Technical and economic analysis of a micro photovoltaic/thermal system working in Polish climatic conditions

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Abstract: The first part of the paper presents some aspects of Polish climatic conditions, especially of solar radiation and solar energy availability. The second part of the paper presents a mathematical model and assumptions used in the analysis of the photovoltaic thermal solar system operation. The analysis has been carried out for the microscale system supplying energy to the standard single-family house or to the grid. The third part of the paper presents an economic analysis of the system under consideration. The analysis has taken into account several financial and regulatory variants: different net metering methods, the NFEP&WM "Prosument" program (grants) and the feed- in- tariffs scheme.

1. Introduction

The biggest problem associated with conversion of solar energy into electricity is related to the relatively low efficiency of this process in most of photovoltaic cells currently available. Typically 15-18% of solar radiation incident on a PV module is converted into electricity (Browne, Borton, McCormack, 2016). Most of the absorbed solar energy is converted to heat, which is lost to the environment. This heat raises temperature of the photovoltaic cells. Efficiency of the photovoltaic cells decreases when the temperature increases. It is a significant problem in case of the building integrated photovoltaics, because in this case the natural cooling of a building by the wind is very limited (Tripanagnostopoulos, 2012).

This problem can be partially avoided through utilization of the “waste” heat from the photovoltaic cells. Such solution is called a photovoltaic thermal - PVT. Using the “waste” heat helps to keep the electrical efficiency of the PVT at the satisfactory level. The heat recovered can be used for example for the preheating of the domestic hot water. For the PV building applications at locations of the low irradiation and the low ambient temperature the cooling by the air circulation can be more useful and cost effective than the PV cooling assured by the liquid circulation (Tripanagnostopoulos, Nousia, Souliotis, Yianoulis, 2002). On the other hand, at locations with high solar irradiation and high ambient temperatures the liquid PV cooling is more efficient than the PV cooling by air circulation and for such cases the heat recovered is usually used to the water preheating (Tripanagnostopoulos, Nousia, Souliotis, Yianoulis, 2002). At locations with substantial irradiation and moderate ambient temperature the air or liquid heat extraction modes can be used according to the application and costs (Tripanagnostopoulos, Nousia, Souliotis, Yianoulis, 2002).

2. Polish climatic conditions

Operation of solar systems is very dependent on the weather conditions, particularly on the availability of solar radiation. In Poland an average annual irradiation on horizontal plane is in a range of 950 - 1150 kWh/m^2 (Chwieduk, 2010). The highest level of irradiation is in the northern part of the country (Pomerania) and the south-eastern part of the country (the Lubelskie Region). In Warsaw (central Poland) the average annual irradiation is about 962 kWh/m^2 (Chwieduk, 1997). The highest solar irradiation occurs in June. In Warsaw the average solar irradiation in June is about 160 kWh/m^2 (Chwieduk, 2010). On the other hand, the lowest solar irradiation occurs in December, and for Warsaw is about 11 kWh/m^2 (Chwieduk, 2010).

Distribution of solar radiation in time is very important. In Poland in a period from October to March (5 months) only about 20% of the annual total radiation is available. Moreover, an average annual percentage of the direct radiation amounts only for 46%. In summer the share of direct radiation is higher and accounts for 56%, but in a period from November to January diffuse radiation varies from 65 to 71% (Chwieduk, 2010). This fact means that only the solar systems which use both direct and diffuse solar radiation can be effectively used in Poland.

Solar operations during the year is in average equal to 1600 hours (Chwieduk, 2010). Polish climatic conditions are characterized by high variations of solar radiation availability in time. During winter solar irradiation and ambient temperature are very low. Low availability of solar radiation is at the same time as the high demand for the space heating. Due to these specific climatic conditions not all types of solar systems can work effectively in Poland.

3. Mathematical model

In this chapter mathematical models used to determine: the availability of solar radiation incident on a receiver; the PV/T operation; and the storage tank dynamics are described.

