Energy 238 (2022) 121988

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

# Experimental investigation on spectrum beam splitting photovoltaic–thermoelectric generator under moderate solar concentrations

S. Mahmoudinezhad [a], D.T. Cotfas [b], P.A. Cotfas [b], Enok J.H. Skjølstrup [c], K. Pedersen [c], L. Rosendahl [a], A. Rezania [a, *]

[a] AAU Energy, Aalborg University, Pontoppidanstræde 111, Aalborg, DK-9220, Denmark
[b] Electrical Engineering and Computer Science Faculty, Transilvania University of Brasov, 500036, Brasov, Romania
[c] Department of Materials and Production, Aalborg University, Skjernvej 4A, DK-9220, Aalborg East, Denmark

A R T I C L E I N F O

*Article history:*
Received 2 October 2020
Received in revised form
22 August 2021
Accepted 2 September 2021
Available online 6 September 2021

*Keywords:*
Photovoltaic
Thermoelectric generator
Spectrum beam splitting
Hybrid system
Power conversion efficiency

A B S T R A C T

An experimental study is carried out to investigate performance of three different solar energy harvesting systems. The critical electrical outputs of a photovoltaic (PV) cell and a thermoelectric generator (TEG) namely voltage, current and maximum power generation are obtained in a PV-only and a TEG-only system. The results are compared with performance of a hybrid photovoltaic-thermoelectric generator-beam splitter (PV-TEG-BS) system. The impact of spectral beam splitting technique on performance of the hybrid system is investigated. The results show that, although using the beam splitting technique decreases power generation of the TEG compared to the TEG-only case, it significantly enhances power generation of the PV cell in the hybrid PV-TEG-BS system and provides a higher overall power generation. By showing remarkable impact of the spectrum splitting technique on performance of the PV, the results of this study provide a guideline for performance evaluation of hybrid PV-TEG-BS systems.


## 1. Introduction

The world's energy demand is growing unprecedentedly due to population growth and industrialization. The fossil fuels, which are the conventional source of energy, are limited resource and are not environment friendly. Therefore, it is essential to drive toward clean and renewable sources of energy. Sun is an inexhaustible source of energy with $1.2 \times 10^5$ TW of solar radiation over earth. This amount of energy dramatically surpasses current world's energy demand that is 13 TW [1]. Efficient utilization of the solar spectrum has been one of the most interesting energy topics. There are various methods and devices to harvest solar energy and convert it into heat and electricity [2,3]. Among the solar energy conversion technologies, the simultaneous use of photovoltaics (PVs) and thermoelectric generators (TEGs) are promising technologies that are based on solid-state and reliable devices and have a long lifetime [4,5].

One technique to enhance conversion of the solar spectrum into useful energy is hybrid PV-TEG. Stack connection of such devices have been investigated with various materials and geometries [6–8]. One of the most straightforward method to provide PV-TEG hybrid module is direct connection of the hot side of the TEG underneath of the PV cell and attaching a heat sink to the cold side of the TEG. Most of studies in this field have focused on such integration of PV-TEG systems [9–11]. As result, a fraction of the solar irradiation is converted into electricity by the PV while the TEG converts a portion of the heat generated by the PV into useful electricity. The direct contact designs of the PV-TEG suffer a major drawback. Although higher temperature on the hot side of the TEG increases the temperature gradient across the module and its efficiency, it reduces the power conversion efficiency of the PV. Therefore, this confrontation may enhance the overall power conversion efficiency by a small margin [12–14]. Reverse efficiency response of the TEG and PV to variation of the operating temperature, therefore, limits applications of such hybrid PV-TEG systems.

Alternatively, the solar spectral splitting method was suggested to achieve full spectrum exploitation by a hybrid PV-TEG system. This method has been used to maximize utilization of solar energy by separation of incident photons with different energy levels and

* Corresponding author.
*E-mail address:* alr@energy.aau.dk (A. Rezania).

https://doi.org/10.1016/j.energy.2021.121988
0360-5442/

wavelengths. Beam splitters are optical components to split incident light at a selected ratio into two separate beams. The sunlight can be separated and radiated on the PV and TEG based on its wavelength. By using the spectral splitting method, PV and TEG will be thermally decoupled and can operate at different temperatures [15,16]. Since efficiency of PVs strongly depends on the operating temperature [17,18], this decoupling technique can improve power conversion efficiency of the PV by decreasing its operating temperature. In addition, the TEG enables to operate at higher temperatures with larger temperature gradient across the module and higher power conversion efficiency.

Vorobiev et al. [19] proposed a hybrid and high-temperature stage solar power system for utilization of the long wavelength solar spectrums. Dissimilar thermoelectric materials and various PV materials with different bandgap values were examined. They found, the hybrid system has high potential to convert solar energy into useful electricity. A general optimization procedure for the hybrid PV-TEG system was proposed by Kraemer et al. [20]. Their study concluded that, segmenting the spectrum into more than two regions does not have a significant impact on enhancement of the power conversion efficiency. Solar concentration also has significant effect on the overall conversion efficiency. Results of a numerical study with the concept of spectrum beam splitting conducted by Ju et al. [21] show that, a hybrid PV-TEG system has better performance compared to the PV-only system at higher solar concentration ratios when high values of heat transfer coefficient are provided by its heat sinks.

The spectrum beam splitting technique has been proposed to utilize a wide range of the solar spectrum. Magnetron sputtering method was used by Sibin et al. [22] with deposition of ITO/Ag/ITO multilayer coatings on glass substrates in order to find the optimum cut-off wavelength, which was obtained~900 nm in their study. Piarah et al. [23] characterized a spectrum splitter of hot and cold mirrors to find the best position of the TEG and PV in their hybrid system. They showed, with using the cold mirror the maximum power generation by the hybrid system is higher than the case the hot mirror is used.

Li et al. [24] found that, the configuration of PV-TEG hybrid systems is a crucial parameter to achieve high power conversion efficiency. Optimization of critical parameters such as concentration ratio and material properties of the TEG is essential for the higher efficiency. The results of their work also showed that, using a high-grade cold energy storage system can increase the output power by the hybrid system up to 30%.

