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Article

An Experimental Study on Transient Response of a Hybrid Thermoelectric–Photovoltaic System with Beam Splitter

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Abstract: In the current study, the electrical responses of a thermoelectric (TE) module and a photovoltaic (PV) cell are investigated in three different systems, namely, a PV-only system, TE-only system, and hybrid TE-PV system with a beam splitter (TE-PV-BS), under variable solar irradiations demonstrating partly cloudy weather conditions. To enhance the deployment of solar energy, a predesigned beam splitter combined with the amorphous silicon TE and PV system is used in the experiments. The impact of the spectral beam splitting technology on the conversion performance of the TE module and PV cell in the hybrid system is studied and compared to the performance of the TE-only and PV-only systems. The electrical output parameters of the TE module and PV cell are obtained for the studied systems, and they are discussed in detail. The results of this work show that the power generated by the PV cell has a stepwise fluctuation similar to the variation in the concentrated solar radiation. Affected by its heat capacity, the power variation is monotonous with the TE module. The results moreover indicate that there is more power generated by the PV cell in the TE-PV-BS hybrid system than by the PV-only system. In comparison, the TE-only system produces more power than the TE module in the hybrid system. Furthermore, the TE-PV-BS hybrid system generates higher and more stable electrical power than the TE-only and PV-only systems, showing a significant advantage of the spectrum management concept.

Keywords: thermoelectric module; photovoltaic cell; spectrum beam splitting; hybrid energy conversion; transient response; maximum power

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1. Introduction

The fast depletion of conventional energy resources threatens the world's energy supply. Worldwide energy demand is outgrowing the existing energy supply from fossil fuels [1–3], which currently provide more than 80% of demanded energy. Due to the unfriendly nature of conventional energy sources to the atmospheric environment, substantial exploration in fields of clean, renewable, and sustainable energy is required. Many nations have new policies to drive toward renewable energy resources due to their exceptional advantages, such as low pollution and inexhaustibility [4,5].

To date, the most exploited alternative to conventional energy resources is solar energy [6,7]. Photovoltaic (PV) technology is a known and efficient technology for direct conversion of solar energy to useful electricity. Nevertheless, in PV cells with high conversion efficiency, less than half of the solar spectrum can be utilized. The rest of the solar irradiation is converted into thermal energy because of the bandgap limitation, recombination, and thermalization, or it is reflected [8]. The energy loss is more considerable in high solar radiations. With increasing production of thermal energy, the temperature of the PV cell increases, which reduces the cell's efficiency [9]. To maximize solar energy utilization, a fraction of the thermal energy can be harvested by thermoelectric (TE) modules. TEs have a long lifetime and no moving parts, and they are highly reliable [10,11], which makes them appropriate choices for integration with PV cells in order to convert a broader range of the solar spectrum into electricity.

Due to the solid-state nature of the TE modules, they can be simply connected to PV cells to make a TE-PV hybrid module where the generated heat is utilized by the TE. This integration of the TE-PV system has been extensively studied [12–14]. The main drawback of such a system is the confrontation between the efficiency of the TE module and PV cell due to the thermal connection of these modules, where the operating temperature has a reverse impact on the efficiency of the TE module and PV cell. At low temperatures, the PV cell has optimum performance, while the TE module does not play an important role in power generation and, consequently, has a negligible impact on overall power production. The spectral splitting method can solve this confrontation, where the TE module and the PV cell can be thermally independent, with each one being able to work at different and desired temperatures [15] to enhance the overall conversion efficiency.

The concept of TE-PV-beam splitting (TE-PV-BS) hybrid systems has been studied since the last decade. Vorobiev et al. [16] described and analyzed two different hybrid systems, in which PV cells operate under low and high-temperature conditions. It was shown that both forms of the hybrid systems can be efficient means to harvest solar energy. Kraemer et al. [17] presented a new scheme for optimizing the TE-PV hybrid system to increase solar energy conversion efficiency. Different solar cells and TE modules are considered and analyzed in their study. The results of their study indicated that in order to have a more straightforward design for the spectrum partition element when the efficiency drop is insignificant, the spectrum needs to be segmented into two regions.