3.1. Mathematical model of solar radiation

The hourly data of: ambient air temperature, solar irradiation and its components have been used as an input climatic data for Warsaw. Hemispherical radiation incident on a plane of the receiver of the defined orientation and inclination has been determined using the isotropic diffuse solar radiation model (Liu-Jordan model). According to this model, solar irradiation incident on a surface of a receiver consists of three components:

- direct radiation,
- diffuse radiation,
- radiation reflected from the ground.

The equation (1) describes solar irradiation incident on the tilted receiver:

$$I_c(t)=I_b(t)R_b(t)+I_d(t)R_d+\left(I_b(t)+I_d(t)\right)\rho_r R_r \qquad \text{Eq. (1)}$$

where:

$I_c(t)$ - total solar irradiation on a tilted plane [J/m^2]; $I_b(t)$ - beam irradiation (direct) on a horizontal plane, [J/m^2]; $I_d(t)$ - diffuse radiation on a horizontal plane, [J/m^2]; $R_b(t)$ - ratio of beam radiation on a tilted plane to that on the horizontal plane, [-]; R_d - ratio of diffused radiation on a tilted plane to that on the horizontal plane, [-]; ρ_r- reflectance, [-]; R_r - ratio of reflected radiation on a tilted plane, [-]; t - time [s]

3.2. Mathematical model of a PVT device

Heat gained from a PV/T device has been calculated according to the formula:

$$Q_u(t) = \eta_{th} \cdot A_{PVT} \cdot \frac{I_c(t)}{\Delta t} \qquad \text{Eq. (2)}$$

where:

$Q_u(t)$ heat gained, [W]; A_{PVT} - area of PV/T, [m^2]; η_{th} - thermal efficiency of PV/T [-];
Thermal efficiency has been calculated according to the formula:

$$\eta_{th} = \eta_0 - a_1 \left(\frac{T_{in} - T_a}{\frac{I_c(t)}{\Delta t}} \right) \qquad \text{Eq. (3)}$$

where:

η_0 - optical efficiency, [-]; a_1 - heat loss coefficient, $\left[\frac{W}{m^2K}\right]$; T_{in} - fluid temperature at inlet of PV/T, [K]; T_a - ambient temperature, [K].

Electric power of the PV/T device in given time has been calculated according to the formula:

$$Q_{el}(t) = \eta_{el} \cdot A_{PVT} \cdot \frac{I_c(t)}{\Delta t} \qquad \text{Eq. (4)}$$

where:

$Q_{el}(t)$ – electric power, [W]; η_{el} - electrical efficiency, [-]; A_{PVT} - area of PV/T, [m^2];

Electrical efficiency has been calculated according to the formula:

$$\eta_{el}(t) = \eta_{ref} \left(1 - B_{ref}\left(T_{c\ PVT}(t) - T_{ref}\right)\right) \qquad \text{Eq. (5)}$$

where:

η_{el}(t) - electrical efficiency of PVT device, [-]; η_{ref} - electrical efficiency at temperature T_{ref}, [-]; B_{ref} - efficiency correction coefficient for temperature, [1/K]; $T_{c\ PVT}(t)$ - temperature of photovoltaic cells , [K]; T_{ref} - reference temperature (STC conditions) = 25 °C

Temperature of photovoltaic cells has been calculated according to the formula especially adapted for this analysis:

$$T_{c\ PVT} = T_{c\ PV} + \left(T_{fluid} - T_a/x\right) \qquad \text{Eq. (6)}$$

where:

$T_{c\ PV}$ - temperature of photovoltaic cells in standard photovoltaic module, [K]; $T_{c\ PVT}$ - temperature of photovoltaic cells in photovoltaic/thermal (PV/T) module, [K]; T_{fluid} - average temperature of cooling fluid in the PV/T, $\left(\frac{1}{2}(T_{in} + T_{out})\right)$, [K]; T_a - ambient temperature, [K]; x - additional factor which allows to consider the reduction of environmental impact in case of the glazed modules, x=1,9; [-];

