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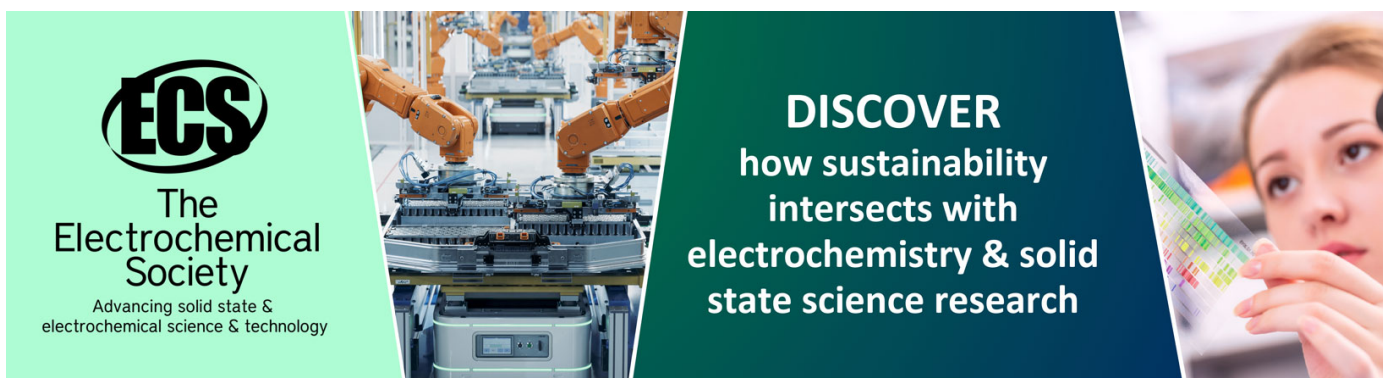
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The influence of orientation of photovoltaic panels on the amount of electric energy production for consumers

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Abstract. The paper presents how the energy demands of selected consumers of electric energy may be satisfied with the use of a photovoltaic plant. The essence of the problem concerns, on one hand, dynamics of change of a daily profile of electric energy consumption by a consumer and on the other hand, provision of properties and parameters of a PV power plant. The production size of electric energy was determined for panels positioned at the 30 degree angle with east, south, west and east and west orientation operating simultaneously. The obtained results were compared with a daily dynamics of electric energy demands for a dairy, sewage treatment plant, water uptake station and rural farms. The analysis was carried out for the selected summer months (June, July and August) based on hourly time intervals both for the energy source and a recipient. Based on the collected data and calculations made, a level of substitution of conventional energy with energy from a PV plant for particular recipients was determined with the use of the coefficient of satisfaction of electric energy demand. Based on the experiment one may expect that the PV energy demand will be satisfied at the level between 23 a d 39%. In this case, the direction of panels' location was not significant. Moreover, the coefficient of energy excess, which a consumer cannot use, was determined. The lowest values of this excess for positioning of panels at the east and west direction simultaneously were achieved. In these conditions, the unused electric energy constituted not more than 7%.

1. Introduction

The environmental issues and raising demand for clean energy are strong stimuli to undertake research for investment needs and within the scope of use of renewable energy sources. Urban environments with regard to high density of energy consumption are considered as one of the most promising locations for renewable energy technological installations [3] however, they are considerably geographically limited. The need to reduce emission of pollution to atmosphere following from the increase of energy consumption caused development of renewable energy sources and their application. Photovoltaic systems are the most popular among various types of available technologies of renewable energy sources (PV) [1,2]. Designing and development of solar systems requires knowledge on the variability and maximum use of solar radiation which gets to the installation. Numerous research concerning determination of the amount of solar radiation which gets to the horizontal surface have been undertaken [4-6]. The amount of energy generated from a photovoltaic



installation depends mainly from the azimuth and tilt angle of an installation. It is commonly known that on the northern hemisphere, an optimal azimuth is in the southern direction but the tilt angle towards the horizon depends on conditions such as geographical latitude, climate, composition of atmosphere and the period of use [7-14].

