly depends on the absorber material [7; 8]. Photovoltaic systems, also known as solar power systems, are developing very fast, because of the efficiency increments and price reduction of PV modules [9]. In recent years, electricity production from PV systems has grown rapidly in the world [10]. However, compared to other countries, solar power usage in Latvia is very low. In terms regarding the use of solar energy for electricity production, Latvia ranks the last among the Baltic States and one of the last in the European Union [11].

Solar irradiance is the amount of power received from the Sun in the form of electromagnetic radiation. It is the main indicator of the amount of electricity that PV modules can produce [12]. It is a variable that is affected by geographical location (mostly latitude), climate zone and weather conditions [13; 14]. The efficiency of PV modules is one of the most important characteristics. It is determined by standard test conditions (STC) at 1000 $W \cdot m^{-2}$ of solar irradiance and PV module temperature of 25 ºC [15; 16]. This means that temperature also has a very big impact on the performance of PV modules.

Excessive heat can significantly reduce the power of the PV modules. It may seem a surprise for many people, but PV module performance is affected negatively by temperature increases, and depending on the location of PV modules, high temperatures can reduce the power of PV modules even by 10-25 % [17; 18]. As the temperature of the PV modules increases, the voltage output reduces. As a result, the power of PV modules decreases [19; 20]. This is the reason, why it is important to research power losses of PV module overheating.

The aim of the study is to determine and compare power losses from PV module overheating in several days with different weather conditions.

Materials and methods

In order to save money from electricity, in early 2019 on the farm Jasmini, which is located in Latvia, Rezekne municipality, Gaigalava parish, a solar PV system was set up on the roof of an agriculture machinery shed, which is located in the geographical 56º42'53.46'' N latitude and 27º3'0.68'' E longitude. In total 22 polycrystalline, also known as multi-crystalline, RECOM Amur Leopard 270 PV modules with a total area of 35.79 m^2 were installed. Each PV module is rated with a nominal power of 270 W, which in total gives the nominal power of 5.94 kW.

PV modules are installed parallel to the roof and are facing the south-west direction with the solar azimuth of 203º. The tilt angle of the PV modules is 30º. PV modules are not shaded and they are relatively high on the roof to achieve better cooling by the wind. This contributes to reduced power loss from PV module overheating. PV modules are connected to the inverter, which converts the DC electricity to AC electricity. The PV system is grid-tied, which means that the excess electricity is sent through the electricity meter to the main grid.

Fig. 1 shows the solar elevation angle, also known as the angular height of the Sun, during the period from sunrise to sunset in different months in the aforementioned geographical location. The red line in Fig. 1 shows the solar elevation angle, when it is directly facing PV modules.