A numerical model was developed by Ju et al. [18] to investigate the impact of cooling efficiency, cutoff wavelength, and concentration ratio on the power generation and efficiency of a TE-PV-BS module. The guidelines for optimization of such a module were also proposed to achieve optimal design. It was found that the cooling system had a significant impact on the performance of the hybrid module, and the TE module contributed around 10% to the overall power generated by the GaAs-$CoSb_3$ hybrid module. Li et al. [19] studied a TE-PV-BS to make best use of solar energy. The results showed that with an increase in solar concentration, the figure of merit, the TE module's temperature on its hot side, and the system efficiency increased. Sibin et al. [20] used the magnetron sputtering method to deposit multilayer coatings composed of Ag and ITO on glass substrates to fabricate a high-performance beam splitter. The performance of the beam splitter was optimized by changing the thickness of the layers. It was found that the NIR-IR reflectance is more than 90% and the visible transmittance is more than 88% for the designed beam splitter and under optimal conditions.

Mahmoudinezhad et al. [21] investigated the impact of an optimal beam splitter on the performance of a TE-PV-BS system. They found that although the power generated by the TE module decreased in the hybrid system, the overall power increased significantly in the hybrid system. Yin et al. [22] developed a new theoretical model for improving the performance of a hybrid module operating under different optical concentration ratios. Their results showed the optimal cutoff wavelength increased at a lower figure of merit of the TE module. Furthermore, the PV cell and TE module's power generation had opposite trends with change in the figure of merit. In order to determine the best location of the TE module and PV cell in a TE-PV -BS system, Piarah et al. [23] characterized both cold and hot mirrors, type TechSpec AOI 50.0, as the spectrum splitter in the system. It was indicated that when a cold mirror is utilized as the spectrum splitter, the maximum power generation can be 40% higher than when a hot mirror is used in the system.

The majority of studies in the field of TE-PV-BS have focused on the modelling of hybrid performance and efficiency. There is a lack of experimental studies on this concept, and the works mentioned above have only considered TE-PV-BS systems under steady-state conditions. Investigation of the transient behavior of TE-PV-BS systems can provide important knowledge of the system's performance under unclear weather conditions, where solar radiation is changing throughout the day. Under such weather conditions, PV and TE power generation is not stable and steady. This study, therefore, endeavors to bridge this gap by using an experimental approach to investigate the transient behavior of a TE-PV-BS hybrid system.

In one study [24], the concept of spectrum splitting was theoretically optimized by advanced numerical optimization methods. The concept is theoretically advantageous, where 21% performance improvement could be obtained by using a particular PV cell based on amorphous silicon. The fabricated beam splitter in this study was, therefore, designed and optimized to match with the particular PV cell and TE module in this experiment. The results for the TE-PV-BS hybrid system were compared with TE-only and PV-only systems to show the impact of application of the spectral splitting technique. The electrical response of the investigated systems was measured and compared under a moderate range of solar concentrations.

2. Beam Splitter and Experimental Setup

The basic concept behind the hybrid system is to enhance energy conversion efficiency. PV efficiency is limited because the wavelengths of the incident light, which are longer than the bandgap wavelength of the PV semiconductor, cannot be converted into useful electrical power. Furthermore, for the converted wavelengths the efficiency is not 100% [25]. Typical PV cells are a single junction made of silicon with efficiencies off 15–20% [25,26]. One way to enhance conversion efficiency of PVs is to use multi-junction cells, where different materials are combined in order to utilize a wider solar spectrum. Such cells can have almost 50% efficiencies; however, these PV cells cost more than single-junction PV cells [27,28].

In the current study, a conventional single-junction PV cell was combined with a TE module that converts sunlight into electricity with a typical efficiency of 4–8% independent of the wavelength of light [29]. The central component in such a hybrid system is the BS, which directs the wavelengths of the incident light onto the target components, the PV cell or the TE module for efficient utilization [17,18]. Hence, an optimal BS must efficiently split the incident light into transmitted and reflected lights, directing them onto the TE module and PV cell, respectively. In order to optimize the design of the BS, a theoretical method is presented in [24], where the BS comprises alternating layers of Si_3N_4 and SiO_2, which are deposited on a glass. For realistic PV cells and TE modules, the relative improvement in efficiency was found to be 21% [24].

A major task in this work was fabrication of a BS based on the design methodology presented in [24]. The fabricated BS, however, contains TiN as the high-index refractive material and SiO_2 as the low-index material. The wavelength-dependent refractive indices can be found in [30]. Alternating layers of these materials were coated onto a substrate of BK7 glass using chemical vapor deposition. When the BS was fabricated, its spectrum splitting behavior was characterized by measuring the reflectance and transmittance for light incident on the BS from different angles. The measurements were performed using a PerkinElmer LAMBDA 1050 spectrometer, and the results are shown in Figure 1, where θ denotes the incident angle. From the TE module and PV cell used in the studied hybrid system, it was found that the PV cell is the most effective component for wavelengths between 468 nm and 702 nm, while the TE module is more effective for all other wavelengths. Hence, ideally, the BS reflects all wavelengths between 468 nm and 702 nm and transmits all others, and the ideal reflectance is shown by the black solid curve in Figure 1. It is seen that the measured reflectance is relatively close to the ideal, showing that the BS works as intended.

