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Thermal aspects of operation of the selected photovoltaic components

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In the study the authors introduced the idea of the operation of the photovoltaic system with possibly low temperature of photovoltaic cell surfaces. The attention was paid both to PV panels which are very popular in Poland and to currently less popular PV roofing tiles. The selected solutions were characterized, which – in the authors' opinion – have a practical impact on lowering of the temperature of operation of photovoltaic cells, and thus increase the system's energy yield. Special attention was paid to the concept of operation of the hybrid PVT collector as well as the selection of roof substrate for PV roofing tiles. Potential benefits resulting from conducted works were indicated for various groups of recipients. The results of first tests and calculations were also presented, which confirm the need of further research works on this issue.

KEYWORDS: photovoltaics, solar collector, Photovoltaic Thermal, PV temperature, photovoltaic roofing tile, power yield, efficiency, roof substrate

1. Introduction

An important problem raised in the media in recent years is energy security. The topic applies to all the producers and consumers of electric energy. Particular discussions conducted in relation to this subject already bear fruit in the form of a number of interesting initiatives. Their goal is both to introduce changes in the existing regulations as well as to develop the technology in order to increase production capacity. Constant increase of the demand for electric energy is visible, most of all, in the dynamically developing technology used to obtain energy from renewable sources. It is in them that the greatest hopes for assuring energy security are placed. Energy generation equipment from the RES (Renewable Energy System) group are characterized by higher and higher efficiency rates, and their process decrease to a level that makes them cost-effective from the consumer's point of view. Apart from the development of existing technologies, also attempts at combining them are made. One of them is combining two technologies of energy generation from solar radiation, referred to as the photovoltaic technology and the thermal technology.

Undoubtedly Building Integrated Photovoltaics (BIPV) also deserves attention. Due to connection with photovoltaic cells some of the construction elements (such as hollow bricks, roofing tiles, glasses) form a consistent whole and are characterized with the properties of both elements. Replacing standard ceramic roofing tile with a solar roofing tile allows not only to obtain thermal insulation or hydro-insulation of the building, but also allows to converse the solar energy into electric energy. Also, the energy is formed in place of its utilization, which is particularly important at the urban areas with dense building development and at the areas distant from the power plant. These elements do not disturb the aesthetics of the landscape and do not require an extra space, hence this element of the BIPV system has the biggest chances to be quickly popularized among building investors and to become commonly used in ecological construction, gradually supplanting traditional photovoltaic panels.

As commonly known from the subject literature [1, 3, 4, 6] the temperature of photovoltaic cells has the impact on the amount of the generated energy, which was shown in Figure 1. Its increase leads to reduction in the value of the obtained voltage, and thus to reduction of the panel's efficiency.

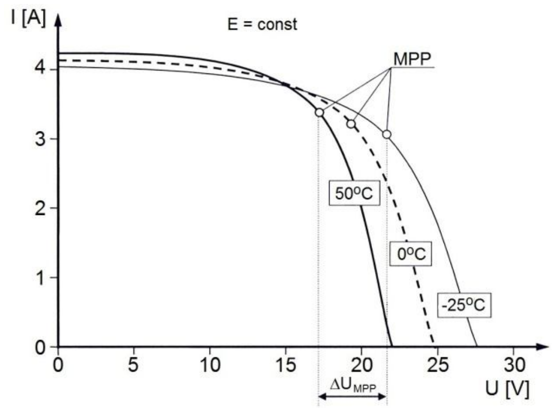

Fig. 1. Voltage current characteristics of the photovoltaic cell depending on the temperature of the cell [6]: MPP – maximum power point

This problem becomes much more complex in case of BIPV components compared to traditional panels installed on a special supportive structure over the roof surface. This results from the structural assumption of the BIPV components which, by replacing construction materials, become an integral part of the building and are thus exposed to variable operation conditions. Under the surface of photovoltaic roofing tiles there is much smaller mass of the air than under a traditional panel, there are different conditions of exchanging heat with the surroundings, and there is also no natural ventilation.