Photovoltaic installations, as devices using solar radiation, which are characterized with great variability in relation to the time of a day or time of a year cannot be an autonomous source of supply in electric energy but can reduce the amount of purchased energy from the system supplier [15]. One of the effective solutions which enable the increase of use of available energy of solar radiation is application of systems for tracing apparent solar movement. Kacira et al., [16] were among those, who carried investigations thereon. They analysed performance of photovoltaic modules mounted in the tracing system towards two axes and proving that the daily profit of the generated energy achieved 29.3% and 34.6% respectively at the rotation towards the vertical axis and in relation to the rotation around the vertical and horizontal axis with reference to the stationary system. Neville, [17] proved that for the one and two-axis tracing system, respectively by 36% and 41% more energy was obtained in comparison to photovoltaic devices operating in the stationary system. On the other hand, Marcos [18] developed a mathematical model to find an optimal orientation and tilt angle of a PV installation in Egypt stating that through a daily change of orientation and tilt angles an increase of the total annual production by 29.18% is possible. Huang and Sun [19] developed a new three-positional tracing system which positioned the PV receptive surface only in three permanent locations (E, S, W). The results proved that an optimal tilt angle in the morning and in the afternoon is about 50° and enabled the increase of the energy production by 24.5%.

According to the cited literature, exploitation research oriented at the maximization of the energy yield from PV systems are carried out independently from the geographical location or climate and focus on the possibility of tracing the sun location. This orientation is just in case of small installations composed of several panels and not in case of micro-installations with the power of a few or a few hundred kilowatts. Therefore, the paper covers the issue of optimization of the east-west positioning of the receptive surface of a PV plant taking into consideration the energy profile of a recipient.

2. Materials and methods

Data for this paper was obtained from three sources. Firstly, data concerning the amount of available solar radiation energy was obtained from long-standing (typical meteorological years and statistical climatic data) available on the websites of the Ministry of Infrastructure and Construction for the location of the research facilities. The analysis was carried out for panels with 30° inclination to the horizon including an hourly distribution of solar radiation energy.

The second source consisted of the authors' own research carried out in the photovoltaic plant located at the Department of Production Engineering and Power Industry of the University of Agriculture in Krakow. The operation of CIGS type thin-layer modules with the capacity of 230 Wp were taken into consideration. Plant configuration enables collection of data on the energy production for panels with east (1.54 kWp), south (4.4 kWp) and west (1.54 kWp) orientation, while, the energy yield was determined in comparison to the value of capacity installed in particular chains of modules.

The paper includes also results of author's own measurements of electric energy consumption by the selected consumers. An hourly profile and their energy demands were determined for two different groups of individual recipients, dairies, sewage treatment plants and two different drinking water uptake stations. Profiles of energy recipients were made with the use of parameter analysers of AS-3 network which register hourly electric energy consumption.

The next stage of work was determination of the hourly distribution of the annual amount of available solar radiation energy for PV modules surface with east, south and west orientation. These calculations were made for determination of the PV plant operation based on previous own studies. They prove that the operation of thin-layer panels starts when the solar radiation intensity exceeds $50 \text{ W}\cdot\text{m}^{-2}$ and lasts to the moment its value drops below $40 \text{ W}\cdot\text{m}^{-2}$.

In order to assess a degree of photovoltaic energy use a coefficient of satisfaction of energy demands of a recipient was defined (V_{pz}). With regard to the amount of available solar radiation energy and the assumed reduction of PV plant capacity to the ordered capacity of a specific recipient, we applied in the research only the period with the best solar conditions i.e. June, July and August. For this period, also the coefficient of electric energy excess obtained from a PV plant was determined (V_{ne}). It determines the amount of energy produced, whose recipient is not able to consume it and it follows from his energy demand profile. Coefficients of energy and energy excess use were defined for four separately analysed orientations of PV panels position.