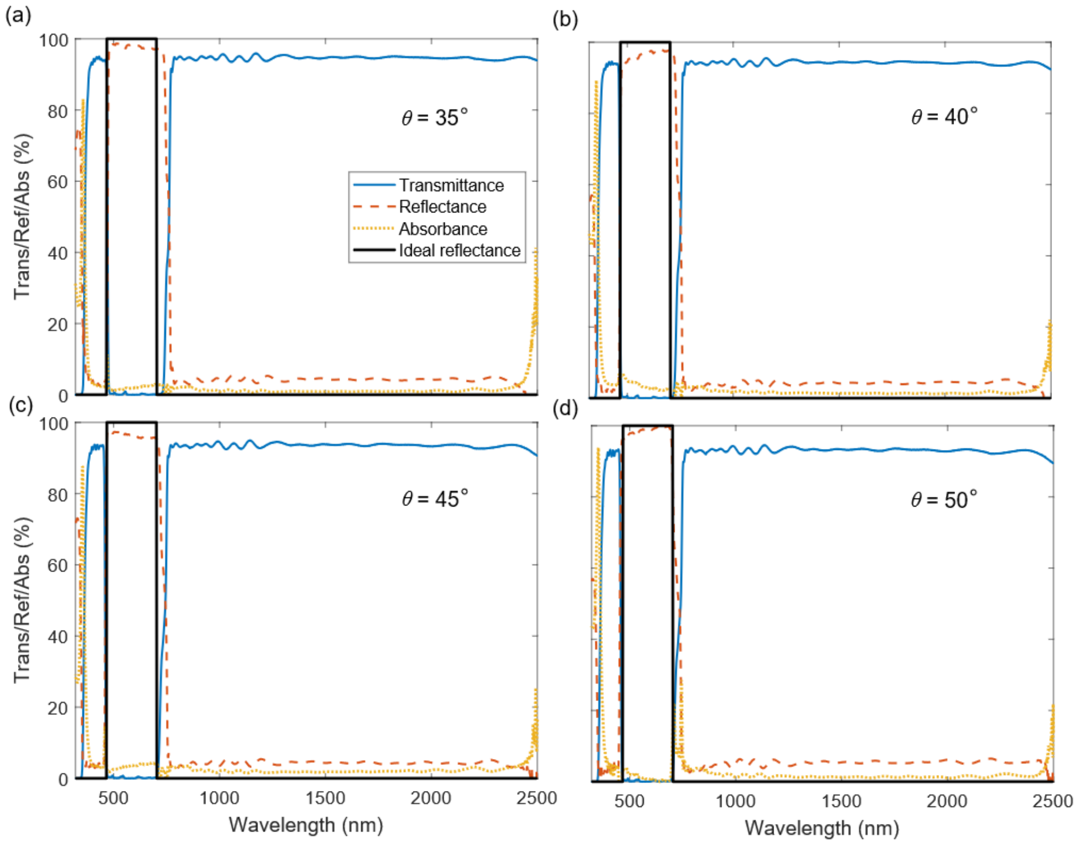


Figure 1. Measured transmittance, reflectance, and absorbance through the beam splitter at different incident light angles as denoted in each panel (**a**) θ = 35° (**b**) θ = 40° (**c**) θ = 45° (**d**) θ = 50°. For line types, refer to the legend in (**a**).

The studied hybrid system consists of a commercial amorphous silicon photovoltaic cell (aSI PV) with 40 mm × 40 mm dimensions and a commercial Stonecold TEC1-12710, Bi_2Te_3 thermoelectric module with dimensions of 40 mm × 40 mm. The TE module's hot side was covered with a graphite adhesive sheet, used as an absorber of solar radiation. The BS, with a size of 137 mm × 137 mm, reflected the visible portion of the solar spectrum onto the aSI PV cell and transmitted the infrared portion of the solar spectrum onto the TE module. The optical characteristics of the BS are shown in Figure 1.