The structural material of the roof surface is also of significant importance, and in particular its thermal properties, index of heat exchange with the surrounding, thermal insulation, etc. Preliminary tests allowed to put forward research hypotheses, which are planned to be proved by conducting parallel, year-long tests of the impact of the substrate type on the amount of generated electrical energy.

2. Obtaining energy from solar radiation

American scientists calculated a few years ago that the amount of energy that reaches our planet from the Sun every hour is equal to the amount consumed by all of human civilization in a year [10]. This means that solar radiation is an efficient source for obtaining energy. The technologies of solar collectors and photovoltaic panels have been independently developed in parallel for decades as part of solar power engineering [4].

In recent years, attempts have been made to combine the two different technologies in order to create a unified hybrid system. A photovoltaic thermal system (also known as a hybrid PV/T system or PVT) is a system which converts the energy of solar radiation into electric energy or thermal energy. The system generates mainly electric energy thanks to the photovoltaic effect and the same device produces warm water thanks to the phenomenon occurring in the solar collectors (in some versions of the system, the air is heated directly). The essence of such a combination of two systems that have operated independently till now is their mutual positive influence [1, 5]. A combination of those systems is presented on Figure 2.

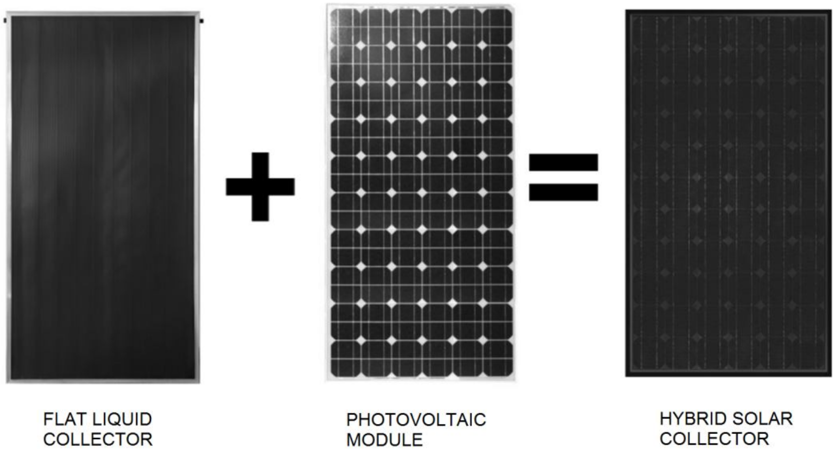

Fig. 2. Illustration of the combination of a collector with a PV module [8]

While analyzing the operation of a solar battery, it is important to remember that the increase of its temperature is always connected with the decrease of the value of the power obtained. This is caused by the increase of the frequency of vibrations of the atoms in the crystalline network that constitutes the structure of a photovoltaic cell. It should be added that vibrations of the crystalline network obstruct the flow of electrons which, in consequence, decreases the value of the electromotive force and, thus, reduces the voltage level [7].

In order to obtain energy from photovoltaic sources, one should remember that their nominal power is specified for the standard test conditions in which the temperature of the cell is 25°C. When the elements are heated by a certain value, the power generation efficiency decreases. This dependency for a typical silicon solar battery is presented on Figure 3 [6].

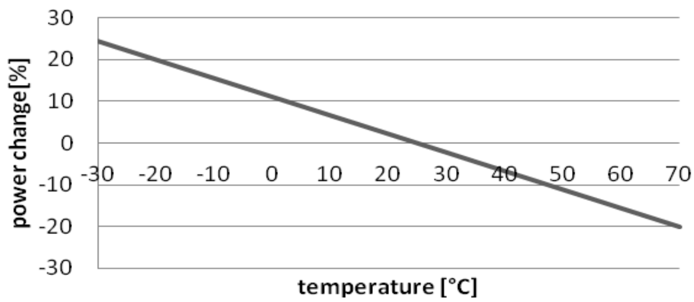

Fig. 3. The graph reflecting percentage fluctuation of the power of a typical solar collector in relation to temperature [7]

Co-operation of photovoltaics and solar collectors in a PVT system is focused on making the amount of electric energy generated from PV elements independent from their temperature. Cooling the cells makes it possible to increase the efficiency of their operation during hot days. Additionally, it should be remembered that the heat which, up till now, was considered as a wasteful and unwanted side effect, will now be used in an effective way.