Temperature of photovoltaic cells in a standard photovoltaic module has been calculated according to formula (Tripanagnostopoulos, 2012):

$$T_{c\ PV} = 30 + 0{,}0175(G - 300) + 1{,}14(T_a - 25) \qquad \text{Eq. (7)}$$

3.3. Mathematical model of storage tank

The storage tank is a tank of complete mixing, the temperature T_s of the storage medium at a time t is uniform throughout the volume of the tank. According to above assumptions, energy balance of the storage tank at a time t can be written as a differential equation of the form, (Chwieduk, 2014):

$$(\rho \cdot c_w \cdot V)\frac{dT_s}{dt} = Q_{in}(t) - Q_{out}(t) \qquad \text{Eq. (8)}$$

where:

T_s - temperature of water in a storage tank, [K]; ρ - density of water, [kg/m^3]; c_w - specific heat of water, [J/(kgK)]; V - volume of a tank, [m^3]; $Q_{in}(t)$ - heat supplied to a tank, [W]; $Q_{out}(t)$ - heat removed from a tank, [W].

There are two tanks in a system under consideration, one big tank for storing heat from the PV/T (preheating) and a smaller tank for domestic hot water. The scheme of the analyzed heating system is shown in fig. 1.

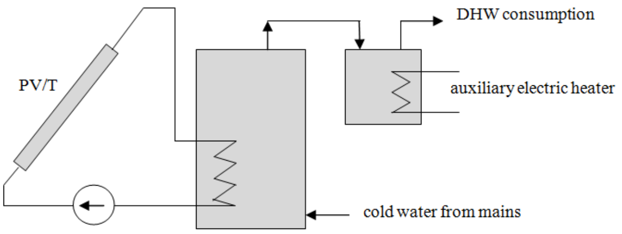

Fig 1. Schematic diagram of the PV/T heating system

An antifreeze mixture is used in the PVT loop, because heating energy is used through the whole year. As it can be seen in the fig. 1, heat from the PV/T loop is supplied to the main storage tank. Then preheated water flows to the other tank, where water is heated by the auxiliary electric heater, if it is required (to reach the required temperature). The main storage tank is supplied by the cold water from mains.

In considered system heat from the PV/T is used plays a preheating role for the domestic hot water. Electricity obtained from the PVT is consumed by electric appliances of a single-family house and surplus of energy is transferred to the grid.

4. Experimental validation of mathematical model of PV/T device

The experimental validation of the PV/T device was completed during Short Term Scientific Mission (STSM) in a frame of the COST Action TU1205 – BISTS – Building Integrated Solar Thermal Systems. Experimental studies were conducted in the Solar Outdoor Laboratory of the University of Patras (Greece). The research was conducted in October - November. Weather conditions during this period in Patras are similar to conditions during summer (July and August) in Poland. At the beginning the glazed PV/T water device was built. A photovoltaic module of nominal power of 50 W (multicrystalline silicon solar cells) with a cooper absorber and insulation was used. Due to the insulation at the back side of the PV/T device, operation of the device was similar to the operation of BIPVT - building integrated PVT device (no natural ventilation - cooling).

Figure 2 presents a cross-section of the PV/T device. The device was tested outdoors, regarding to its electrical and thermal performance. As a coolant the water from mains was used in an open system (water leaving the PVT device was sent to drains). Thermocouples were used to measure temperature at different points.