$$V_{pz(E,S,W,E-W)} = \frac{E_{pv(E,S,W,E-W)} - E_{n(E,S,W,E-W)}}{E_c} \cdot 100\% \quad (1)$$

$$V_{ne(E,S,W,E-W)} = \frac{E_{n(E,S,W,E-W)}}{E_{pv(E,S,W,E-W)}} \cdot 100\% \quad (2)$$

where:

E_c – consumption of electric energy in the facility

$E_{PV(E,S,W,E-W)}$ – energy generated in a PV plant for east (E), south (S), west (W) orientation with the positioning of panels towards east and west (E-W),

$E_{n(E,S,W,E-W)}$ – energy excess generated in a PV plant for east (E), south (S), west (W) orientation with the positioning of panels towards east and west (E-W),

3. Results and discussion

For conditions presented in the Materials and methods chapter, analyses of solar radiation energy availability were carried out for data, where a photovoltaic plant, constructed with thin-layer panels generates electric energy. After these border values were included, an annual availability of solar energy for hourly intervals of time in relation to the panels orientation was presented in figure 1.

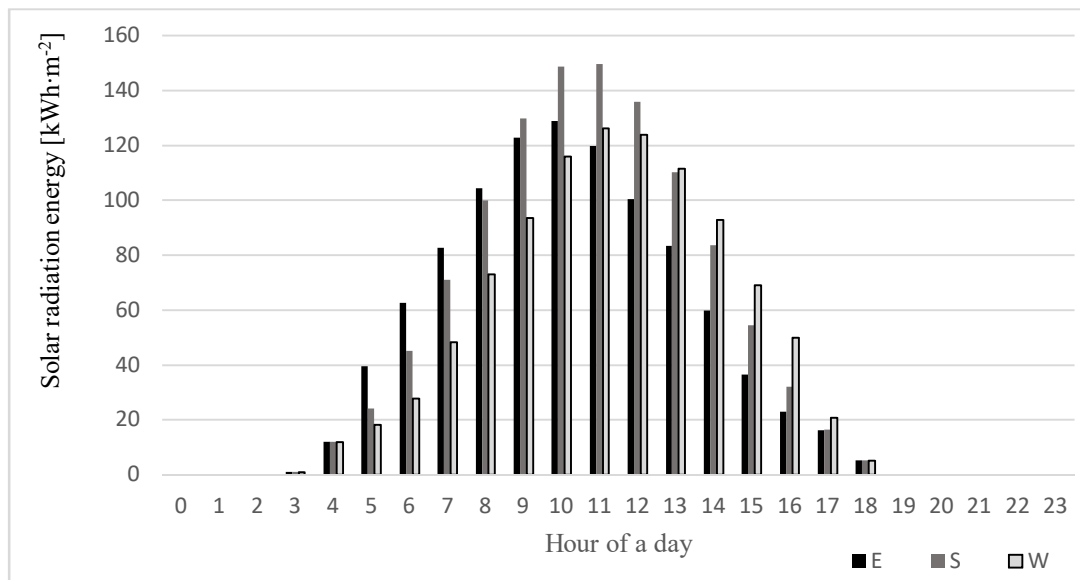


Figure 1. Impact of azimuth of PV module surface on hourly annual amount of available solar radiation energy which enable operation of installation.

The analysis shows that the change in panels orientation from southern to eastern and western one enabled enhancement of the solar radiation energy availability in the morning and afternoon with

simultaneous reduction of maximum values in the afternoon. The biggest amount of energy, as expected, was obtained in case of the south orientation of panels. It achieved the value of $1120 \text{ kWh}\cdot\text{m}^{-2}$ in a year's scale. The change of the azimuth towards east reduced energy availability to almost $1000 \text{ kWh}\cdot\text{m}^{-2}$ and the lowest amount of energy was obtained for the western azimuth ($989.4 \text{ kWh}\cdot\text{m}^{-2}$). The operation of a PV plant is influenced not only by annual availability of solar radiation energy but also by the level of energy in shorter time ranges, which influences the efficiency of energy conversion. Figure 2 presents the characteristics of variability of average daily amounts of available solar radiation energy in an annual period for the selected orientations of panels towards east (E), south (S) and west (W).