2.1. Types of PVT systems

Hybrid systems can be divided into two groups depending on their construction. Most of all, PVT systems based on the construction of a flat liquid collector can be distinguished. The photovoltaic cell is cooled in such a system by an absorber equipped with a heating coil in which the heating medium collecting the heat circulates. Installations of this type are connected to the building similarly to traditional solar collectors. The connection of a sample installation of PVT systems is presented on Figure 4.

PVT systems based on the construction of air heating collectors in which the collector is cooled by means of the air flowing under the photovoltaic cell are much less popular in Poland. Such a solution is much simpler and cheaper but it works only in specific types of investments where the heated air is needed, particularly during the summer months [9].

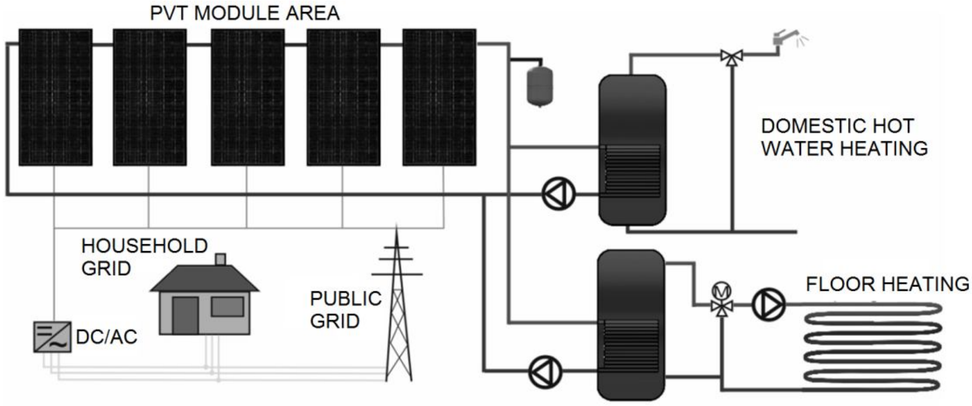

Fig. 4. Sample uses of PVT systems PVT [14]

An example of such a solution is the "SolarDuct PV/T" system produced by the SolarWall company. Standard PV modules are fitted on a specially prepared frame. Both parts are matched in such a way that makes the air flow directly under the modules. In this way, the cells will be cooled and the heat will be transferred to the heating and ventilation systems of the building by a special perforated absorber.

Thanks to the installation which operates in such a way, the consumption of conventional energy needed to heat the building is decreased. At the same time, the efficiency of the PV system is increased by up to o 10%. Apart from generating thermal energy, the SolarDuct PV/T system also constitutes a complete support structure for the PV system which makes the investment more cost-effective [12].

2.2. The purpose of investing in PVT

Advantages

The main advantage of using PVT, apart from the reduction of the operation temperature of the photovoltaic cells, is space savings. Instead of two separate installations, solar collectors for water heating, and a photovoltaic installation for electric energy generation, just one installation is fitted on the roof. Such a solution means that part of the investors with limited usable roof space do not have to choose between heat generation and electric energy generation.

Also the costs of such an installation are much lower than in the case of two traditional installations (solar collectors and photovoltaics). What is more, in the case of PVT with fully integrated construction, it is currently possible to obtain refinancing at the level of 45% for the modules including the hydraulic part of the installation.