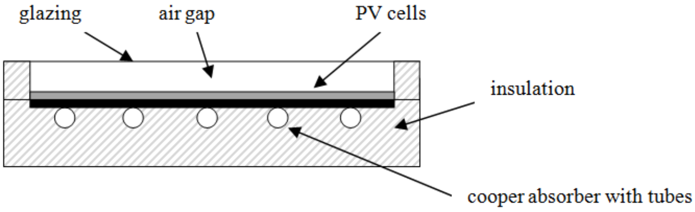

Fig 2. Cross section of the main PV/T geometry

Thus the following temperatures were measured: cooling fluid temperature at the inlet

T_{in} [°C], cooling fluid temperature at the outlet T_{out} [°C], temperature of the PV top side surface $T_{pv\ top}$ [°C], temperature under PV back side surface $T_{pv\ back}$ [°C], temperature of the cooper absorber top side surface $T_{abs\ top}$ [°C], temperature of the cooper absorber back side surface $T_{abs\ back}$ [°C], temperature of the insulation inside the device T_{insul} [°C], ambient temperature T_a [°C]. Solar radiation incident on the PV module plane (G) was measured by the Kipp and Zonen pyranometer. Cooling fluid mass flow m [kg/s] was determined by measurements of the time of filling the tank of a known volume. Electric voltage [V] and electric current [A] of the PV/T device were also measured. During tests the PV module was connected to a load, simulating real system operation and in order to avoid extra water heating. The steady state tests were performed during noon (±2 h), with systems oriented to the sun in order to ensure almost constant value of the incoming solar radiation. To determine the electrical output the load was disconnected for a short time and the current I [A] and the voltage V [V] of the PV module were measured. Thus, the I–V curve was determined for the system operating conditions. Then the values of the current I_m and the voltage V_m at the maximum power point of the PV module operation were determined. The values of I_m and V_m and the incident solar radiation (of irradiance G) have been used to calculate the PV module electrical efficiency η_{el} for the system aperture area A, in the following way:

$$\eta_{el} = (I_m \cdot V_m)/(AG)$$

Eq. (9)

The electrical measurements have been also used to determine the electrical efficiency as a function of the PV cells operating temperature. The electrical efficiency of photovoltaic cells drops significantly with increasing cell temperature. For a cell temperature of 21 °C the electrical efficiency is about 0.11, and for the cell temperature of about 93 °C the electrical efficiency is about 0.065. The relative decrease in the electrical efficiency is roughly 40%.

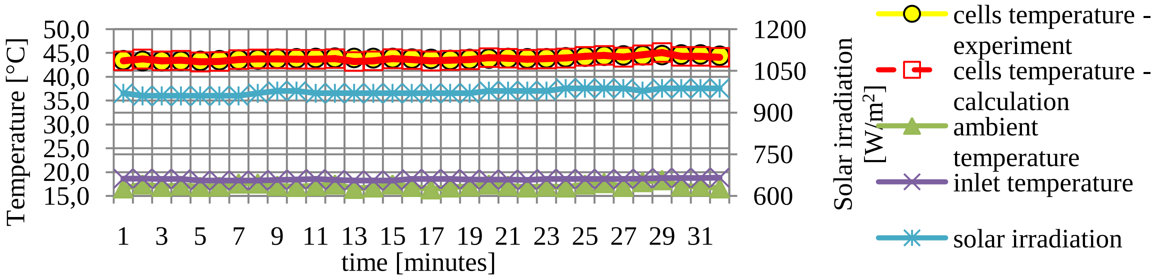

Fig. 3. Distribution of Photovoltaic cells temperature, comparison of experimental data and results of calculations

One of the main purposes of the tests was to validate the equation 6 and 7 approximating the temperature of photovoltaic cells of the PV/T device. Figure 3 presents the temperature of the cells determined by the approximating formula and obtained from the measurement. Distribution of the fluid temperature at the inlet of the PVT, the ambient temperature and solar irradiance are also presented in the figure. As can be seen in fig. 5 the formula used to calculate the temperature of the cells fairly well approximates the temperature of the cells obtained during the experiments.

5. Economic analysis

Operation of the thermal part of the PVT system has been compared to the water heating system using an electric heater taking into account economic aspects. Three cases of the support mechanisms have been considered.