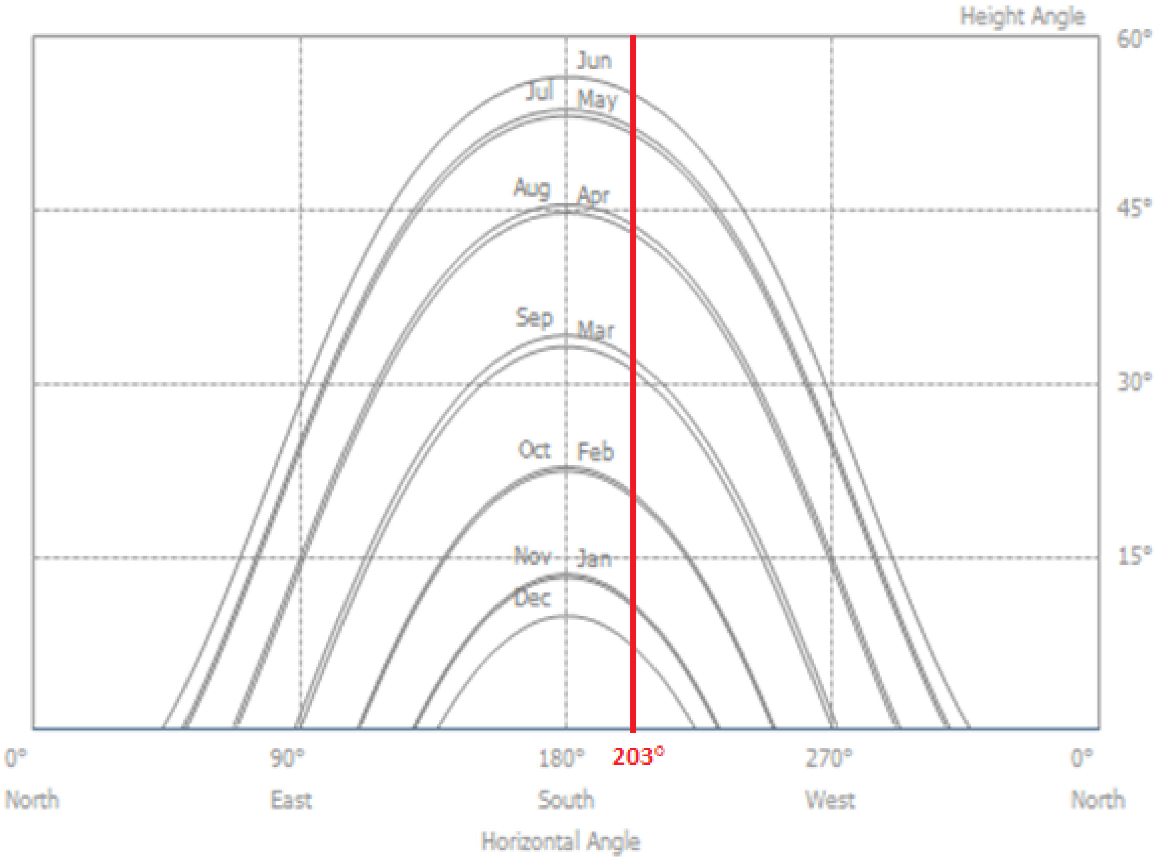

Fig. 1. **Solar elevation angle in different months**

PV modules are facing the south-west direction (azimuth of 203º). This means that theoretically the peak period of electricity production will not be at midday approximately from 12:00 to 13:15, when the sun is the highest, but about an hour later at approximately from 13:15 to 14:30.

Inputting the geographical location of the PV system in the solar PV system design software PV*SOL premium 2019 (R9), it was determined that in average it would be possible to produce 6616 kWh of electricity per year using this specific PV system. However, considering that the azimuth, tilt angle and other factors are not ideal, it was determined that the performance ratio of this specific PV system is 84.1 %. In other words, by using this PV system it is possible to generate 5564 kWh of electricity per year on average. Furthermore, by using the software it was determined that from 10:00 to 18:00 PV modules approximately produce from 75 % to 90 % of all electricity. This is also the time period, when the farm usually has the highest electricity consumption.

The study to determine the power loss due to PV module overheating took place in spring of 2019. In total 4 temperature sensors were used in order to measure the temperature for the study. The first temperature sensor (T1) was used to determine the ambient temperature and 3 temperature sensors (T2, T3 and T4) were used to determine the temperature of PV modules. For data to be more objective, the PV module temperature sensors were mounted on different PV modules at different places and heights. The placement of the temperature sensors on the PV modules is shown in Fig. 2.

Fig. 2. **Placement of temperature sensors on PV modules:**
T1 – ambient temperature sensor; T2, T3, T4 – PV module temperature sensors

The temperature sensors are connected to the Baltic Instrument ltd LLU four-channel thermometer, whereas it is connected to the Baltic instrument ltd LLU data logger. Afterwards, during data processing, the average PV module temperature (T_{avg}) was calculated from all 3 PV module temperature sensors (T2, T3 and T4).

The solar irradiance was measured with a pyranometer CM3. It is connected to the Baltic instrument ltd LLU dual channel amplifier, whereas it is connected to the Baltic instrument ltd LLU data logger. The Baltic instrument ltd LLU data logger records temperature and solar irradiance every minute. The data logger, inverter and other devices are located inside the shed (Fig. 3).