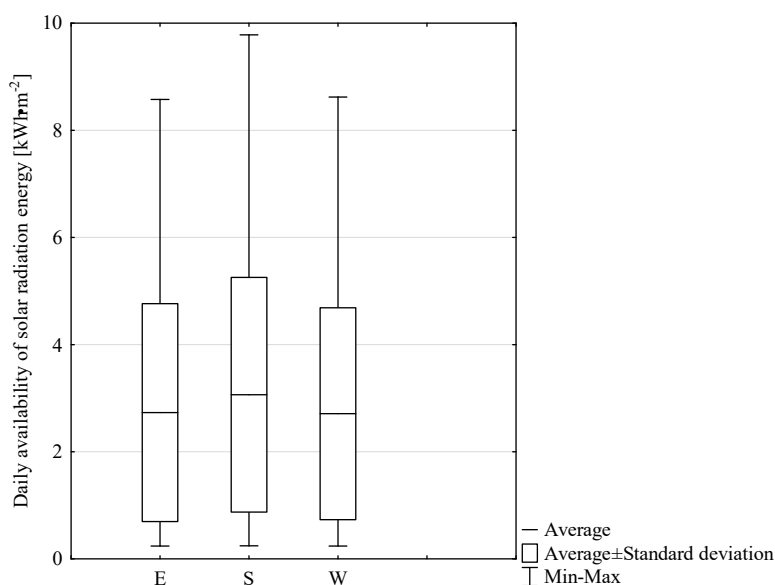


Figure 2. Characteristics of location and distribution of average daily amounts of available solar radiation energy in annual period for E, S and W azimuth.

To evaluate whether the average daily amounts of available solar radiation energy in relation to orientation of panels differ statistically between each other, a significance test of difference between the averages was carried out for them. The analysis which was carried out in *Statistica* program, proves that for the assumed level of significance ($p = 0.05$) there is no basis to reject a zero hypothesis about the equivalence of the average daily availability of solar radiation energy in the annual period for E, S and W orientation.

Changes in the total intensity of solar radiation on the surface with 30° tilt to the horizon in particular hours in relation to the surface orientation depend also on the season of the year. Table 1 presents characteristics of the available level of solar radiation for three selected characteristic months of the year.

Table 1. Characteristics of monthly availability of solar radiation energy with the value which enables the operation of a plant in relation to PV module orientation.

Month:	Amount of available solar radiation energy [$\text{kWh}\cdot\text{m}^{-2}$] for PV module orientation towards:		
	E	S	W
January	25.7	33.6	24.6
March	66.4	73.9	62.1
June	152.2	161.7	156.2

The analysis shows (Table 1) that in winter months the highest amount of available solar radiation energy occurs for panels with south orientation. It mainly results from the Earth's orbit, which causes that the places of sunrise and sunset shift during the year and the height of Sun over the horizon changes in the moment of culmination. For January, available amount of solar radiation energy for the tilt angle of 30° along with the change of its orientation was within $24.6 \text{ kWh}\cdot\text{m}^{-2}$ to $33.6 \text{ kWh}\cdot\text{m}^{-2}$ which constitutes less than 3% of the annual sum of radiation. Increase of the monthly sums of radiation after the panels orientation change from the south to the east and west one is visible since spring to autumn and its highest participation was reported in June. For this month, the change in panel setting caused a change of radiation by over 6% towards the south.

In order to assess differences in solar radiation energy availability in relation to the panels orientation for the selected characteristic months analysis of daily availability of energy amount for these time intervals was carried out. Results of analysis were presented in figure 3 and in table 2.