Case 1 is considering program NFEP&WM "Prosument" (grants). Program NFEP&WM "Prosument" is a program for the individual end–user who can get a grant and a loan based on a preferential interest rate to install the renewable energy system. In case of electricity production the grant is equal to 40% of the total cost of the system and the loan covers the rest (60%). In case of thermal energy production the grant is equal to 20% of the total investment costs and the loan covers the rest (80%). The interest rate of the loan is 1%. This program does not provide support for the PVT system in direct way. However, for the purposes of the presented economic analysis it can be assumed that the considered PVT operates as a standard PV system (40% grant + 60% loan).

Case 2 is considering feed-in tariff and net metering. When the Renewable Energy Law was under elaboration the feed-in tariffs system (fixed energy prices for the sale of electricity to the grid) and net metering system were to be introduced. The prices of electricity produced by the photovoltaic system with capacity of up to 3 kW had to be equal to 0,75 PLN/kWh. Net metering would allow energy consumers who generate own electricity to use it at any time, not only when it is generated. Electricity produced by the micro system based on renewable energy sources would be compared with the electricity taken from the grid. Consumer would be charged only for the difference between energy produced and taken. The period in which energy would be balanced was to be 6 months. It was assumed that the Feed-in tariffs would have been considered only for the surplus of energy put to the grid). Although such a system was planned it was never put in force because the Renewable Energy Law was changed.

Case 3 is considering system of discounts. Recently in Poland, according to the latest changes in the Renewable Energy Law, a system of discounts has been put into force. In case of a micro renewable energy system of a capacity lower than 10 kW, for every 1 kWh of electric energy produced by the micro system and sent to the power grid the energy of 0,8 kWh can be taken out of the grid without costs. Power grid is treated as a storage of energy with an efficiency of 80%. Fixed charges are incurred regardless.

6. Results

Table 2 presents the selection of the most important parameters of the analyzed system. Five cases have been analyzed with 2, 4, 6, 8 and 10 PVT modules. Volume of 100 liters of storage tank for every 1 square meter of the PVT system has been assumed. Technical parameters of the PVT module have been adopted on a basis of the technical data of the commercially available PVT devices.

Table 3 presents five cases under consideration. It shows number of modules, total surface area of the PVT modules and total cost of the installation. The total cost of the installation has been assumed according to an offer of one of the manufacturers of PVT modules.

For the purpose of the simulation operation of PV/T installation, distribution of domestic hot water and electricity were assumed. Figure 4 presents the share of energy produced by the PVT systems of different surface area of PVT receiver in total energy demand for DHW and electricity.

Table 1. Parameters of the analyzed system

No.	Symbol	Description	Value
1.	η_{ref}	electrical efficiency at temperature T_{ref}, [-]	0.144
2.	B_{ref}	efficiency correction coefficient for temperature, [1/K]	0.005
3.	P	electric power of one PVT module, [W]	200
4.	$A_{PV/T}$	area of one PV/T module, [m^2]	1.305
5.	η_0	optical efficiency of PVT (thermal part), [-]	0.715
6.	a_1	heat loss coefficient, $\left[\frac{W}{m^2K}\right]$	7.98

Table 2. Cases which were analyzed

No. of case	I	II	III	IV	V
Number of PV/T modules	2	4	6	8	10
Area of PVT modules [m^2]	2.61	5.22	7.83	10.44	13.05
Total cost of the installation [PLN]	15 950	21 230	25 080	29 260	33 000

Generally, as can be expected, with the increase of the system size, the share of the PVT energy input increases for the same demand. In the analyzed system the PVT modules are glazed and because of that the thermal gains are relatively high. Unfortunately, high temperatures of the PVT caused by the use of glazing do not allow to achieve high production of electricity. In addition, the production of electricity is reduced due to optical losses resulting from the use of glazing.

Electrical energy produced by the systems under consideration is small and does not cover a totally electricity demand. To get more electricity more constant heat removal from the storage tank, especially in summer, is required. The temperature in the storage tank is often too high to cool the PVT.