Bjørk and Nielsen [25] investigated the highest theoretical performance that can be achieved by an hybrid PV-TEG system using spectrum beam splitting technique. They showed the power conversion efficiency using the hybrid systems is insignificant under non-concentrated sunlight. In addition, for the hybrid system, the figure of merit (zT) of thermoelectric materials should be high to provide a more efficient system than the PV-only system. Yin et al. [26] proposed a design for optimal stricter and temperature distribution in the TEG in a hybrid PV-TEG and BS (PV-TEG-BS) system, and found that the optimal cutoff wavelength decreases when thermoelectric materials with higher zT values are used.

Hybrid PV-TEG-BS systems have a great potential for integration with other energy systems. Mohammadnia et al. [27] showed potential of energy conversion of concentrated PV-TEG module integrated with beam splitter (BS) and Stirling engine. Their results indicate that, the proposed system play a significant role as an efficient hybrid renewable technology in future by enhancing power conversion efficiency of the solar irradiation into electricity compared to the conventional solar energy systems.

Although PV-TEG-BS systems have been considered, there is still a lack of a reliable experimental study to evaluate actual performance of such hybrid systems. Most of the studies mentioned above were investigated by numerical or analytical methods. Moreover, overall energy conversion efficiency of the hybrid PV-TEG-BS generators has not been compared to performance of PV-only or solar TEG-only systems.

This paper, therefore, aims to bridge this gap by studying performance of three experimental platforms, and comprising PV-only, TEG-only, and PV-TEG-BS hybrid systems. The main target of this study is not only to provide a guideline for performance investigation of the PV-TEG-BS system, but also to show the remarkable impact of using spectrum splitting concept on performance of the hybrid systems. In this regard, the system's performance is investigated over moderate range of solar concentrations. The electrical output characteristics and maximum power generation of each studied modules are obtained and discussed for different concentrations. In the second section of this paper, the methodology for design and manufacturing of the beam splitter is described. In the third section, the components used in the experimental setup are described in detail. Section 4 presents the obtained experimental results along with the discussion of results of this work. In the last part of this paper, concluding remarks are presented.

## 2. Beam splitter

For design and fabrication of the BS, the optimization models involved the optimal cutoff wavelength of the BS. In order to achieve more realistic investigation of performance of such hybrid system, the actual construction and performance of the BS needs to be obtained in practice. A theoretical method for determining the optimal design of the BS was presented in Ref. [28], where the BS consists of alternating layers of $SiO_2$ and $Si_3N_4$ deposited on glass. Such a one-dimensional structure gives rise to a photonic bandgap, where light cannot propagate within the structure and is instead reflected [29]. When the BS is placed at an angle of 45°, the reflected light from the BS is directed onto the PV cell. The principle of the method in Ref. [28] is to optimize the thicknesses of the individual layers of the $SiO_2$ and $Si_3N_4$, such that the wavelengths of the incident light are directed onto that component where they are most efficiently utilized (PV or TEG). It was found in Ref. [28] that the relative improvement in total efficiency can be 21% when a PV cell [30] is combined with a TEG with an efficiency of 8% [31].

The BS in this work is constructed based on the principles presented in Ref. [28], however $Nb_2O_5$ has been applied instead of $Si_3N_4$ as the high-index material in the BS. The efficiency of the used PV is shown in Fig. 1 (a) along with a constant efficiency of the TEG module assumed at 5%. The curves intersect at wavelengths of 468 nm and 702 nm. Hence in this interval, the efficiency of the PV is higher than for the TEG. It is therefore desired that these wavelengths are reflected onto the PV, while other wavelengths are transmitted onto the TEG. Measurements of reflectance and transmittance of the BS are shown in Fig. 1 (b, c), respectively, where quantities of an ideal BS are depicted. As shown, all quantities are relatively close to the ideal case for the considered angles of the incident light. The reflectance and transmittance are for an average of s- and p-polarized light, as sunlight is an equal mixture of these two polarizations [32].

## 3. The experimental setup

The tested PV-TEG-BS hybrid system consisted of a $Bi_2Te_3$ based thermoelectric module (TEC1-12710 STONECOLD) with dimensions of $40\ mm \times 40\ mm \times 3.3\ mm$ covered with graphite adhesive sheet for better absorbing of the solar radiation, a beam splitter with size of $137\ mm \times 137\ mm$ and a $40\ mm \times 40\ mm$ commercial