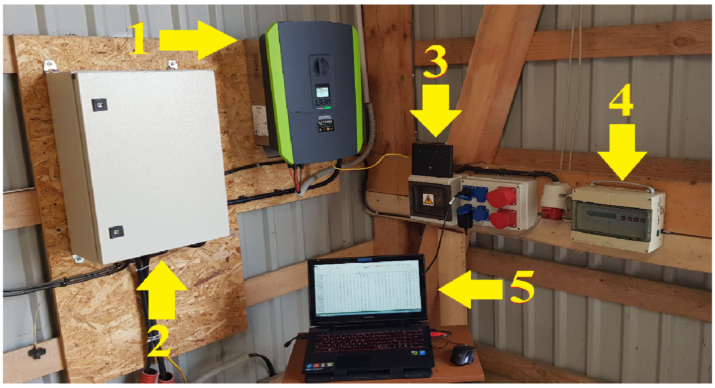

Fig. 3. **Equipment inside the shed:**
1 – inverter; 2 – electric panel; 3 – wireless router; 4 – data logger; 5 – laptop

The wireless router is connected to the inverter and uploads the data to the website www.piko-solar-portal.com (Fig. 4). In the website it is possible to see the produced electricity, power and other information of the PV system at any specific time range. The website www.suncalc.org (Fig. 5) was used to determine the position of the Sun. In the website it is possible to see the solar azimuth angle and solar elevation angle in any specific time, as well as the time of sunrise and sunset on any day.

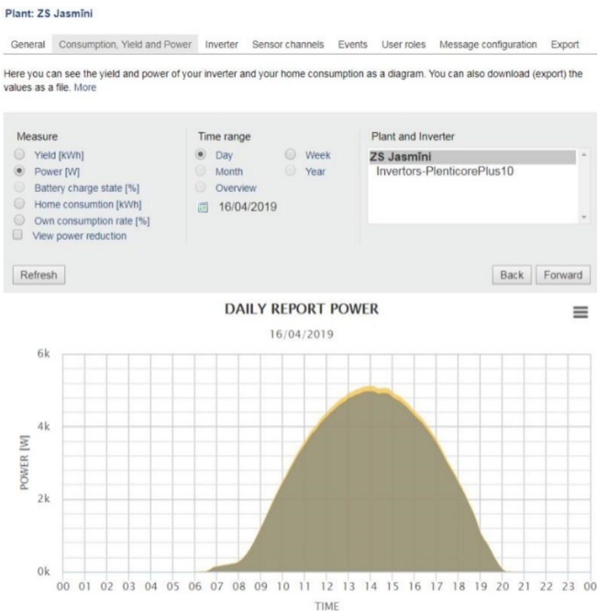

Fig. 4. **Website www.piko-solar-portal.com**

Fig. 5. **Website www.suncalc.org**

Measurements from sunrise to sunset were obtained from April to May, however, for better data analysis only measurements from 4 days were used: April 16, April 20, April 27 and May 8. These days were chosen, because they had relatively different weather conditions that affected the performance of PV modules.

The total area of PV modules is 35.79 m^2 with the total nominal power of 5.94 kW. However, for data to be more objective for further calculations, comparisons and results from the PV module area of 1 m^2 were used. Dividing the total nominal power with the total area gives us the nominal power of 165.97 W for 1 m^2 (165.97 W·m^{-2}) of PV modules.

According to the technical characteristics of RECOM Amur Leopard 270 PV modules, power loss from PV module overheating above 25 ºC is 0.4 % per 1 ºC (0.4 % ·ºC). To calculate the power loss from PV module overheating formula (1) was used. After using formula (1), it is possible to calculate power losses in W·m^{-2}.

$$P_L = (T_{PV} - 25)\ 0.4\,, \tag{1}$$

where P_L – power losses, %;
T_{PV} – PV module temperature, ºC.

