Investigation of the photovoltaic cell/ thermoelectric element hybrid system performance

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Abstract. The PV/TEG hybrid system, consisting of the photovoltaic cells and thermoelectric element, is presented in the paper. The dependence of the PV/TEG hybrid system parameters on the illumination levels and the temperature is analysed. The maxim power values of the photovoltaic cell, of the thermoelectric element and of the PV/TEG system are calculated and a comparison between them is presented and analysed. An economic analysis is also presented.

1. Introduction
The solar energy can be converted in electrical energy using photovoltaic cells and panels (PV) or in thermal energy using solar collector. These two energy sources are very important in the actual climatic context and the global installed capacity is 177 GW for solar PV and 406 GWth for solar hot water [1].

The researchers and producers work has been translated into a variety of photovoltaic cells and panels. Variety consists in: the types of materials and structures used to produce photovoltaic cells, type and number of junctions, the indoors or the outdoor applications, levels of illumination normal light up one sun (1 sun = 1000W/m²) or concentrated light more than one sun (until 1000 suns). The silicon is the most commonly used material in residential and industrial applications. The monocrystalline and polycrystalline silicon photovoltaic cells are used in large applications and the amorphous silicon solar cells are used in small applications such as garden illumination lamps. The multijunction photovoltaic cells are used in concentrated light.

The efficiency of the photovoltaic cells for the representative type at standard test condition STC [2]: the illumination level 1 sun, the temperature of photovoltaic cell 25°C and air mass 1.5 is given in table 1. The efficiency of the photovoltaic cells is influenced by the levels of illumination, the temperature, the inclination angle between light and cell, the wind speed, the degradation rate and the material parameters [3]. The temperature of the photovoltaic cells is a critical factor for their efficiency. The efficiency of monocrystalline photovoltaic cell decreases with 0.4%/°C if the temperature increases. The time life of the photovoltaic cells substantially decreases, if they work at high temperature, over 80°C [4]. The irradiance is another critical factor for the efficiency of the photovoltaic cells. The spectral distribution of the natural sunlight contains the infrared part, thus the

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The temperature of the photovoltaic cells increases when the sunlight falls on them and the irradiance increases, reaching in some cases a temperature of 83°C [5].

### Table 1. Efficiency for different types of photovoltaic cells at STC.

| Type               | Area    | Efficiency |
|--------------------|---------|------------|
| Monocrystalline Si | 143.7 cm² | 25.6 ± 0.5 % |
| Polycrystalline Si | 243.9 cm² | 20.8 ± 0.5 % |
| Amorphous Si       | 1.001 cm² | 10.2 ± 0.3 % |
| GaAs (thin film)   | 0.99 cm²  | 28.8 ± 0.9 % |
| InGaP/GaAs/InGaAs  | 1.047 cm² | 37.9 ± 1.2 % |
| GaInP/GaAs, GaInAsP/GaIn⁸ | 0.052 cm² | 46.0 ± 2.2 % |

*The light intensity is 508 suns*

The efficiency of the photovoltaic cells can be increased if the irradiance increases and the cells temperature decreases. The decreasing of the photovoltaic cells’ temperature has to be realized without energy consumption. This can be made by using natural cooling, in this case the efficiency being lower, by using the solar collector - realizing the PVT system or by using the thermoelectric element.

The thermoelectric element can be used for heating or cooling if DC current is applied based on the Peltier effect, or it can generate electrical power if there is a temperature gradient between the two parts of the thermoelectric element based on the Seebeck effect.

The figure of merit, ZT where T is the absolute temperature and Z is given by the equation (1) dictated the efficiency of the thermoelectric element. The power factor of the thermoelectric element is defined as $\alpha^2\sigma$.

$$ZT = \frac{\alpha^2\sigma}{k} T$$

(1)

where $\alpha$ is the Seebeck coefficient, k represents the thermal conductivity and $\sigma$ is the electrical conductivity.

The figure of merit for the first generation of the thermoelectric elements, before the years 1990, was under 1 [7] and their efficiencies were very low, thus their applications were limited. After this period, the number of the applications quickly increases because the figure of merit becomes double or more than doubles [8]. The figure of merit for the important thermoelectric elements is given in table 2.

### Table 2. Figure of merit for different types of thermoelectric materials.

| Materials                  | ZT  | Temperature [K] |
|---------------------------|-----|-----------------|
| Bi₃Te₅/Sb₂Te₃ [9]          | 2.4 | 300             |
| Cu–BiTeSe                 | 1.1 | 373             |
| PbTe/Ag₅Te [6]            | 1.6 | 773             |
| SnSe [11]                 | 2.6 | 923             |
| AgPb₈SnSbTe₆S₂ [6]         | 1.8 | 800             |
2. Materials and methods

The temperature of the solar cell increases when the natural or artificial light falls on it. The generated power of the photovoltaic cell can be increased using a thermoelectric element for cooling it, while at the same time generating additional power.