These experiments were performed under concentrated solar light provided by using a 320 mm × 320 mm Fresnel lens placed on a two-axis sun tracker (ST). The ST was controlled by an NI myRIO tool using mathematical algorithms for the calculation of the ST's correct position, implemented in NI LabVIEW FPGA [31]. The light concentration ratio varied between 12 and 25 to study the transient response of the systems. The solar irradiation and the transient weather conditions were simulated by moving the system through the Fresnel lens's focal point. This replacement was performed using two stepper motors controlled by the NI myRIO device. The system setup is shown in Figure 2. More information on the light homogeneity and uniformity of the irradiance can be found in [31].

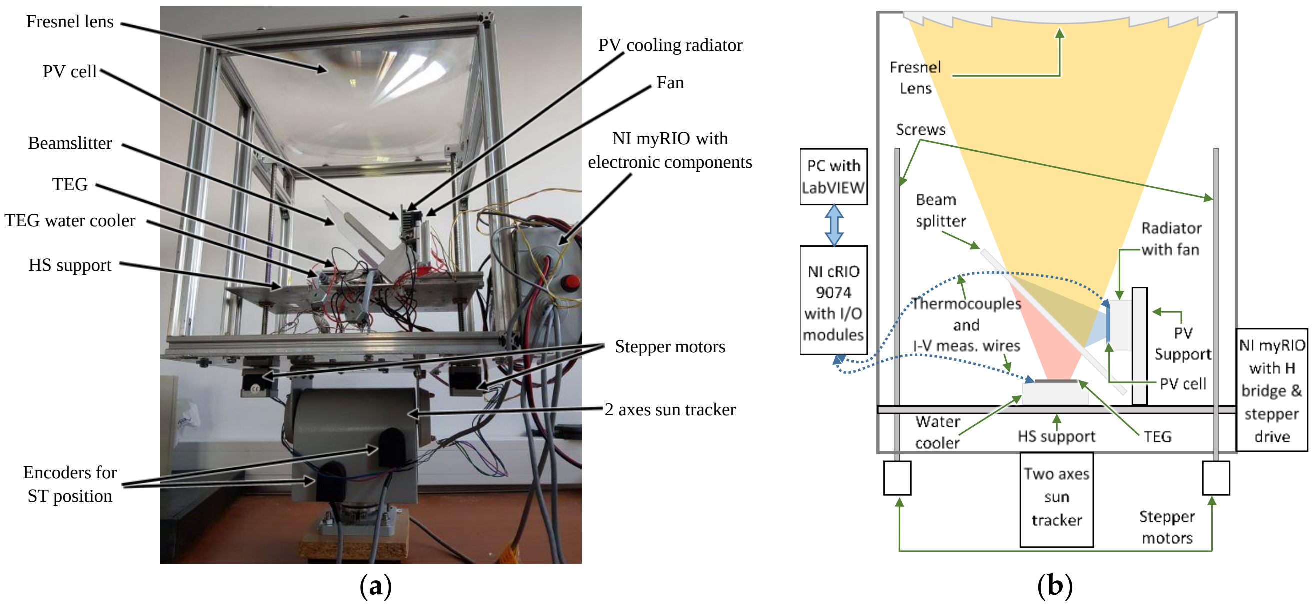
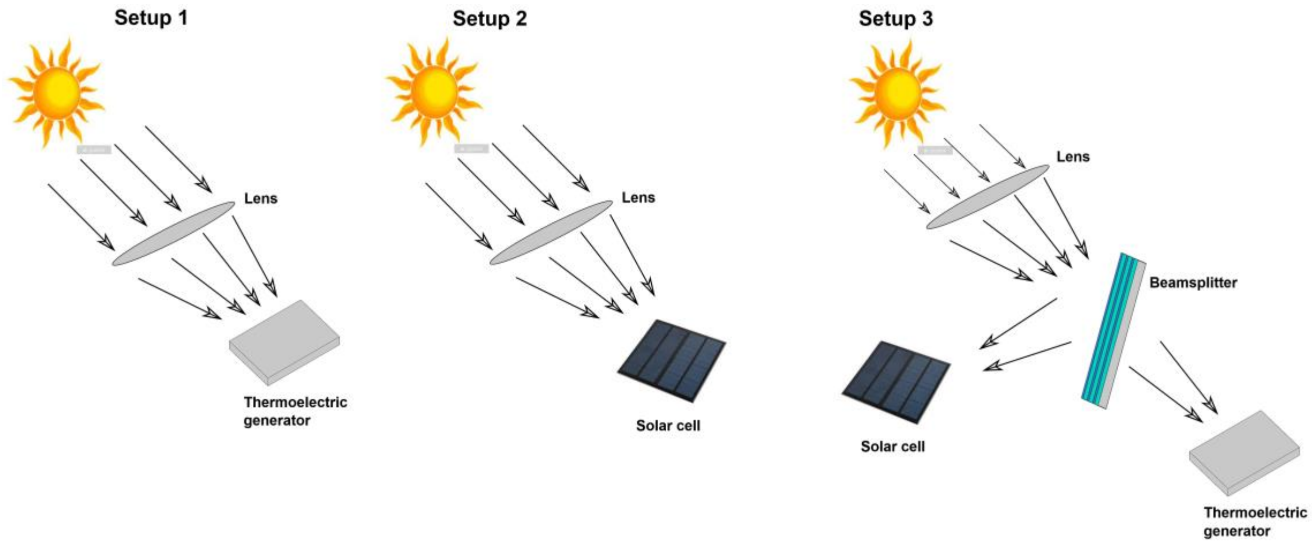