Results and discussion

The first measurements were taken on April 16 from 6:06 to 20:19. The weather was sunny and clear throughout the day. The ambient temperature (T1) ranged from 1.5 ºC to 18.2 ºC, but on average it was 12.4 ºC and PV modules overheated up to 40.8 ºC. The highest solar elevation angle was 43.39º at 13:11. Also at this time the highest solar irradiance 691.2 W·m^{-2} was observed. Measurements of the solar elevation angle, irradiance and temperature on April 16 are shown graphically in Fig. 6.

The second measurements were taken on April 20 from 5:55 to 20:28. The weather throughout the day was very unstable due to mostly cloudy skies with only occasional sunlight. The ambient temperature ranged from 3.0 ºC to 17.8 ºC, but on average it was 12.1 ºC and PV modules overheated up to 39.5 ºC. The highest solar elevation angle was 44.79º at 13:10, but the highest solar irradiance was 824.5 W·m^{-2} at 13:40. Measurements of the solar elevation angle, irradiance and temperature on April 20 are shown graphically in Fig. 7.

The third measurements were taken on April 27 from 5:38 to 20:42. The weather was sunny and clear until noon, but later it became cloudy with only occasional sunlight. The ambient temperature ranged from 6.8 ºC to 28.3 ºC, but on average it was 20.4 ºC and PV modules overheated up to 53.5 ºC. The highest solar elevation angle was 47.11º at 13:09. Also at this time the highest solar irradiance 703.5 W·m^{-2} was observed. Measurements of the solar elevation angle, irradiance and temperature on April 27 are shown graphically in Fig. 8.

The fourth measurements were taken on May 8 from 5:13 to 21:05. The weather throughout the day was relatively cold, but mostly sunny. The ambient temperature ranged from 0.1 ºC to 16.8 ºC, but on average it was 10.4 ºC and PV modules overheated up to 44.8 ºC. The highest solar elevation angle was 50.36º at 13:08, but the highest solar irradiance was 816.2 W·m^{-2} at 13:30. Measurements of the solar elevation angle, irradiance and temperature on May 8 are shown graphically in Fig. 9.