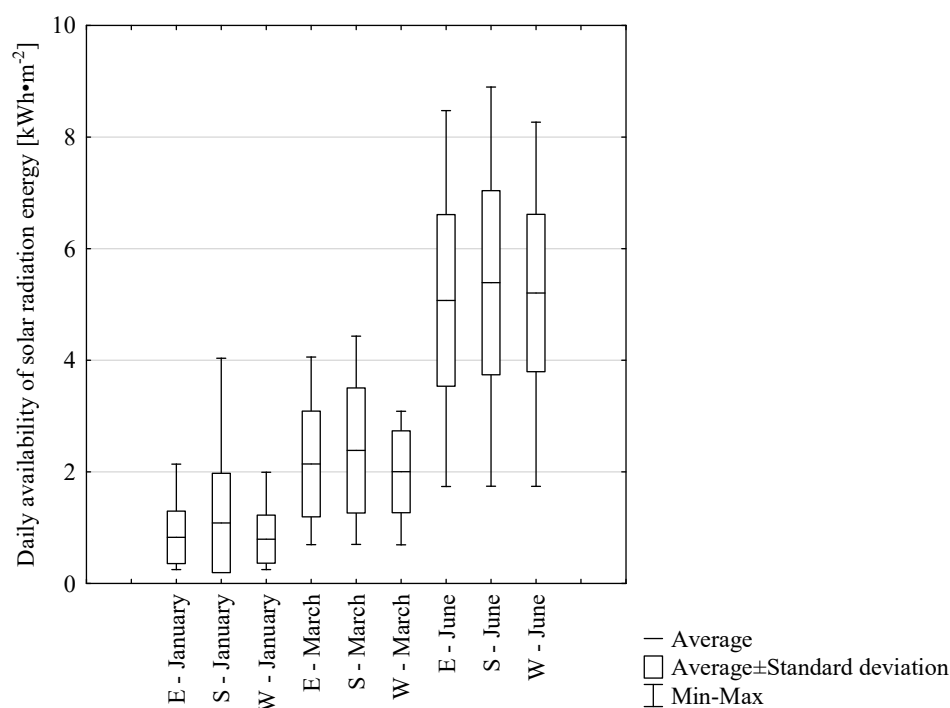


Figure 3. Characteristics of location and distribution of daily availability of solar radiation energy with value which enables operation of installation in relation to photovoltaic panels orientation for selected months.

Assessment of significance of differences between the average daily amount of solar radiation energy with the value which enables the operation of installation for particular orientations of photovoltaic panels in the selected months was carried out in *Statistica* program. The test showed that at the level of significance $p=0.05$ there are statistically significant differences which enable rejection of a zero hypothesis and stating that the analysed months differ with a daily average availability of energy. However, no significant differences were found in the availability of energy in a particular month at the change of the PV module orientation.

Table 2. Average daily availability of solar radiation energy for the selected months with the value which enables the installation operation in relation to photovoltaic panels orientation for the selected months.

Month:	Average daily availability of solar radiation energy [kWh·m ⁻²] for the following orientations:			The level of significance p between the average daily availability of energy in relation to orientation	
	E	S	W	E towards S	W towards S
January	0.83	1.09	0.79	0.16	0.12
March	2.14	2.39	2.00	0.37	0.12
June	5.07	5.39	5.21	0.44	0.64

However, despite no statistically significant differences between the average daily amount of available solar energy in a given month in relation to the orientation of panels, research was continued with regard to the fact that changes in the hourly profile of availability of energy were observed. Since, available energy is used for satisfaction of local energy needs of recipients with various energy demand profiles.

Average daily profiles of hourly energy demand for selected 6 recipients with a varied energy demand in particular day times were used in the research. Because of a great scope of hourly energy consumption between particular facilities (Table 3) reduced profiles of hourly energy demand, presented in figure 4 a and b were developed. Profiles of energy demands of recipients and availability of energy from a PV plant was carried out in the same time periods.

Table 3. Characteristics of electric energy demand of selected recipients.