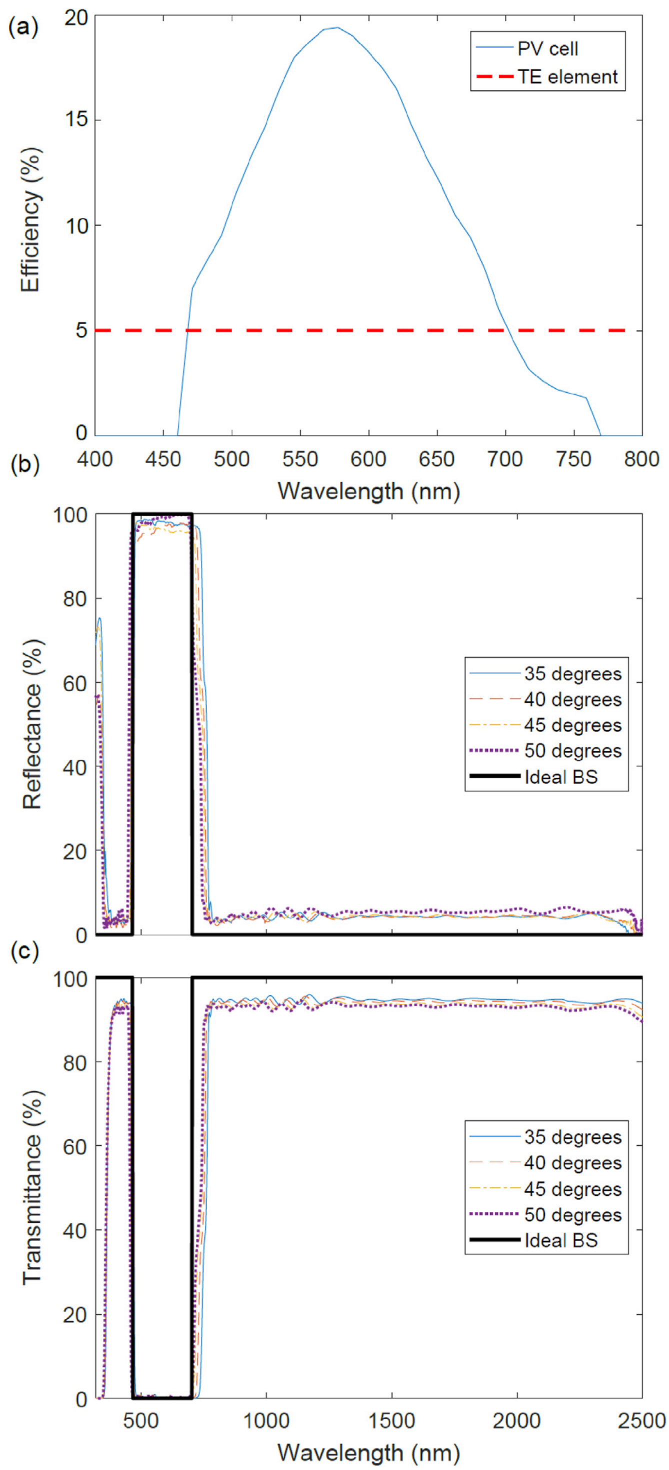


**Fig. 1.** (a) Shows the efficiency of the PV cell and the TEG module, from which it is found that the optimal cutoff photonic bandgap of the beam splitter is from 468 to 702 nm. (b) and (c) show, respectively, the measured reflectance and transmittance of the beam splitter, where the incident angle is shown in the legends. The shown quantities are averages of s- and p-polarized light.

amorphous silicon (a-Si) solar cells (see Fig. 2). The PV-TEG-BS hybrid system was mounted on a sun tracker with a concentration system based on the Fresnel lens. The measurements were performed at Transilvania University of Brasov, Romania with coordinates of 45.6427° N, 25.5887°E and elevation of 538 m.

The two axes sun tracker system is used to precisely position the systems perpendicular to the sun's ray. The sun tracker used in this study consisted of the tripod used as support, the pan/tilt device J-PT-1008-D improved with two encoders, one for each axis to ensure the positioning of the concentrated sunlight system on the two axes, and the control system based on NI myRio system. The positioning of the concentrated system is performed by using a mathematical algorithm, thoroughly described in Ref. [33] and implemented in LabVIEW graphical programing language. A 320 $mm \times 320$ $mm$ circular non-imaging optics Fresnel lens was used to concentrate the sunlight, so that the measurements could be performed for different solar concentrations.

The NI cRIO 9074 platform with Real-Time Controller was used to perform the measurements. The performance of the a-Si PV and TEG was investigated using the current-voltage characteristics and via capacitor techniques [34]. Five modules of the NI cRIO platform were used. Two of them measured the current and voltage of the a-Si PV and TEG, a one of the modules measured the temperature on the cold and hot sides of the TEG, on the back surface of the PV and the ambient temperature using K-type thermocouples. The last module was used to trigger the I–V characteristics of the PV and TEG measurements. The cold side of the TEG was thermally connected to a heat sink made of copper with milled channels cooled by water as the working fluid.

## 4. Result and discussion

Fig. 3 shows the three different systems considered in this study. In the first setup, namely TEG-only system as can be seen in Fig. 3(a), the TEG is exposed to the concentrated light. In the second setup, the PV-only system, the PV cell is subjected to the concentrated light (see Fig. 3(b)). The third system is the hybrid system consisting of the PV cell, TEG and the BS, named as the PV-TEG-BS hybrid system in this study, (see Fig. 3(c)).

The most common classification of concentrated photovoltaic modules is by the degree of concentration, which is expressed in number of “suns”. This number indicates the intensity of the light that hits the photovoltaic cell. For the solar concentration between 2 and 10 suns, that are called low concentration systems, no cooling and tracking system is necessarily required. For the moderate solar concentrations, between 10 and 100 suns, a one-axis tracking system and a passive cooling system can be sufficient. For the high solar concentration systems, namely more than 100 suns, a dual axis tracking system is required in most instances in addition to an active cooling system. The level of the solar concentration can vary with changing the distance between the setup and the Fresnel lens. In this study, the range of solar concentration varies between 13 suns for the lowest distance and 26 suns for the highest distance between the Fresnel lens and the hybrid module.

The system performance is evaluated based on variation of the solar concentrations in this study. Hence, the open-circuit voltage, short-circuit current, and maximum power generation are plotted with variation of the solar concentration, as also shown in Refs. [2,4]. In order to evaluate and compare the performance of the TEG and PV individually, as well as the hybrid system, the electrical output of each module is measured individually. Fig. 4 shows these results for different solar concentrations varying from 13 suns to 26 suns. For the PV-only system in Fig. 4(a), by increasing the solar concentration and the temperature of the cell, the short circuit current increases while the open-circuit voltage drops. The maximum power generation by the PV-only, however, increases with the solar concentration.

The solar concentration and temperature are two key parameters that affect the short circuit current and open circuit voltage of PV cells. By increasing the temperature, the amount of thermally