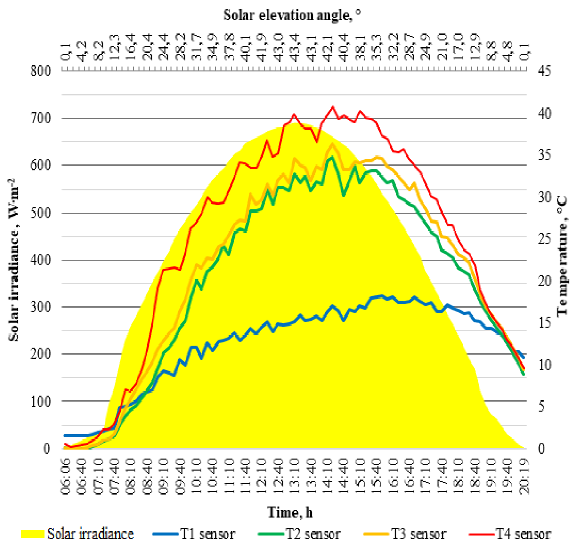

Fig. 6. **Solar elevation angle, irradiance and temperature on April 16**

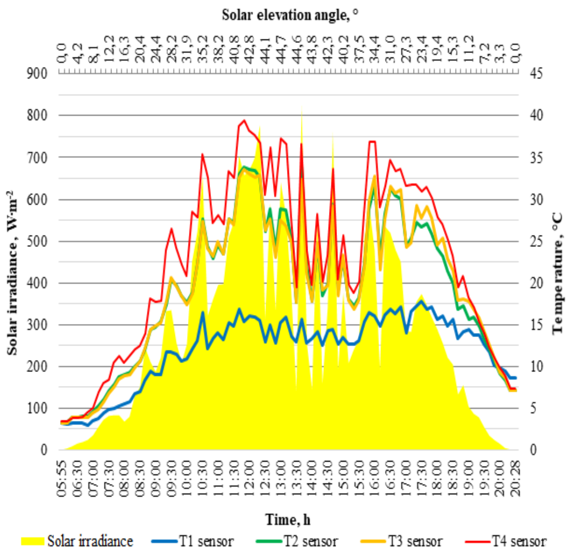

Fig. 7. **Solar elevation angle, irradiance and temperature on April 20**

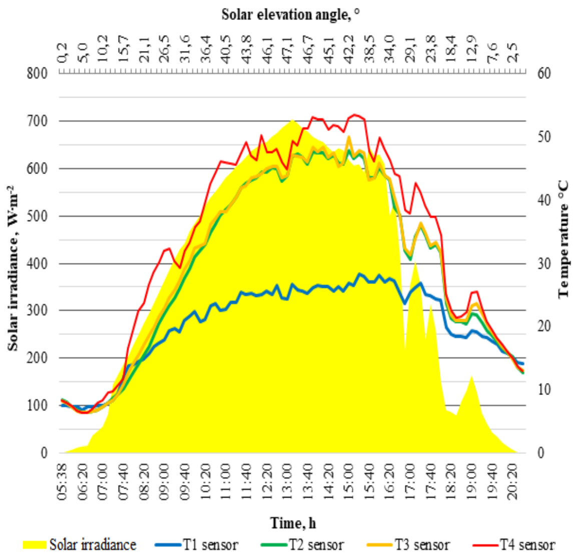

Fig. 8. **Solar elevation angle, irradiance and temperature on April 27**

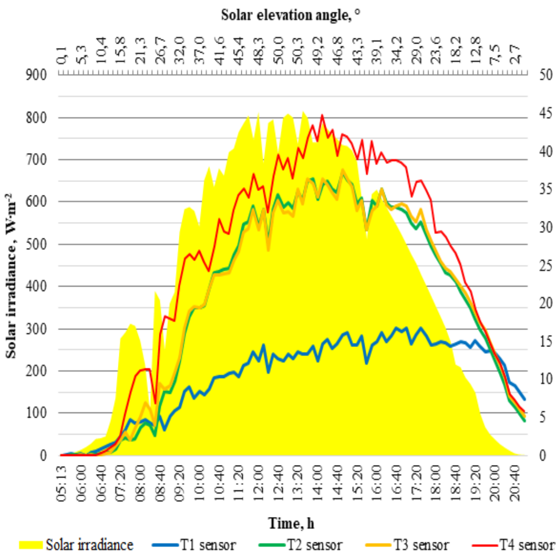

Fig. 9. **Solar elevation angle, irradiance and temperature on May 8**

On April 16, in total PV modules produced 37.9 kWh of electricity or 1059 Wh·m^{-2}. PV power reached 142.74 W·m^{-2} at 14:20, when the Sun was directly facing PV modules at the solar azimuth angle of 202.7º. Power losses from PV module overheating were observed from 10:50 to 17:50, when the average temperature (T_{avg}) of PV modules exceeded the STC temperature of 25 ºC. Power losses from PV module overheating reached 7.02 W·m^{-2}. Measurements of the solar azimuth angle, PV module average temperature, power and power loss on April 16 are shown graphically in Fig. 10.

On April 20, in total PV modules produced 26.37 kWh of electricity or 737 Wh·m^{-2}. PV power reached 154.28 W·m^{-2} at 13:40, when the solar azimuth angle was 190.1º. Power losses from PV module overheating were occasional and were up to 5.72 W·m^{-2}. Measurements of the solar azimuth angle, PV module average temperature, power and power loss on April 20 are shown graphically in Fig. 11.

On April 27, in total PV modules produced 33.51 kWh of electricity or 936 Wh·m^{-2}. PV power reached 128.86 W·m^{-2} at 13:40, when the solar azimuth angle was 190.8º. Power losses from PV module overheating were observed from 9:00 to 18:00. Power losses from PV module overheating reached 12.63 W·m^{-2}. Measurements of the solar azimuth angle, PV module average temperature, power and power loss on April 27 are shown graphically in Fig. 12.