Reduction of the costs connected with the installation, which results from the lower amount of work to be conducted on the surface of the building in comparison to the implementation of two systems is also worth noticing. This is applicable also to the fitting of PVT modules itself which, in most cases, have been designed to match traditional PV installation clamps. Figure 5 presents a photo of a PVT module which differs from PV only with hydraulic clamps.

PVT is also characterized by 50% higher efficiency than comparable conventional module. At the same time, manufacturers of photovoltaic thermal systems guarantee considerably longer service life of the photovoltaic cells thanks to the operation in lower temperatures [11].

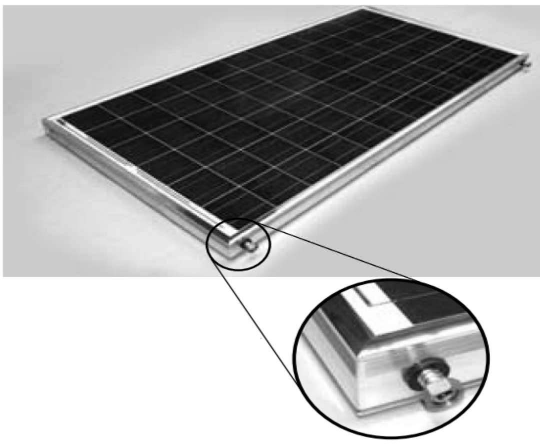

Fig. 5. Hybrid IPVT 300 Hybryda module [8]

Disadvantages

A disadvantage of this system is the mutual dependency of both systems. The most appropriate system operation time from the system efficiency point of view is summer time characterized by high insolation and high temperatures. It is then that both of the implemented systems operate at the highest efficiency level. On the one hand, it is possible to obtain low-temperature heat in the form of water heated to the temperature of 45°C, on the other hand, the operation of PV at lowered temperature in favorable insolation conditions. Thus, in order for the PVT modules to operate in an efficient way, it is necessary for the operation of the cell to be maintained at a low level, that is 35-45°C. It should be underlined that a PV system is relatively rarely heated to the temperature of more than 50°C.

Another disadvantage of PVT is the scale of the system. In the case of installations fitted on family houses, the photovoltaic component often takes up the area of over a dozen or a few dozen m^2, which means that a problem with receiving such a great amount of heat may arise in the summer period. In winter, on the other hand, a hybrid PV/T system will generate considerably higher heat losses than a traditional collector installation due to the lack of a selective absorber and the appropriate amount of thermal insulation. This translates to lower temperatures of the heating medium obtained from them.

The thermal insulation of hybrid modules is also not as good as in the case of traditional solar collectors. Due to that fact, they are characterized by much higher heat loss levels and the temperature of the heating medium obtained from them is lower than in solar collectors.

3. Tests of roof substrates

3.1. Test stand

The objective of the conducted tests is to determine the impact of structural material of the roof substrate on the amount of generated electrical energy, with identical weather conditions. To this purpose, a special roof structure was built (on a flat roof of the existing building) consisting of identical photovoltaic roofing tiles placed on different surfaces. The roof fragments visible in the figure consist of the following materials (from the left respectively):

1) roofing membrane with the insulation from mineral wool (roof 1),
2) roofing membrane without the insulation (roof 2),
3) planks covered with roofing paper together with insulation from mineral wool (roof 3).

In order to reflect the operation conditions most frequently encountered in reality, presented materials (planks, membrane) were selected and insulation of the roof with mineral wool was either applied or not. In order to ensure identical ambient conditions (ambient temperature, solar exposure) tests were conducted on all three systems at the same time, throughout the whole year, on selected days of each month. Owing to that the impact of weather conditions on tested parameters will be also defined. In order to ensure the most optimal conditions of the system's operation during the whole year, the photovoltaic cells were directed southwards and inclined at an angle of 37º to ground level [2-4, 6].