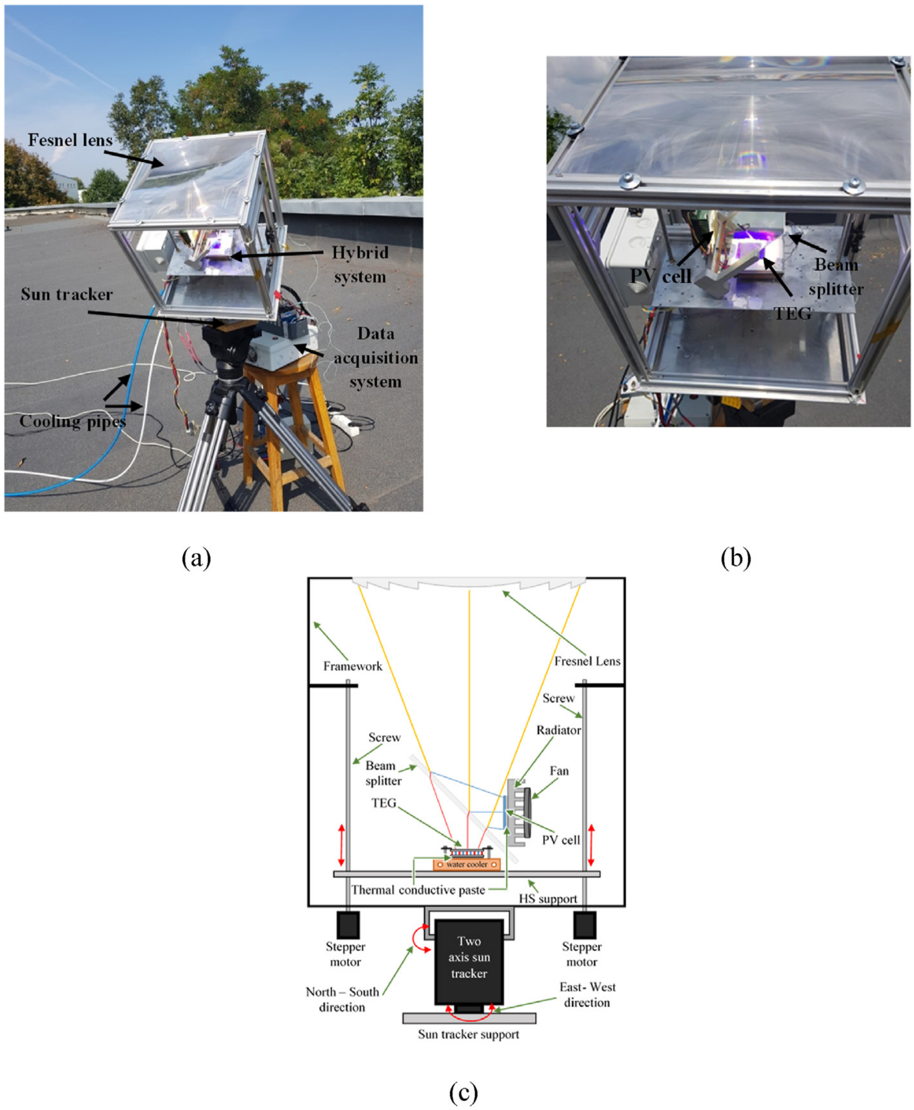


**Fig. 2.** a) Overview of the experimental setup; b) Hybrid system c) Schematic of the experimental setup.

created carriers in the cell, and accordingly, photogenerated current enhances marginally. Since the value of the short circuit current and the photogenerated current are almost the same, as result the temperature has an insignificant impact on the short circuit current. Therefore, the only crucial parameter which has a direct proportion with the short circuit current of the PV cell is the concentration ratio. The temperature of the cell has more significant impact on the open circuit voltage of the PV. This inversely proportional relationship decreases the open circuit voltage as the temperature increases.

Fig. 4(b) shows the electrical output of the TEG including the open circuit voltage, short circuit current and maximum power increases with the solar concentration. The zT and the temperature gradient across the TEG are two main parameters for estimating performance of a TEG. Since the zT has a negligible variation with the temperature in this study [35], the most dominant parameter is the temperature difference across the TEG. Increasing the solar concentration enhances the temperature difference across the TEG, so that the current, voltage and power generation increases accordingly.

Although, the same trend in the results and performance are seen for the PV and TEG in the hybrid TEG-PV-BS system, as can be seen in Fig. 5, the values of the electrical output of the hybrid system are notably different with the electrical output of the other individual systems. For instance, the maximum power generated by the PV in the PV-only system varies from 0.121 W to 0.178 W when the solar concentrations changes from 13 suns to 26 suns, while the maximum power generation is in range of 0.341 W and 0.444 W in the PV-TEG-BS system. The results show that, application of the hybrid PV-TEG-BS technique enhances the power output from 2.8 to 2.5 times in range of the studied solar concentrations.

As shown in Figs. 4(a) and Fig. 5(a), the spectral light management has a significant impact on the power generation by the PV cell. In the PV-only system, the cell is exposed to the whole of the solar spectrum. Therefore, a fraction of the long wavelength of the solar spectrum, which is not desired for the PV and cannot convert into useful electricity, is converted into heat [36]. This leads to the increment in the temperature of the PV cell and decreasing its output power. The favorable range of the solar spectrum wavelength for the a-Si solar cell is between 300 and 800 nm including the visible part of the spectrum, 400–760 nm [37]. The spectra with wavelength smaller than 300 nm and larger than 800 nm are