On May 8, in total PV modules produced 41.38 kWh of electricity or 1156 Wh·m^{-2}. PV power reached 149.37 W·m^{-2} at 13:40, when the solar azimuth angle was 191.8º. Power losses from PV module overheating were observed from 10:30 to 18:30. Power losses from PV module overheating reached 8.34 W·m^{-2}. Measurements of the solar azimuth angle, PV module average temperature, power and power loss on May 8 are shown graphically in Fig. 13.

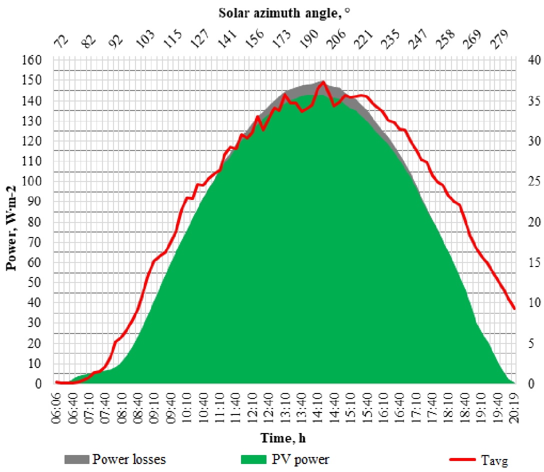

Fig. 10. **Solar azimuth angle, PV power and power losses on April 16**

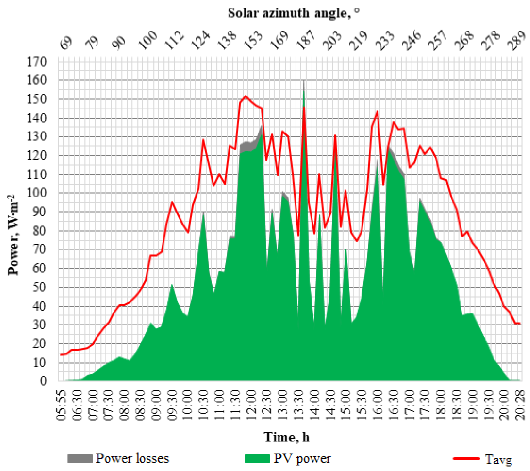

Fig. 11. **Solar azimuth angle, PV power and power losses on April 20**

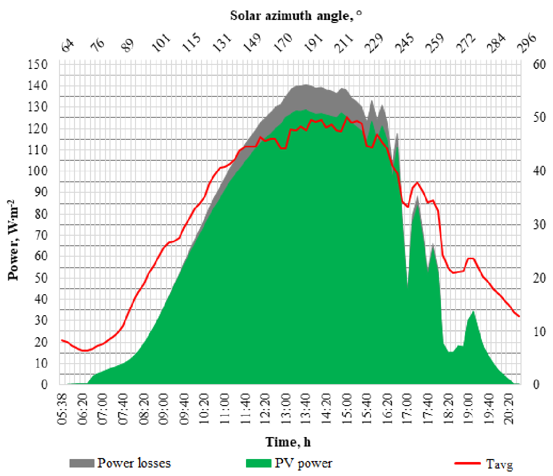

Fig. 12. **Solar azimuth angle, PV power and power losses on April 27**

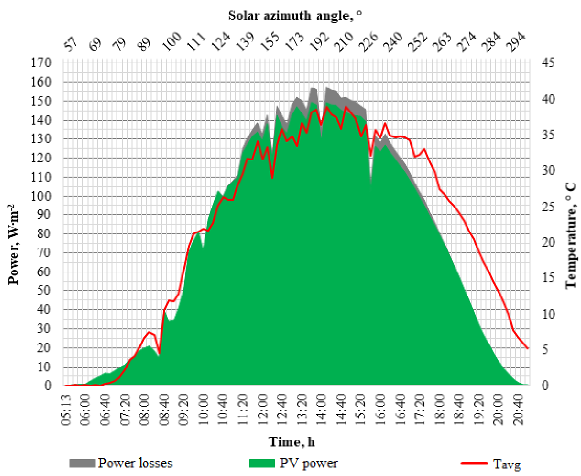

Fig. 13. **Solar azimuth angle, PV power and power losses on May 8**

Analysing and comparing the graphs in Fig. 6-13, it is clear that the different weather conditions had a very big impact on the performance of the PV modules. All obtained measurements from sunrise to sunset from Fig. 6-13 are summarized in Table 1.