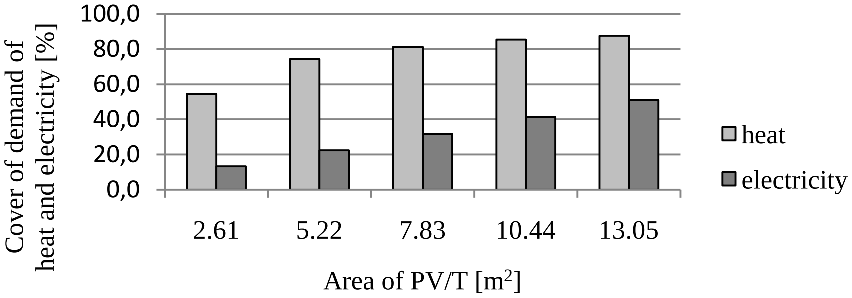

Fig 4. The share of energy produced by the PVT systems in total energy demand for DHW and electricity

Figure 5 presents the payback time of different sizes of the PVT system for various economic cases. Case 1 represents situation with the discounts system and the "Prosument" program, together. Case 2 refers to the net metering and feed-in tariffs, together and Case 3 to the discounts system, only.

Calculations of the financial savings have been performed assuming that the analyzed PVT system replaces the electric heater in DHW system and electric energy for all appliances is bought from the grid. As can be seen in fig 5, the best results (with the shortest payback time) are obtained for the case based on the "Prosument" program. Depending of the size of the system, payback time varies from 8.2 to 9.1 years. Unfortunately, this is only a hypothetical case because the "Prosument" program provides funding for the solar thermal collectors and photovoltaics separately, but does not provide funding of the PVT modules.

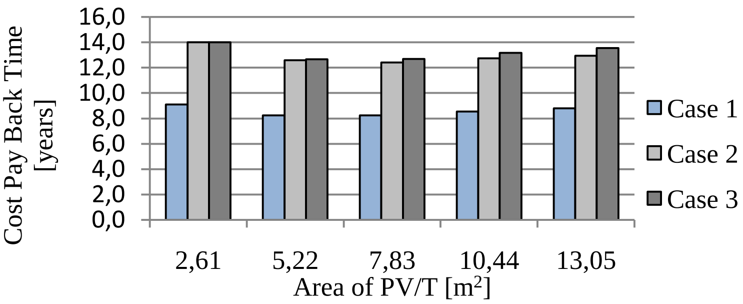

Fig. 5 Cost payback time of the analyzed PVT systems and financial schemes

Differences in the payback time between the case 2 and 3 are small. This is due to the fact that electric energy gained by the PVT system is very small taking into account the total annual energy demand and almost all energy gained is consumed at site (not sent to the grid). Currently in Poland, the existing regulations cause that selling energy produced by the micro renewable energy system to the grid is economically unprofitable. A better solution is to consume as much energy produced as possible at site.

7. Conclusions

The main conclusions are following:

- Polish climate is characterized by high variations of solar energy availability. Due to so specific climatic conditions not all types of solar systems can work effectively in Poland. It is always worth to consider the seasonal utilization of solar systems (during spring - summer).
- Well selected size of the PVT glazed modules can operate effectively in Polish climatic conditions, providing a part of the energy demand for both DHW domestic hot water and electricity.
- Costs of PVT systems are high, slightly higher than the costs of the standard solar thermal system and the photovoltaic system working for the same demand but separately. The PVT systems should be supported to be more economically effective, for example in a form of grants. However, installation of PVT may be applied when the space for installation (e.g. roof surface) is very limited.
- The best solution for the PV/T system is constant heat removal from the PVT modules and the storage tank to keep the temperature of the working fluid at low level. When the heat consumption is small the temperature of the fluid rises quickly and cooling of the PVT modules becomes impossible.
- In case of the glazed PVT heat gains are larger than in the unglazed PV/T modules, but the yield in electricity is somewhat lower, mainly by the optical losses and higher temperature cells.

8. References

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