With the help of an automated metering system the information on the instantaneous value of the current, voltage and power obtained during the process of photovoltaic conversion is collected from each set of the tested photovoltaic roofing tiles. The density of the solar radiation power (E [W/m^2]), the temperature of the roofing tile operating area ($T1$ [ºC]) as well as the air space between the roofing tile and the roof structure (*T2* [ºC]) are also subject to measurements. The temperature and air humidity are also measured.

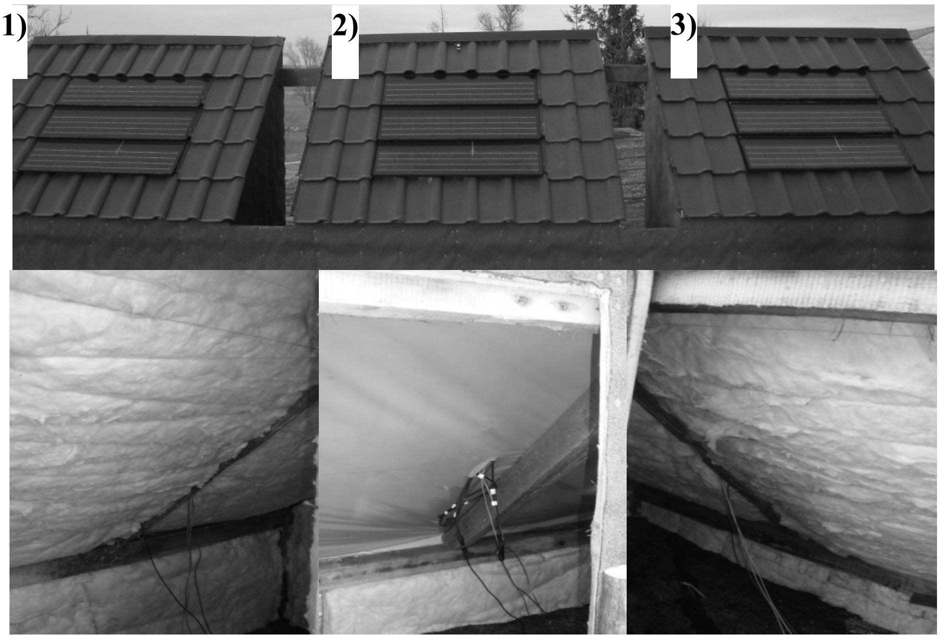

Fig. 6. Test stand – roof structures with different substrates

The metering system is composed of:

a) FOTTON 52 W photovoltaic roofing tiles (3 tiles connected in series on each system) [13],
b) 20-channel recorder,
c) PT100 temperature sensors,
d) current pincers,
e) resistors constituting load (essential to determine the current voltage characteristics of the solar roofing tile and to define the parameters in the maximum power point (MPP),
f) personal computer (PC).

The metering system was executed in line with the relevant requirements of the operation in the open area, such as waste or temperature.

Distribution of sensors and components of one of the three roofs (with planks, roofing paper and wool) was presented in Figure 7. For the remaining two types of substrate placement of metering elements is identical.

The implemented metering system allows to record the data samples, change measurement parameters as well as calculate and store test results. The target result of the calculation will be table and graphic specifications of the obtained results in order to conduct the analysis of energy yields on various roof substrates in the same geographic location and under the same operation conditions. The correctness of data coming from the metering system will be periodically verified using traditional meters of the power density of radiation, temperature, current and voltage.

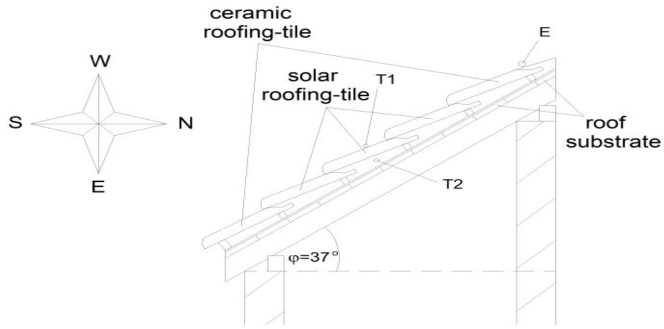

Fig. 7. Diagram of distribution of roof components and sensors

3.2. Results of preliminary measurements

The analysis of exemplary measurements and the characteristics conducted on 29.06.2013 at 12:00 to 13:00 hours at certain load of PV modules (Figure 8, Figure 9 and Figure 10) allows to draw the first conclusions concerning the impact of the substrate on the operation of the photovoltaic system.