		Recipients:					
		1	2	3	4	5	6
P_u	kW	20	40	220	90	60	60
$E_{d\ min}$	kWh	180.4	239.0	1085.6	683.3	540.0	575.3
$E_{d\ \dot{s}r}$	kWh	209.9	373.5	2304.5	1265.9	682.1	669.8
$E_{d\ max}$	kWh	233.5	454.2	2731.2	1603.1	1039.5	825.6
V_E	%	7.9	18.5	18.7	21.6	16.1	8.6
P_{min}	kW	3.7	5.0	21.1	14.9	0.1	0.0
$P_{\dot{s}r}$	kW	8.7	15.6	96.0	52.7	28.4	27.9
P_{max}	kW	16.1	34.9	220.1	86.0	55.2	52.2
V_p	%	31.2	38.8	67.4	25.7	44.0	53.6

where: P_u – ordered capacity of a plant, E_d – daily consumption of electric energy, V_E and V_p – coefficient of variability of respectively electric energy consumption and power demand, P – power demand, recipient.: 1,2 - rural households; 3 - Regional Dairy Cooperative; 4 - municipal sewage treatment plant,; 5,6 - drinking water uptake stations.

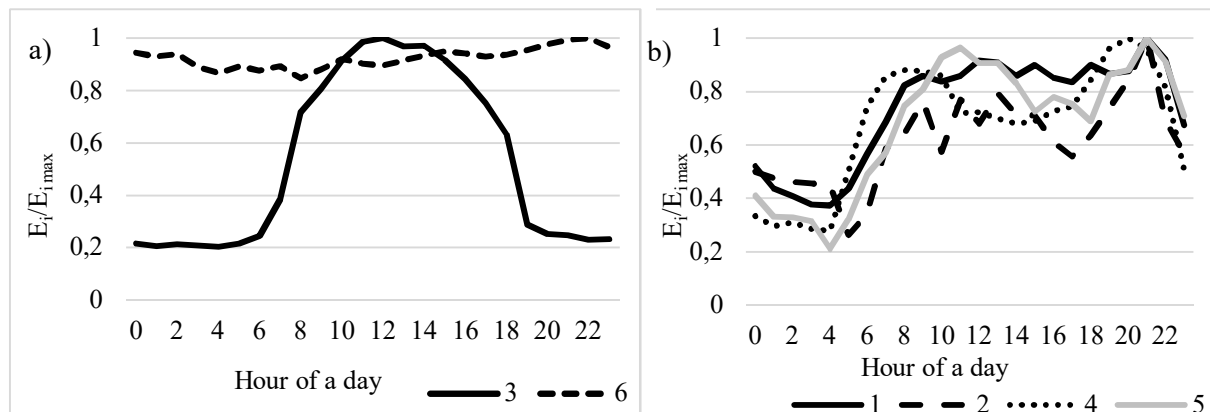


Figure 4. Reduced consumers' demand profiles for electric energy by: a) low, b) high daily variability of hourly electric energy consumption.

where:

E_i - hourly energy consumption on a particular day,

$E_{i,max}$ - maximum hourly energy consumption on a particular day.

Since, within analogical period of time, electric energy consumption and amount of energy generated in a plant were measured, it was possible to compare a degree of satisfaction of energy demand for particular facilities in relation to photovoltaic panels orientation. Before starting to indicate a degree of satisfaction of energy demand all results were reduced to the hourly periods and the power of photovoltaic plants for all facilities was assumed at the level of ordered capacity.

Simulations which were carried out enabled determination of indexes which describe cooperation of a photovoltaic plant with a particular object in relation to panels orientation. Particular results of analyses were set in table 4 and in figure 5 a daily energy demand profile for facilities and availability of energy from PV plant for the selected days with various amount of available solar energy was presented.

Table 4. Characteristics of the impact of PV panels orientation on the percentage degree of satisfaction of electric energy demand of final recipients in summer months.