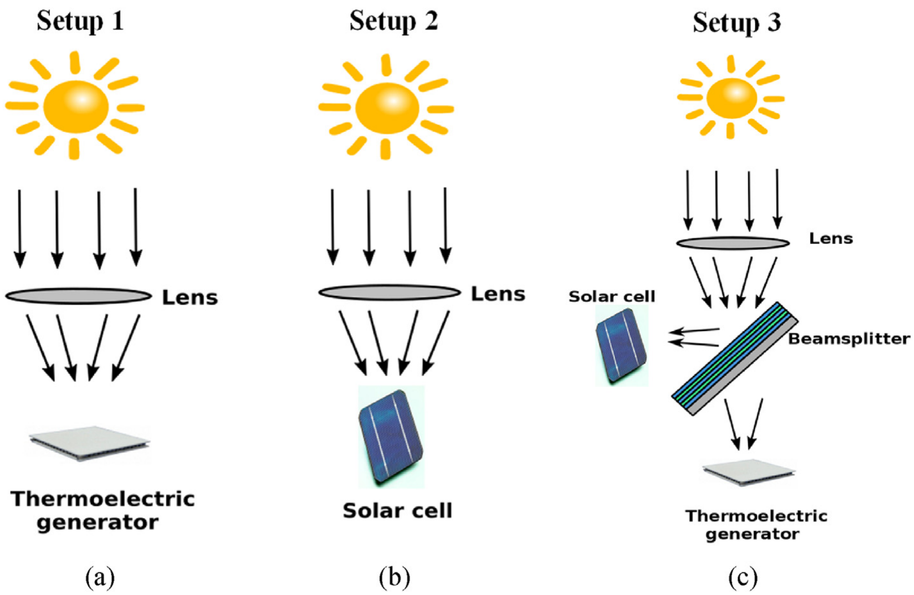


**Fig. 3.** (a) TEG-only system (b) PV-only system (c) PV-TEG-BS hybrid system.

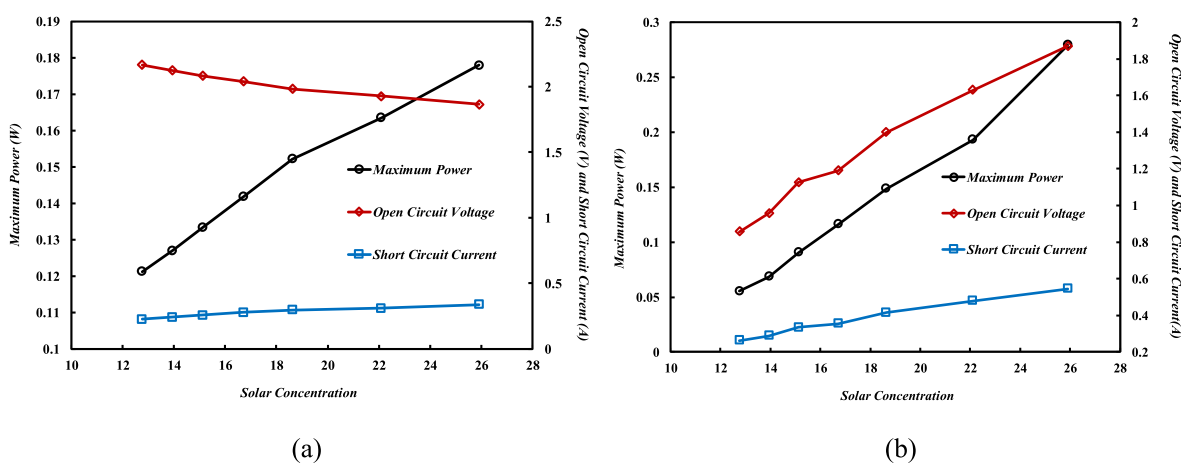


**Fig. 4.** Open circuit voltage, short circuit current, and maximum power by (a) PV in PV-only system (b) TEG in TEG-only system.

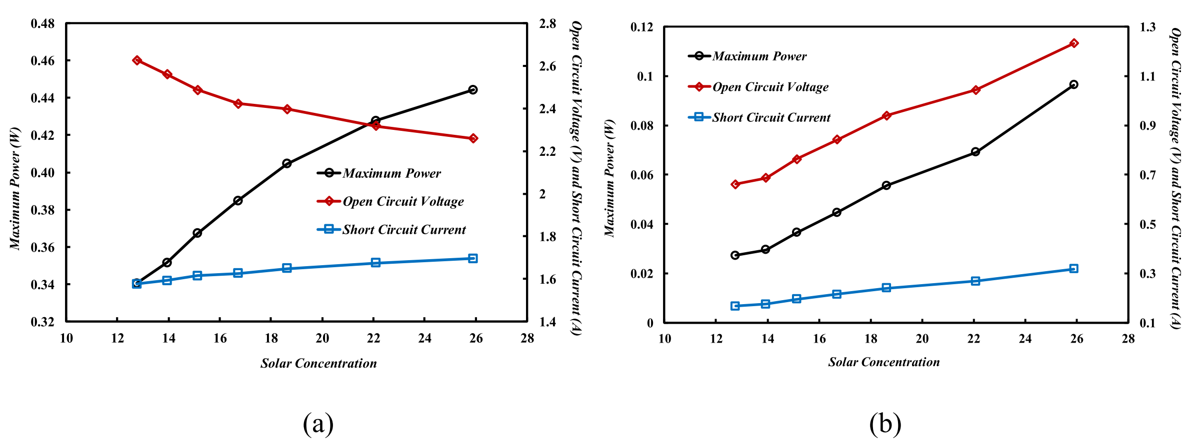


**Fig. 5.** Open circuit voltage, short circuit current, and maximum power by (a) PV (b) TEG, in PV-TEG-BS hybrid system.

outside of the bandgap of the PV cell and transform into heat and reduce the PV power conversion efficiency [11–38]. The beam splitter designed and fabricated in this study reflects the desired range of the solar spectrum on the PV cell in order to provide higher conversion efficiency in the PV cell.

In the TEG-only system, the TEG is exposed to the whole solar spectrum, and consequently, the temperature gradient and power output are higher than the same module in the PV-TEG-BS system.

In the hybrid system, the BS reflects the low wavelength solar spectrum to the PV, therefore, the TEG cannot utilize the whole spectrum of the solar irradiation. While in the TEG-only system, the total energy of the photons in the spectrum hits the TEG hot surface, photons in the wavelengths range of 400–760 nm are reflected onto the PV in the PV-TEG-BS hybrid system. Thus less energy is absorbed by the TEG. Figs. 4(b) and Fig. 5(b) illustrate that, over the considered range of the solar concentration, the maximum power of the TEG varies between 0.055 W and 0.279 W for the TEG-only system, while this variation is between 0.027 W and 0.096 W in the PV-TEG-BS system. As result, the maximum power generation by the TEG in the PV-TEG-BS hybrid system is 49% and 34% of the power generation in the TEG-only system for the solar concentrations of 13 and 26, respectively.

The variation of the maximum power generated by the PV and TEG in the studied systems is shown in Fig. 6 for different solar concentrations. As can be seen, the maximum power has a proportional relationship with the solar concentration, which means the higher solar concentration leads to a higher power output. Amongst the studied systems, the highest power is measured for the PV-TEG-BS system. It is worthy to note that, the maximum power generated by the PV in the hybrid system is even more than the summation of the power generated by the PV-only and TEG-only systems. This result shows the significant impact of the solar spectrum splitting technique on enhancement of the PV performance. This happens for all the studied solar concentrations except for the 26 suns. At the highest studied solar concentration, the power generation in the TEG-only system becomes notable due to creation of the large temperature difference across the module. Another notable result of this study, shown in Fig. 6, is variation of the maximum power generation by the PV and TEG in the individual systems. At the low solar concentrations (<18.6 suns), the maximum power by the PV is higher than that one in the TEG, but at high solar concentrations (>18.6 suns) the maximum power output by the TEG is higher than that one in the PV. The results shows critical impact of the temperature on the power generation by the semiconductor based devices.