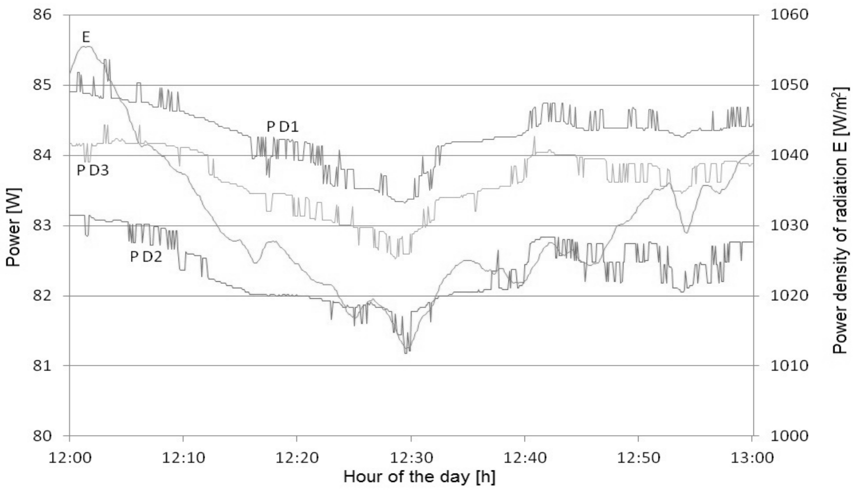

Fig. 8. Characteristics of the obtained power and power density of radiation depending on the hour of the day: *E* – power density of solar radiation, *P D1* – power yield on roof 1 (with membrane and wool), *P D2* – power yield on roof 2 (with membrane), *P D3* – power yield on roof 3 (with planks, roofing paper and wool)

The included characteristics allow to clearly observe sudden changes of the obtained power depending on power density of solar radiation (Figure 8). The biggest power is obtained from the system placed on the membrane and mineral wool, a little lower on the roof with planks and roofing paper, while the lowest on the roof membrane. In this case, the difference in power amounts to about 2.3%, that is about 2 W. However, it shall be noted that the rated power of the tested system amounted only to 156 W (3 photovoltaic roofing tiles, 52 W each). With the actual system, with the installed power of, e.g. 2 kW, the difference would already amount to almost 50 W, that is as much as the value of the power from one photovoltaic cell. Also, with the power density of radiation of about 1030 W/m^2 the power obtained from the system in the maximum power point at 12:00 hours amounted to respectively 122.8 W on roof 1, 119 W on roof 2 and 113.2 W on roof 3, that is maximum power difference amounted already to about 8.4%. It may be assumed that proper load of PV photovoltaic cells will also have the impact on the differences in the obtained power.

In order to determine the characteristic electrical parameters deciding about the properties of the cell (such as power P, maximum power P_{max}, efficiency η, filling coefficient FF) the values from measurements conducted on the test stand as well as the following formulas were used [4, 6]:

$$P = UI \quad [\mathrm{W}] \tag{1}$$

$$P_{\max} = U_M I_M \quad [\mathrm{W}] \tag{2}$$

$$\eta = \frac{U_M I_M}{ES} 100 \quad [\%] \tag{3}$$

$$FF = \frac{U_M I_M}{U_{0c} I_{sc}} \quad [-] \tag{4}$$

The determined values of the above-mentioned parameters on the three of the tested roofs on the said day at 12:00 hours, with the optimum load of the PV system as well as for the average values in the hourly time framework between 12:00 and 13:00 hours were specified in table 1.