PV panels orientation	Coefficient [%]	Recipients:					
		1	2	3	4	5	6
E	V_{pzE}	35	34	37	34	30	27
	V_{neE}	8	20	5	12	9	2
S	V_{pzS}	38	37	39	35	31	28
	V_{neS}	3	17	4	14	8	0
W	V_{pzW}	32	29	37	28	25	23
	V_{neW}	4	23	5	17	10	1
E-W	V_{pzE-W}	35	35	35	34	29	26
	V_{neE-W}	1	11	3	7	6	0

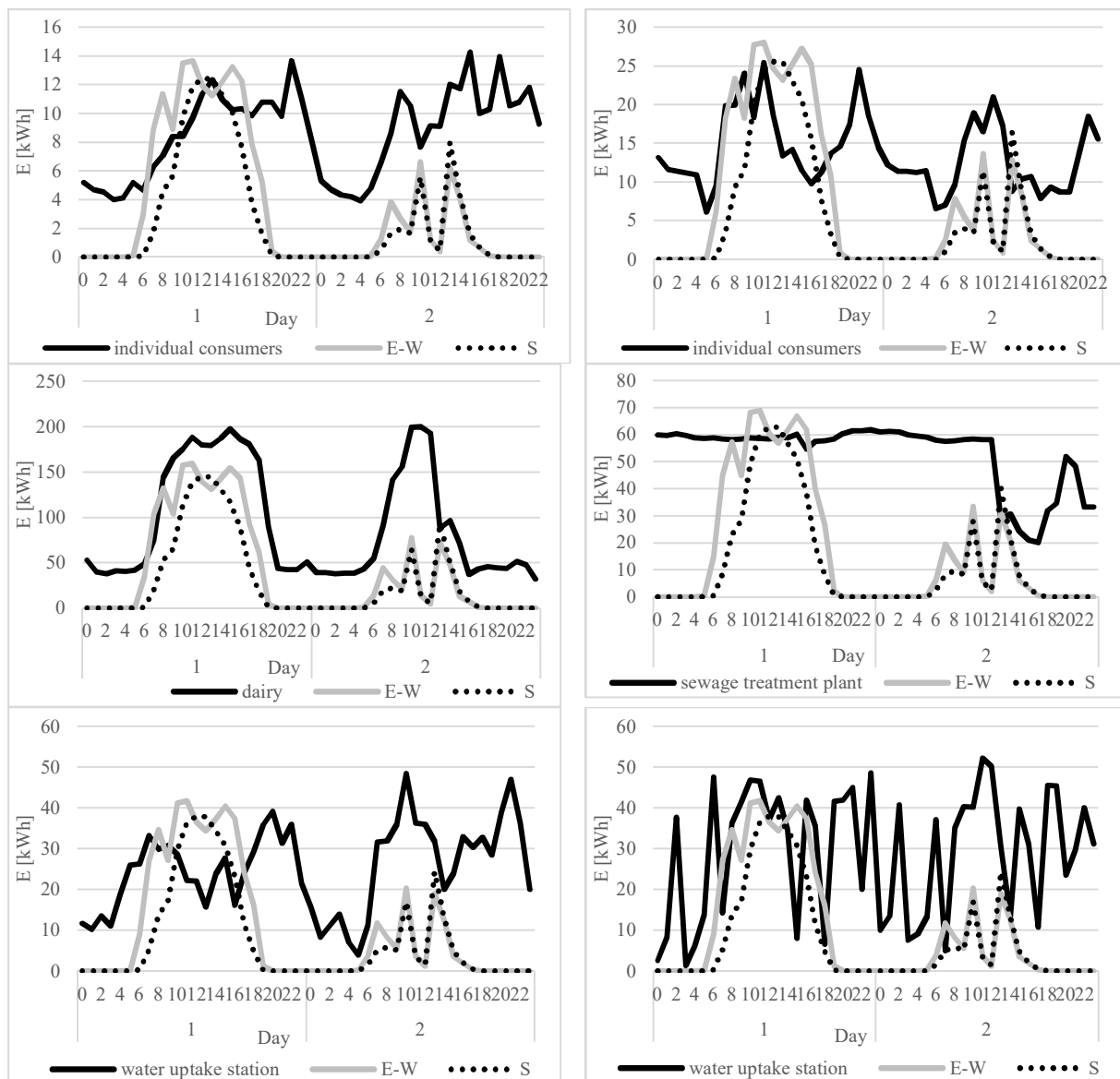


Figure 5. Daily profiles of consumers' energy demands along with characteristics of available energy from photovoltaic plant (1- sunny day, 2 - cloudy day).