However, the time of sunrise and sunset was different on each day. As a result, the daylight duration was also different on each day. To achieve more objective results the obtained data were analysed from 10:00 to 18:00. This period of time was chosen, because PV modules produce approximately from 75 to 90 % of all electricity at this time and the farm usually has the highest electricity consumption.

Table 1

Summary of obtained measurements

Measurement	Day of obtained measurements			
	April 16	**April 20**	**April 27**	**May 8**
Sunrise time, h	6:06	5:55	5:38	5:13
Sunset time, h	20:19	20:28	20:42	21:05
Daylight duration	14 h 13 min	14 h 33 min	15 h 4 min	15 h 52 min
Lowest ambient temperature, ºC	1.5	3.0	6.8	0
Highest ambient temperature, ºC	18.2	17.8	28.3	16.8
Highest PV module temperature, ºC	40.8	39.5	53.5	44.8
Highest solar elevation angle, º	43.39	44.79	47.11	50.36
Highest solar irradiance, W·m^{-2}	691.2	824.5	703.5	816.2
Highest PV power, W·m^{-2}	142.74	154.28	128.86	149.37
Highest power losses, W·m^{-2}	7.02	5.72	12.63	8.34
Total produced electricity, kWh	37.9	26.37	33.51	41.38
Produced electricity, Wh·m^{-2}	1059	737	936	1156

One of the most important parameters of PV modules is PV efficiency. It is a measurement used to show how much solar irradiance PV modules can convert into power [20]. To calculate the average efficiency of PV modules from 10:00 to 18:00, formula (2) was used.

$$\eta = \frac{P}{G}\ 100\,\%\,, \tag{2}$$

where η – efficiency of PV modules, %;
P – PV power, W·m^{-2};
G – solar irradiance, W·m^{-2}.

After all necessary calculations, the most important results from 10:00 to 18:00 are summarized in Table 2.

Table 2

Summary of results from 10:00 to 18:00

Parameter	Day of obtained measurements			
	April 16	**April 20**	**April 27**	**May 8**
Average solar irradiance, W·m^{-2}	567.96	432.74	560.81	665.37
Average ambient temperature, ºC	15.49	14.68	25.35	13.50
Average PV module temperature, ºC	31.07	27.03	43.07	32.85
Average power losses, %	2.43	0.81	7.23	3.14
Average power losses, W·m^{-2}	3.20	1.25	7.98	4.15
Average PV power, W·m^{-2}	116.82	77.13	103.51	122.51
Average efficiency of PV modules, %	20.57	17.82	18.46	18.41

Mathcad and Mathlab mathematical packages were used for data processing and mathematical modelling. Nonlinear multivariable regression (3) was observed. The coefficient of determination R^2 is also calculated to describe the accordance of the theoretical relationship to obtained data.

$$P = a_0 + a_1 G + a_2 G^2 + a_3 T_{PV} + a_4 {T_{PV}}^2 + a_5 G T_{PV}\ , \tag{3}$$

where P – PV power, W·m^{-2};
a_i – constant that describes the effect of solar irradiance and PV module temperature on PV power;
G – solar irradiance, W·m^{-2};
T_{PV} – PV module temperature, ºC.