The main goals of the paper are to design and study the behavior of the PV/TEG hybrid system which consists of the photovoltaic cells, PV, and the thermoelectric element TEG, see figure 1.

The experimental set-up consists of, see figure 2:

- The cooling system based on an aluminium block cooled with water. The water flowing is assured using a water pump. The inlet water temperature is quasi constant due to using a water tank.
- The thermoelectric element used is Stonecold, made from Bi₂Te₃, the ceramic material used is alumina, Al₂O₃, with dimensions 6.2 cm/6.2 cm/4.8 cm. The TEG is mounted on the aluminium block. The thermic contact between the TEG and the aluminium block is realized with thermal adhesive tape with 0.1 mm thickness and its thermal conductivity is 2 W/m·K.
- The photovoltaic cells, with dimensions of 6 cm/6 cm. Three types of photovoltaic cells were used for this study: monocrystalline silicon, mSi, polycrystalline silicon, pSi, and amorphous silicon aSi. The photovoltaic cell is thermally connected with the hot part of the thermoelectric element using a thermal tape with 1 mm thickness and its thermal conductivity is 6 W/m·K.
- The illumination system based on nine halogen bulbs powered with a Keithely programmable dc power source.
- The linear actuator - it is used to vary the illumination levels of the photovoltaic cells.
- The temperature monitoring system-it consists of nine k thermocouples and a NI cRIO module for temperature measurement. The nine thermocouples are distributed as follows: three for monitoring the temperature of the cold part of TEG, three for monitoring the temperature of the hot part of TEG and the temperature of the back of the photovoltaic cell and three for monitoring the water temperature: inlet, outlet and for the water tank.
- The I-V characteristic system – two electronic loads and NI cRIO integrated system are used to measure the I-V characteristic of the photovoltaic cell and the thermoelectric element simultaneously.
- The PC with a proper software for control, measurements and analysis of the data, developed LabVIEW graphical programming language.

Figure 1. The PV/TEG hybrid system a) the thermoelectric element mounted on the aluminum block; b) the monocrystalline silicon photovoltaic cell mounted on the thermoelectric element.
2.1. Photovoltaic cells

The I-V characteristic is a very important tool for the characterization of photovoltaic cells. The analysis of the photovoltaic cell I-V characteristic can be done using the equivalent circuit and the mathematical model [12]. The choice of the equivalent circuit and the mathematical model is in function of the conduction mechanism. The most commonly used equivalent circuit is the one diode model, see figure 3.

\[
I = I_{sc} - I_o \left( e^{\frac{V + I R_s}{n V_T}} - 1 \right) - \frac{V + I R_s}{R_{sh}}
\]

where \( I_{sc} \) is the short circuit current, \( n \) represents the ideality factor of diode, \( R_s \) is the series resistance, \( R_{sh} \) is the shunt resistance, \( I_o \) represents the reverse saturation current, \( V_T = kT/q \), \( k \) denotes the Boltzmann constant, \( T \) is the temperature of the solar cell and \( q \) is the electronic charge.

The analytical five point method developed by Chan et al. can be used to determine the important parameters of the photovoltaic cells [12].
2.2. Thermoelectric element

The equivalent electric circuit of the thermoelectric element is very simple. It consists of a voltage source and the internal resistance [13]. The thermal-electrical equivalent circuit is presented in figure 4 [14,15]. The thermoelectric element is characterised by the thermal conductance $K$, the internal resistance and the Seebeck coefficient [14].

\[ I = \frac{\alpha N \Delta T - V}{R_i} = \frac{\alpha N \Delta T}{R_i + R_L} \]  

where $N$ is the number of p-n junctions, $\Delta T$ represents the temperature difference between the hot part and cold part of the thermoelectric generator and $R_L$ is the load resistance.

\[ R_i = \frac{2NL}{a\sigma} \]  

where $L$ is the length, $a$ represents the area of the thermoelectric element and $\sigma$ is the effective conductivity of the material.

\[ \eta = \left( \frac{T_h - T_c}{T_h} \right) \frac{\sqrt{1 + T_m T_c^2} - 1}{T_h} \frac{1}{\sqrt{1 + T_m T_c^2} + \frac{T_c}{T_h}} \]  

where $T_h$ is the temperature of the thermoelectric element hot part, $T_c$ is the temperature of the thermoelectric element cold part, $T_m$ is the average temperature between the $T_h$ and $T_c$.