The conversion efficiency of the studied systems can be simply defined as a ratio of the power output over the input solar irradiation as can be seen in equations (1)–(5). Fig. 7 shows the conversion efficiency of the PV and TEG versus variation of the solar concentration. A higher temperature gradient, due to the higher solar concentration over the TEG, enhances its power conversion efficiency. Due to utilizing the whole solar spectrum by the TEG in the TEG-only system, the efficiency of the TEG in this system is higher than that one in the PV-TEG-BS system.

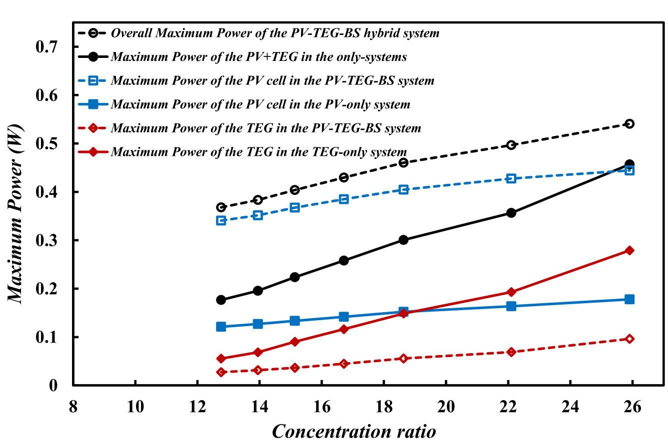


**Fig. 6.** Maximum generated power by different systems.

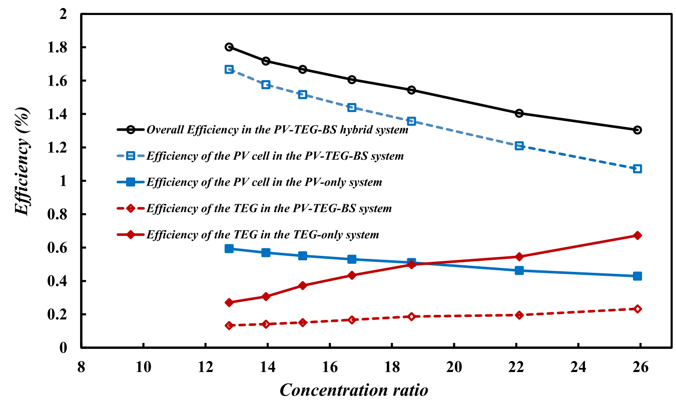


**Fig. 7.** Efficiency of the PV cell and TEG in the different systems.

$$\text{Efficiency of the TEG in the PV}-\text{TEG}-\text{BS system} = 100 \times \frac{\text{Maximum Power of the TEG in the PV}-\text{TEG}-\text{BS system}}{\text{Solar Concentration} \times 1000 \times \text{Area}} \tag{1}$$

$$\text{Efficiency of the TEG in the TEG}-\text{only system} = 100 \times \frac{\text{Maximum Power of the TEG in the TEG}-\text{only system}}{\text{Solar Concentration} \times 1000 \times \text{Area}} \tag{2}$$

$$\text{Efficiency of the PV cell in the PV}-\text{only system} = 100 \times \frac{\text{Maximum Power of the PV cell in the PV}-\text{only system}}{\text{Solar Concentration} \times 1000 \times \text{Area}} \tag{3}$$

$$\text{Efficiency of the PV cell in the PV}-\text{TEG}-\text{BS system} = 100 \times \frac{\text{Maximum Power of the PV cell in the PV}-\text{TEG}-\text{BS system}}{\text{Solar Concentration} \times 1000 \times \text{Area}} \tag{4}$$

$$\text{Overall Efficiency of the PV}-\text{TEG}-\text{BS system} = 100 \times \frac{\text{Overall Power of the PV}-\text{TEG}-\text{BS system}}{\text{Solar Concentration} \times 1000 \times \text{Area}} \tag{5}$$

As shown in Fig. 7, the variation of the PV efficiency has an opposite behavior compared with the TEG. As known, the efficiency of PVs has an inversely proportional relationship with the operating temperature variation [39], that means as temperature increases with the solar concentration, the efficiency drops. The PV efficiency in the PV-TEG-BS system is higher than that one in the PV-only system because of receiving the favorable range of the wavelength of the solar spectrum. The PV has the main contribution to the overall power generation in the hybrid system. Therefore, the variation of the overall efficiency of the PV-TEG-BS system has the same trend as the variation of the PV efficiency in Fig. 7. As mentioned, the PV cell used in the experiments is a-Si type solar cell. For a commercially available a-Si PV cell, the power conversion efficiency is below 6% at one sun illumination [40]. Especially the a-

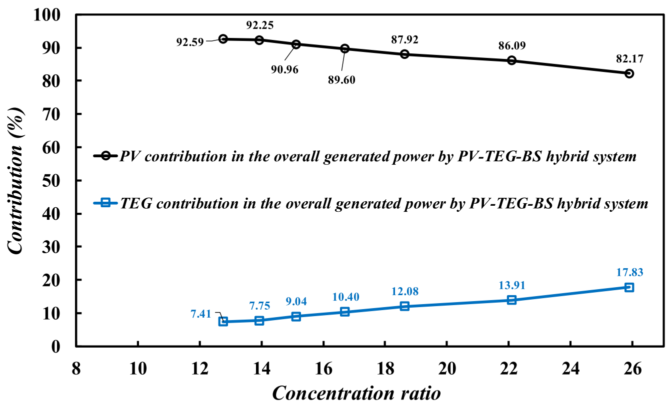


**Fig. 8.** Contribution of the PV and TEG in the overall generated power by the hybrid system.

Si PV cell used in this study has a lower efficiency since a commercial cell for garden light application is used.