After accomplishing all necessary calculations, the equation (4) is received.

$$P = -48.5 + 0.032G + 4.4\ 10^{-5}G^2 + 4.96T_{PV} - 0.03T_{PV}{}^2 + 6\ 10^{-4}GT_{PV}\ . \tag{4}$$

The coefficient of determination $R^2 = 0.98$ shows a strong accordance of the theoretical relationship to obtained data. The graphical interpretation of the PV power, PV module temperature and solar irradiance is shown in Fig. 14.

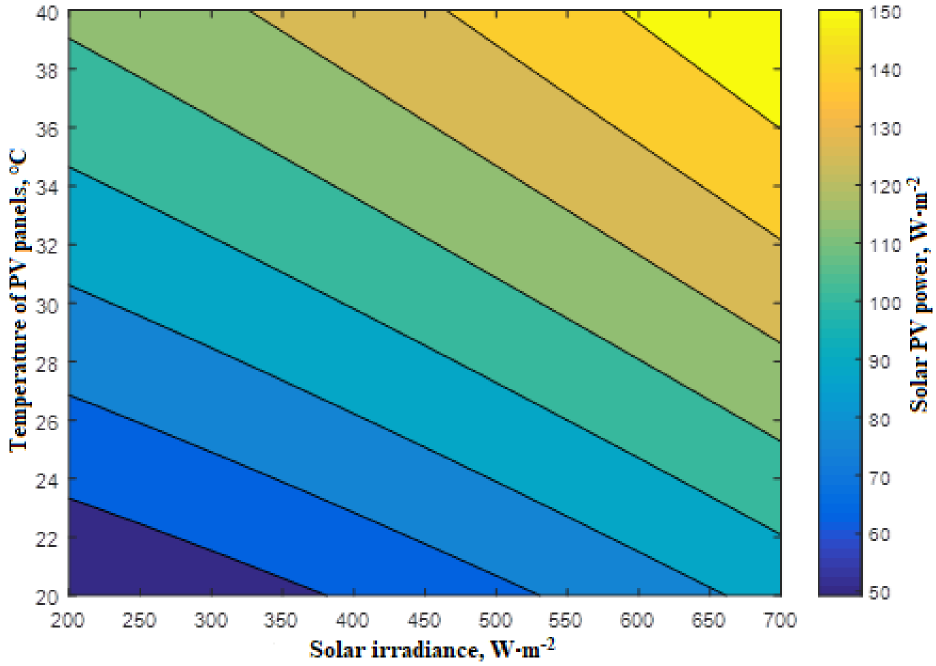

Fig. 14. **Graphical interpretation of PV power, PV module temperature and solar irradiance**

In equation (4) the part $-0.03T_{PV}$ shows that, as the PV module temperature increases, the PV power begins to decrease, and as a result, the efficiency of PV modules begins to decline.

Conclusions

1. The highest solar irradiance on a clear day is usually, when the solar elevation angle is the highest, but the most PV power is, when the Sun is directly facing PV modules.
2. The average efficiency of PV modules from 10:00 to 18:00 was 18.82 %. The highest efficiency of PV modules 20.57 % was on April 16, when the weather throughout the day was sunny and clear with the average solar irradiance of 567.96 $W \cdot m^{-2}$. The lowest efficiency of PV modules 17.82 % was on April 20, when the weather throughout the day was cloudy with only occasional sunlight and the average solar irradiance was 432.74 $W \cdot m^{-2}$.
3. High temperature causes power loss. On April 27 PV modules overheated up to 53.5 ºC. As a result, power loss from PV module overheating was up to 12.63 $W \cdot m^{-2}$, but on average from 10:00 to 18:00 it was 7.98 $W \cdot m^{-2}$. Comparing the results of April 16 and April 27, when the average solar irradiance was almost the same, but the PV module temperature was 12 ºC higher on April 27, the PV module efficiency on April 16 was 2.11 % higher.
4. High solar irradiance and low ambient temperature are ideal factors for PV modules. The highest average PV power from 10:00 to 18:00 was 122.51 $W \cdot m^{-2}$ on May 8, when the average solar irradiance was 665.37 $W \cdot m^{-2}$ and the average temperature of PV modules was 32.85 ºC.

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