2.3. Methods

The important parameters of the photovoltaic cells, such as the short circuit current, the open circuit voltage $V_{oc}$, the maximum power $P_{max}$, the fill factor $FF$, the efficiency and the parameters of the thermoelectric element, such as the short circuit current, the open circuit voltage, the maximum power and the internal resistance are calculated.

The experimental set-up allows the determination of the important parameters of the two components of the PV/TEG hybrid system in function of the illumination levels. The spectral distribution of the halogen light has an important infrared part and the temperature of the photovoltaic cell increases. The performance of photovoltaic cell decreases with the temperature growth. The thermoelectric element was introduced in the system to assure the temperature decrease. The temperature difference between the temperature of the hot part of the thermoelectric element, which is bonded on the back of the photovoltaic cell and the temperature of the cold part of the thermoelectric
element, which is bonded on the aluminum block, is dependent on the illumination levels. The aluminum block is cooled with water. Its goal is to maintain the cold part temperature of the thermoelectric element quasi constant.

The I-V characteristics of the PV/TEG hybrid system components are measured for each illumination level every two minutes. The measurements begin when the light is turned on and the temperature of the components is equal, and they are stopped when the temperature of the hot part of the thermoelectric element remains quasi constant.

The temperature of the PV/TEG hybrid system components is measured in three points using the k type thermocouples.

The system control, the parameters monitoring and the data acquisition is realized using the cRIO system and the adequate software built in the LabVIEW programming language.

3. Results and discussions

3.1. Effects of illumination levels

The PV/TEG hybrid system is characterized at eight illumination levels from 720 W/m² to 1080 W/m². The I-V characteristics of the photovoltaic cells in function of the irradiance are presented in figure 5. The short circuit current increases proportionally with irradiance for both the photovoltaic cells. The open circuit voltage remains quasi constant because the decreasing caused by the temperature increasing is compensated by the increase in irradiance.

a) b)

Figure 5. The I-V characteristics of the photovoltaic cells: a) mSi; b) pSi.
Figure 6. The difference temperature of the thermoelectric element vs irradiance.

The temperature difference between the hot and cold parts of the thermoelectric element is dependent on the irradiance, see figure 6. The temperature difference increases proportionally with the irradiance growth. The highest temperature difference is obtained for mSi/Bi₂Te₃ hybrid system and the lowest for mSi/Bi₂Te₃ hybrid system. This can be explained by the fact that the amorphous silicon photovoltaic cell is encapsulated and the heat transfer is lower than for the other photovoltaic cells.

The important parameters of the photovoltaic cells and the thermoelectric element were determined and they are given in Table 3. The maximum power generated by the photovoltaic cells and by the thermoelectric element, as well as the efficiency of the photovoltaic cell are higher for the mSi than for the pSi and aSi. This result makes the mSi/ Bi₂Te₃ hybrid system the most suitable one to be used in real applications.

Table 3. The parameters of the PV/TEG hybrid system components.

| Materials | Photovoltaic cell | Thermoelectric element |
|-----------|------------------|------------------------|
|           | I [W/m²] | V_{oc} [V] | I_{sc} [A] | P_{max} [W] | FF [%] | η [%] | T_{PV} [°C] | V_{oc} [V] | I_{sc} [A] | P_{max} [mW] | R_i [Ω] | ΔT [°C] |
| mSi/Bi₂Te₃ | 720    | 0.599    | 1.057   | 0.474   | 74.90 | 18.30 | 28.6 | 0.064 | 0.107 | 1.69 | 0.597 | 4.4 |
|           | 820    | 0.599    | 1.214   | 0.542   | 74.44 | 18.35 | 30.0 | 0.078 | 0.133 | 2.59 | 0.591 | 5.2 |
|           | 860    | 0.600    | 1.316   | 0.583   | 73.90 | 18.84 | 30.8 | 0.082 | 0.137 | 2.79 | 0.600 | 5.4 |
|           | 920    | 0.599    | 1.424   | 0.627   | 73.46 | 18.93 | 31.8 | 0.089 | 0.155 | 3.40 | 0.577 | 5.9 |
|           | 960    | 0.599    | 1.470   | 0.645   | 73.25 | 18.66 | 32.1 | 0.093 | 0.156 | 3.62 | 0.598 | 6.1 |
|           | 1000   | 0.599    | 1.533   | 0.671   | 73.11 | 18.65 | 32.5 | 0.095 | 0.159 | 3.77 | 0.600 | 6.2 |
|           | 1020   | 0.599    | 1.574   | 0.687   | 72.89 | 18.70 | 33.0 | 0.099 | 0.165 | 4.07 | 0.602 | 6.4 |
|           | 1080   | 0.599    | 1.646   | 0.716   | 72.62 | 18.41 | 33.2 | 0.101 | 0.167 | 4.19 | 0.603 | 6.8 |
| pSi/Bi₂Te₃ | 720    | 0.580    | 0.973   | 0.418   | 74.12 | 16.14 | 29.9 | 0.057 | 0.094 | 1.34 | 0.607 | 3.7 |
|           | 820    | 0.581    | 1.114   | 0.476   | 73.56 | 16.12 | 30.8 | 0.067 | 0.110 | 1.84 | 0.607 | 4.2 |
|           | 860    | 0.582    | 1.192   | 0.511   | 73.69 | 16.50 | 31.2 | 0.072 | 0.123 | 2.19 | 0.585 | 4.5 |
|           | 920    | 0.582    | 1.291   | 0.551   | 73.24 | 16.62 | 31.8 | 0.079 | 0.130 | 2.55 | 0.605 | 4.9 |
|           | 960    | 0.585    | 1.333   | 0.570   | 73.14 | 16.50 | 31.4 | 0.081 | 0.139 | 2.87 | 0.604 | 5.1 |
### 3.2. Temperature effect