Fig. 6 indicates that, the power generated by the TEG in the PV-TEG-BS system has less impact on the overall power generation of the hybrid system. Fig. 8, however, shows the contribution of the TEG in the overall power generation enhances with increasing the solar concentration while the contribution of the PV cell decreases at higher solar concentrations. As the solar concentration increases from 13 to 26, the power generation contribution of the TEG increases from 7.41% to 17.83%, and the contribution of PV decreases from 92.59% to 82.17%, respectively. Therefore, by increasing of the solar concentration and, thus, the heat flux and operating temperature, the TEG plays a more considerable role in the overall power generation by the PV-TEG-BS hybrid system.

## 5. Conclusions

Performance of PV and TEG modules was investigated experimentally in three configurations of solar power systems, namely a PV-only, TEG-only and PV-TEG-BS hybrid systems, under moderate solar concentrations. For each of the systems, electrical outputs of the modules are obtained and discussed. The results show that, the spectral management of solar irradiation has a significant impact on the performance and electrical output of the modules. The results show that, the power generation by the PV in the PV-TEG-BS system is higher compared with that of the PV-only system because of thermal management by the spectral beam splitting technique. On the contrary, the power output by the TEG in the TEG-only system is higher than the share of power generation by the TEG in the hybrid system. Nevertheless, the contribution of the TEG in the overall power generation enhances at higher solar concentration in the PV-TEG-BS system. The PV-TEG-BS system showed higher power conversion efficiency than the PV-only and TEG-only systems in the studied range of solar concentrations. The results of this study provide a guideline for performance estimation of hybrid PV-TEG-BS systems. In order to make this system functional and more commercially viable, improving the ability of the system to compete effectively with the other types of hybrid systems is required in terms of both performance and cost.

## Credit author statement

S. Mahmoudinezhad: Writing – original draft, Experimental setup, Experimental data, Visualization. D.T. Cotfas: Methodology, Writing – original draft, Experimental setup, Experimental data, Data curation. P.A. Cotfas: Methodology, Writing – original draft, Experimental setup, Experimental data, Data curation. Enok J.H. Skjølstrup: Conceptualization, Writing – original draft, Visualization. K. Pedersen: Methodology, Supervision, Investigation. L. Rosendahl: Methodology, Supervision. A. Rezania: Conceptualization, Methodology, Editing- Original draft preparation, Investigation, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

[1] Crabtree GW, Lewis NS. Solar energy conversion. Phys Today 2007;60(3):37–42. https://doi.org/10.1063/1.2718755.
[2] Mahmoudinezhad S, Rezania A, Cotfas PA, Cotfas DT, Rosendahl LA. Transient behavior of concentrated solar oxide thermoelectric generator. Energy 2019;168:823–32. https://doi.org/10.1016/j.energy.2018.12.001.
[3] Otanicar TP, Taylor RA, Telang C. Photovoltaic/thermal system performance utilizing thin film and nanoparticle dispersion based optical filters. J Renew Sustain Energy 2013;5(3). https://doi.org/10.1063/1.4811095.
[4] Mahmoudinezhad S, Cotfas PA, Cotfas DT, Rosendahl LA, Rezania A. Response of thermoelectric generators to Bi2Te3 and Zn4Sb3 energy harvester materials under variant solar radiation. Renew Energy 2020;146:2488–98. https://doi.org/10.1016/j.renene.2019.08.080.
[5] Chen WH, Liao CY, Hung CI, Huang WL. Experimental study on thermoelectric modules for power generation at various operating conditions. Energy 2012;45(1):874–81. https://doi.org/10.1016/j.energy.2012.06.076.
[6] Kossyvakis DN, Voutsinas GD, Hristoforou EV. Experimental analysis and performance evaluation of a tandem photovoltaic-thermoelectric hybrid system. Energy Convers Manag 2016;117:490–500. https://doi.org/10.1016/j.enconman.2016.03.023.
[7] Zhu W, Deng Y, Wang Y, Shen S, Gulfam R. High-performance photovoltaic-thermoelectric hybrid power generation system with optimized thermal management. Energy 2016;100:91–101. https://doi.org/10.1016/j.energy.2016.01.055.
[8] Mahmoudinezhad S, Rezaniakolaei A, Rosendahl LA. Numerical parametric study on the performance of CPV-TEG hybrid system. Energy Procedia 2019;158:453–8. https://doi.org/10.1016/j.egypro.2019.01.131.
[9] Teffah K, Zhang Y. Modeling and experimental research of hybrid PV-thermoelectric system for high concentrated solar energy conversion. Sol Energy 2017;157:10–9. https://doi.org/10.1016/j.solener.2017.08.017.
[10] Mahmoudinezhad S, Ahmadi Atouei S, Cotfas PA, Cotfas DT, Rosendahl LA, Rezania A. Experimental and numerical study on the transient behavior of multi-junction solar cell-thermoelectric generator hybrid system. Energy Convers Manag 2019;184(January):448–55. https://doi.org/10.1016/j.enconman.2019.01.081.
[11] Liao T, Lin B, Yang Z. Performance characteristics of a low concentrated photovoltaic- thermoelectric hybrid power generation device. Int J Therm Sci 2014;77:158–64. https://doi.org/10.1016/j.ijthermalsci.2013.10.013.
[12] Mahmoudinezhad S, Rezania A, Rosendahl LA. Behavior of hybrid concentrated photovoltaic-thermoelectric generator under variable solar radiation. Energy Convers Manag 2018;164(March):443–52. https://doi.org/10.1016/j.enconman.2018.03.025.
[13] Cui T, Xuan Y, Yin E, Li Q, Li D. Experimental investigation on potential of a concentrated photovoltaic-thermoelectric system with phase change materials. Energy 2017;122:94–102. https://doi.org/10.1016/j.energy.2017.01.087.
[14] Mahmoudinezhad S, Rezania A, Cotfas DT, Cotfas PA, Rosendahl LA. "Experimental and numerical investigation of hybrid concentrated photovoltaic – thermoelectric module under low solar concentration. Energy 2018;159:1123–31. https://doi.org/10.1016/j.energy.2018.06.181.
[15] Osborn DE, et al. Spectral selectivity applied to hybrid concentration systems. Sol Energy Mater 1986;14(3–5):299–325. https://doi.org/10.1016/0165-1633(86)90055-9.
[16] Mojiri A, Taylor R, Thomsen E, Rosengarten G. Spectral beam splitting for efficient conversion of solar energy - a review. Renew Sustain Energy Rev 2013;28:654–63. https://doi.org/10.1016/j.rser.2013.08.026.
[17] Green M, et al. Solar cell efficiency tables (version 40). IEEE Trans Fuzzy Syst 2012;20(6):1114–29. https://doi.org/10.1002/pip.
[18] Rezania A, Rosendahl LA. Feasibility and parametric evaluation of hybrid concentrated photovoltaic-thermoelectric system. Appl Energy 2017;187(1 February):380–9. https://doi.org/10.1016/j.apenergy.2016.11.064.
[19] Vorobiev Y, González-Hernández J, Vorobiev P, Bulat L. Thermal-photovoltaic solar hybrid system for efficient solar energy conversion. Sol Energy 2006;80(2):170–6. https://doi.org/10.1016/j.solener.2005.04.022.
[20] Kraemer D, Hu L, Muto A, Chen X, Chen G, Chiesa M. Photovoltaic-thermoelectric hybrid systems: a general optimization methodology. Appl Phys Lett 2008;92(24). https://doi.org/10.1063/1.2947591.