When analyzing the efficiency values obtained on individual systems one may note analogical dependencies as quoted before, concerning the obtained power. As it is not possible to determine the value of the short-circuit current and the idle state voltage for time framework between 12:00 and 13:00 hours, their empirical values were assumed on the basis of archive measurements made in analogical conditions.

The values of filling coefficients FF also confirm the assumption that proper load of PV cells has the impact on the value of power. When the cells are not properly loaded (as in case of time framework between 12:00 and 13:00 hours) this coefficient amounts to about 0.5, while at 12:00 hours (with the optimum load) the value of about 0.7 was obtained.

Table 1. Values of electric parameters of the systems tested on individual roofs

Hour	Roof	S	E	I_M	U_M	P_{max}	I_{sc}	U_{oc}	η	FF
		[m^2]	[W/m^2]	[A]	[V]	[W]	[A]	[V]	[%]	[-]
12	roof 1	1,2	979,4	4,88	25,16	122,78	5,37	31,74	9,93	0,72
	roof 2			4,82	24,68	119,0	5,40	31,39	9,63	0,70
	roof 3			4,74	23,89	113,2	5,15	30,80	9,16	0,72
12-13	roof 1		1030,2	3,09	26,67	82,36	5,37	31,74	6,67	0,49
	roof 2			3,10	27,21	84,31	5,40	31,39	6,82	0,49
	roof 3			3,21	26,04	83,64	5,15	30,80	6,76	0,53

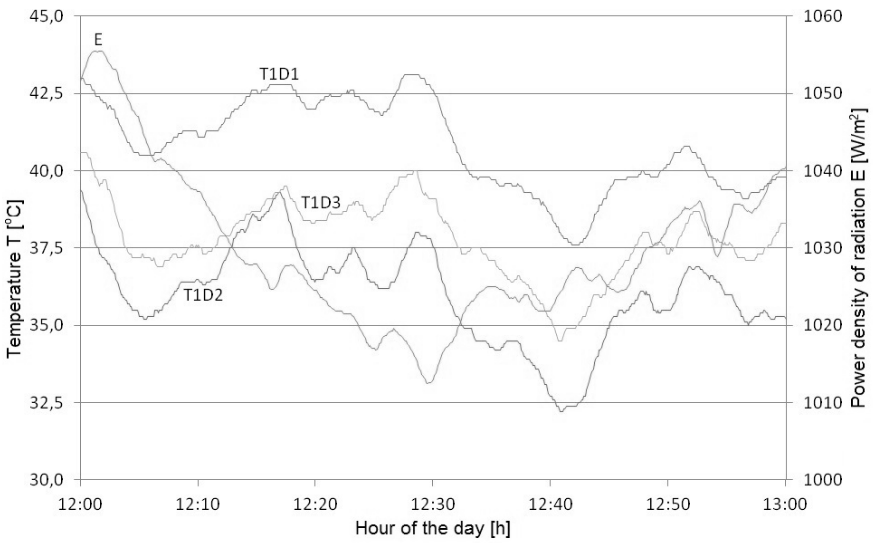

Fig. 9. Characteristics of the temperature of PV cells as well as power density of radiation depending on the hour of the day: *E* – power density of solar radiation, *T1D1* – temperature of PV cells on roof 1 (with membrane and wool), *T1D2* – temperature of PV cells on roof 2 (with membrane), *T1D3* – temperature of PV membranes on roof 3 (with planks, roofing paper and wool)

The temperature of PV cells also changes along with the change of the solar exposure, however this change obviously takes place only after some time (Figure 9). The temperature of the air found in the gap between the roofing tile and the substrate is much more stable and it grows with the lapse of time during the system's operation (Figure 10).

The yellow roof membrane reflects the heat in the roof gap and also heats the PV cells from the bottom (and not only from the top via sunrays). The black roofing paper and planks absorb a certain part of heat from the air. Mineral wool insulates the roof and prevents free exchange of heat and the air found under the roof on the attic.