The temperature of the photovoltaic cell can vary in general, under 1000 W/m² natural sunlight conditions, from 50°C to 80°C depending on the climatic zone and on the type of the materials being used.

Using the PV/TEG hybrid system, the temperature of the photovoltaic cell at 1000 W/m² irradiance is for mSi 32.5°C, pSi 33.1°C and aSi 35.7°C. A substantial difference can be observed between the working temperatures. The gain in maximum power for the mSi and pSi is 7%, and for the aSi is 5%, because the temperature of the photovoltaic cell can reach 53°C for the irradiance by 1000 W/m² without the TEG element.

The evolution of the I-V characteristic’s thermoelectric element in time when the mSi photovoltaic cell is considered, is presented in figure 6. The temperature difference between the hot and cold part of the TEG becomes quasi constant after 8 min for the mSi and pSi and after 14 min for the aSi. The time difference can be accounted for due to the photovoltaic structure: mSi and pSi are unencapsulated and aSi is encapsulated.

![Figure 7. The evolution in time of the I-V characteristics of the thermoelectric element.](image)

### 3.3. Economic analysis

The cost of the PV/TEG hybrid system is calculated using the available price of the photovoltaic cells and of the thermoelectric element. The price of the Wp (Watt peak – is the generated power by the photovoltaic cell under 1000W/m² irradiance) photovoltaic cell depends on the used material. The number of the p-n pairs, the material and the internal resistance of the thermoelectric element give the effective cost.

The comparative cost of the PV/TEG hybrid system components in function of the maximum power is presented in Table 3. The PV/TEG hybrid system is not cost effective yet, because the price
of the thermoelectric element is high. The system becomes attractive when the price of the thermoelectric element substantial decreases and its efficiency increases.

**Table 4.** The comparative cost of the PV/TEG hybrid system.

| Materials             | PV [$$] | TEG [$$] | PV/TEG [$$] | $P_{\text{max}}$ [W] | $$/ W_p$$ |
|-----------------------|---------|----------|-------------|----------------------|-----------|
| mSi (nonencapulated)  | 1.4     | 40       | 41.4        | 0.675                | 61.3      |
| pSi (nonencapulated)  | 1.2     | 40       | 41.2        | 0.595                | 69.2      |
| aSi (encapsulated)    | 1       | 40       | 41          | 0.088                | 465       |

4. Conclusions

Three types of the PV/TEG hybrid systems, built using mSi, pSi, aSi photovoltaic cells and Bi$_2$Te$_3$ thermoelectric element, were realized and characterized. The important parameters, such as the short circuit current, the open circuit voltage, the maximum power, were determined at different illumination levels and temperatures for both of the PV/TEG hybrid system components. The fill factor and the efficiency of the photovoltaic cell and the internal resistance of the thermoelectric element were also determined.

Analysing the three types of the PV/TEG hybrid systems, the mSi/ Bi$_2$Te$_3$ hybrid system is the best solution. Also, a comparison of the price required to obtain 1 W$_p$ with the three systems shows that the mSi/ Bi$_2$Te$_3$ has a lower price. Due to the high price of the thermoelectric element there are few practical applications. The number of applications will increase if the researcher’s effort will be materialized in new types of materials with higher efficiency and optimized structure. Using the graphene and nanomaterials, whose efficiency can reach 20%, could prove to be a promising solution for the future.

The temperatures of the photovoltaic cells decrease if the thermoelectric element is used. This has two positive effects: the photovoltaic cells produce more energy and the life time of the photovoltaic cells increases, because the temperature is a critical ageing factor.

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