[21] Ju X, Wang Z, Flamant G, Li P, Zhao W. Numerical analysis and optimization of a spectrum splitting concentration photovoltaic-thermoelectric hybrid system. Sol Energy 2012;86(6):1941–54. https://doi.org/10.1016/j.solener.2012.02.024.

[22] Sibin KP, et al. Design and development of ITO/Ag/ITO spectral beam splitter coating for photovoltaic-thermoelectric hybrid systems. Sol Energy 2017;141: 118–26. https://doi.org/10.1016/j.solener.2016.11.027.

[23] Piarah WH, Djafar Z, Syafaruddin, Mustofa. The characterization of a spectrum splitter of Techspec AOI 50.0mm square hot and cold mirrors using a halogen light for a photovoltaic-thermoelectric generator hybrid. Energies 2019;12(3). https://doi.org/10.3390/en12030353.

[24] Li Y, Witharana S, Cao H, Lasfargues M, Huang Y, Ding Y. Wide spectrum solar energy harvesting through an integrated photovoltaic and thermoelectric system. Particuology 2014;15:39–44. https://doi.org/10.1016/j.partic.2013.08.003.

[25] Bjørk R, Nielsen KK. The maximum theoretical performance of unconcentrated solar photovoltaic and thermoelectric generator systems. Energy Convers Manag 2018;156(September 2017):264–8. https://doi.org/10.1016/j.enconman.2017.11.009.

[26] Yin E, Li Q, Xuan Y. "A novel optimal design method for concentration spectrum splitting photovoltaic–thermoelectric hybrid system. Energy 2018;163: 519–32. https://doi.org/10.1016/j.energy.2018.08.138.

[27] Mohammadnia A, Rezania A, Ziapour BM, Sedaghati F, Rosendahl L. Hybrid energy harvesting system to maximize power generation from solar energy. Energy Convers Manag 2020;205:112352. https://doi.org/10.1016/j.enconman.2019.112352.

[28] Skjølstrup EJH, Søndergaard T. Design and optimization of spectral beamsplitter for hybrid thermoelectric-photovoltaic concentrated solar energy devices. Sol Energy 2016;139:149–56. https://doi.org/10.1016/j.solener.2016.09.036.

[29] Novotny L, Hecht B. Principles of nano-optics. second ed. Cambridge University Press; 2012.

[30] Meier J, et al. Potential of amorphous and microcrystalline silicon solar cells. Thin Solid Films 2004;451(452):518–24. https://doi.org/10.1016/j.tsf.2003.11.014.

[31] Goldsmid Julian H. Introduction to thermoelectricity. First edit. Springer; 2010.

[32] Würfel P. Physics of solar cells: from basic principles to advanced concepts. second ed. 2009. second edi.

[33] Cotfas PA, Cotfas DT, Gerigan C, Machidon OM. System design to study hybrid systems in concentrated light using Fresnel lens. In: Proc. - 2017 int. Conf. Optim. Electr. Electron. Equipment, OPTIM 2017 2017 intl aegean conf. Electr. Mach. Power electron. ACEMP 2017; 2017. p. 753–8. https://doi.org/10.1109/OPTIM.2017.7975059.

[34] Cotfas DT, Cotfas PA, Ursutiu D, Samoila C. Current-voltage characteristic raising techniques for solar cells. Comparisons and applications. In: Proc. Int. Conf. Optim. Electr. Electron. Equipment. OPTIM; 2010. p. 1115–20. https://doi.org/10.1109/OPTIM.2010.5510373.

[35] P. Specifications, "Thermoelectric cooler STONECOLD PM-40x40-53 PM-40X40-53," pp. 1–3.

[36] Shang A, Li X. Photovoltaic devices: opto-electro-thermal physics and modeling. Adv Mater 2017;29(8):1–8. https://doi.org/10.1002/adma.201603492.

[37] Cengel AJGYA. Heat and mass transfer: fundamentals and applications. fifth ed. New York, NY, USA: McGraw-Hill Education; 2015.

[38] Lin J, Liao T, Lin B. Performance analysis and load matching of a photovoltaic-thermoelectric hybrid system. Energy Convers Manag 2015;105:891–9. https://doi.org/10.1016/j.enconman.2015.08.054.

[39] Karafil A. Temperature and solar radiation effects on photovoltaic panel power. J New Results Sci 2016;5(November):48–58.

[40] Cotfas DT, Cotfas PA, Machidon OM. Study of temperature coefficients for parameters of photovoltaic cells. Int J Photoenergy 2018;2018:5945602. https://doi.org/10.1155/2018/5945602.