Although the biggest power was obtained on the membrane and wool substrate only a slightly lower value of the power yield can be observed on the planks with the roofing paper. This substrate seems to be the most appropriate, because as the only one from the tested substrates it is characterized with big stability of power and temperatures, which – in a longer perspective of the operation – may be the most significant.

It will be possible to draw the precise conclusions after analysing all the measurements from the whole year under different conditions. Then it will be possible to determine which substrate process proves better throughout all the seasons of the year as well as relate that to thermal properties of individual materials.

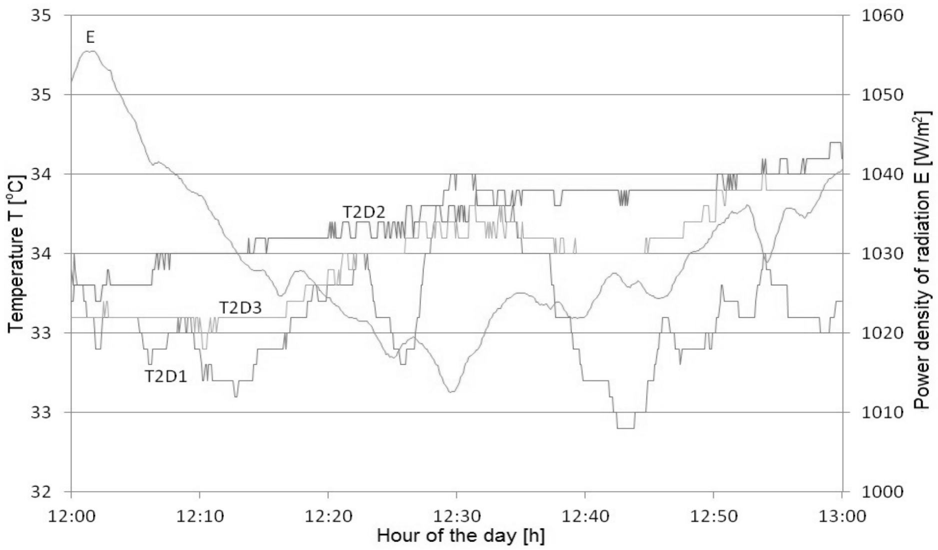

Fig. 10. Characteristics of the air temperature in the roof gap as well as power density of radiation depending on the hour of the day: *E* – power density of solar radiation, *T2D1* – temperature of the air in the gap on roof 1 (with membrane and wool), *T2D2* – temperature of the air in the gap on roof 2 (with membrane), *T2D3* – temperature of the air in the gap on roof 3 (with planks, roofing paper and wool).

4. Conclusions

Although in theory they combine the advantages of two systems whose popularity is constantly growing, in practice PVT systems seem to be a solution that has not been completely thought out. Although the manufacturers assure up to 300% higher efficiency in comparison to a traditional PV system, the increase in real operational conditions is a few dozen percent.

In the future, the results of the conducted tests should indicate the type of roof substrate allowing to obtain the best operation parameters of photovoltaic roofing tiles as well as to maximize the power yields from the PV systems. Also, the detailed analysis of results in time should give the guidelines connected with profitability and return of capital expenditure of the potential modern solutions in the field of BIPV technologies. The objective of the study is to collect as much reliable operational information as possible, having impact on the parameters of operation and profitability of photovoltaic roofing tiles for different groups of persons, such as: manufactures, design engineers, scientists, investors as well as final users.

Knowledge about the impact of the substrate and the selection of the collector structure on the temperature of the cells will indicate further directions for tests aimed at improving thermal conductivity of structural materials for roof substrates as well as to introduce optimal solution in the PVT area. Undoubtedly, using PVT systems will be economically justifiable in the case of many investments, but their installation must be preceded with diligent technology and cost analysis.

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