The analyses show that the photovoltaic plant constructed on thin-layer photovoltaic panels with the power equal to arbitrary power in summer enables satisfaction of energy demand within 23 to 39%. For the investigated facilities, it was reported that the change of orientation of panels' positioning from the south to the east and west one slightly affected the change of satisfaction of energy demand. However, for all facilities, east-west orientation of panels enabled increase of use of the generated energy in a PV plant for own needs which proves better adjustment of an hourly profile of energy demand to its availability. In order to assess whether the reported differences in the satisfaction and amount of generated energy excess after change of the orientation of panels are statistically significant, a test of significance of differences between average degree of satisfaction of energy demand and coefficients of energy excess on particular days covered by the research was carried out. The obtained values of the level of significance $p=0.05$ between indexes determined for the south orientation and after the change of orientation was set in table 5.

Table 5. Characteristics of differences in level of energy demand satisfaction and energy excess after the change of PV panels orientation from the south to east and west one.

PV panels orientation towards:	Coefficient:	Level of significance p between degree of satisfaction of energy demand and amount of energy excess after change in PV panels orientation from south (S) to east (E), west (W) and after power was distributed east-west (E-W) for consumer:					
		1	2	3	4	5	6
E	V_{pzE}	0.79	0.63	0.89	0.85	0.98	0.85
	V_{neE}	0.00	0.08	0.26	0.01	0.03	0.00
W	V_{pzW}	0.26	0.19	0.26	0.41	0.18	0.37
	V_{neW}	0.32	0.03	0.00	0.01	0.02	0.00
E-W	V_{pzE-W}	0.24	0.62	0.48	0.52	0.42	0.13
	V_{neE-W}	0.00	0.82	0.03	0.01	0.00	-

The analysis proves that for the accepted coefficient of significance no statistically significant differences in the degree of satisfaction of energy demand in relation to positioning of PV panels was not reported. However, differences in the amount of excess of generated energy for particular settings of panels which could not have been used with regard to lack of uniformity of demand and availability of energy were reported. Its lowest amounts occurred when PV panels were set towards east and west. For such positioning, the index of excess of unused energy did not exceed 7%. The highest amounts of unused energy for own purposes, obtained from a PV plant occurred when panels were set towards west and achieved the level of 23%.

4. Conclusions

The analysis shows that for the level of significance of 0.05 there are no basis to state that the average daily availability of solar radiation energy in a year period is different for azimuth E, S and W. Despite that, studies were carried out because changes in the hourly profile of availability of solar radiation energy were reported.

For a photovoltaic plant with rated power equal to contractual capacity of the facility constructed based on thin-layer photovoltaic panels in summer period energy demand may be satisfied between 23 and 39%. On the other hand, the change of orientation of panels' positioning from the south to the east and west one slightly affects a degree of satisfaction of energy demand. However, for all investigated facilities distribution of PV panels symmetrically towards east and west enables the increase of the use of generated energy for own needs which proves better adjustment of an hourly profile of energy demand to its availability.

It was reported during the tests that the manner of positioning panels affects the amount of the generated energy excess, which could not have been used by the investigated establishments. Its lowest amounts occurred when PV panels were set towards east and west symmetrically. For such setting the index of excess of unused energy did not exceed 7%. On the other hand, the highest amounts of unused energy for own purposes, obtained from a PV plant occurred when panels were set towards west and achieved the level of 23%.

Acknowledgements

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