Figure 2. (**a**) The system setup; (**b**) schematic of the experimental setup.

The system used for characterization of the hybrid system was established with the NI cRIO 9074 platform. The platform contains five cRIO I/O modules, and the NI 9215 and NI 9227 modules were used for voltage and current measurement in the TE module and PV cell, respectively, during the IV characteristic measurements. The IV characteristics are obtained using a self-developed dynamic load based on the capacitor technique [32]. The NI 9211 and NI 9213 modules were used to measure the PV cell's temperatures and the TE module's hot and cold side temperatures using K thermocouples, which were placed on the back side of the aSI PV, on the cold and hot sides of the TE, and one in the ambient air. The NI 9401 module was used for triggering the IV characteristics of the TE module and PV cell at the desired moment of time. The PV cell and TE module were cooled using two cooling systems. For the aSI PV cell, we used a CPU radiator with a fan. For the TE module, a self-developed water copper cooler was used. The cooling water system used a copper parallelepiped with milled channels. The inlet water temperature was maintained quasi constant at 20 °C, using a high-capacity water tank and ensuring a water flow of 2 L/min. It is worth noting that the cooling method and implemented heat sink play a crucial role in the power generation of the TE module and PV cell. Using a water cooling system leads to higher power being generated by the PV cell. The software application for the entire system control, measurements, and data analysis was developed in NI LabVIEW. The maximum temperature of the PV cell was 75 °C when used in the hybrid system and 110 °C when used alone at maximum solar radiation of 25.9 suns.

3. Result and Discussion

In order to determine the significance of using the BS in the hybrid system, three different systems, namely a TE-only system, PV-only system, and hybrid TE-PV-BS system, were assembled and experimentally examined. The systems studied under time-dependent solar irradiations are shown in Figure 3.



(a) (b) (c)

Figure 3. (**a**) TE-only system; (**b**) PV-only system; (**c**) TE-PV-BS hybrid system.

The experimental results for the conversion efficiency and power generation of the three systems accomplished in the random cloudy weather are not easy to analyze. To evaluate the transient behavior and the systems' performance under different levels of solar irradiations, an optional solar concentration pattern, shown in Figure 4b,d and Figure 5b,d, was selected and applied to the systems. By adjusting the distance between the TE-PV-BS system and the Fresnel lens, variable solar irradiation was provided. The maximum amount of the applied solar irradiation was equal to 25 suns (one sun is 1000 W/m^2.), while minimum solar irradiation equal to 12 suns was applied to the system. Therefore, this experimental work represents a TE-PV-BS system under a solar concentration of 25 suns but in semi-cloudy weather conditions. The main advantage of applying this arbitrary pattern is that the variation in the TE module and PV cell output power and system efficiency can be precisely tracked and interpreted.

The key performance parameters of the TE module and PV cell, such as open-circuit voltage, short-circuit current, and maximum output power, were achieved and compared for different systems. Figure 4 shows the variation in parameters for the PV-only and the TE-only systems. The parameters are measured every 10 s, while the measurements started as the systems were at the steady-state condition with 26 solar concentrations.

Figure 4a,b and Figure 5a,b indicate the variation in electrical response of the PV cell in the PV-only and the TE-PV-BS systems, respectively. The maximum power and short-circuit current both have stepwise variations and follow the solar irradiation pattern. The open-circuit voltage, however, has a different response to the solar irradiation change. Area (1) in these figures displays that, with declining solar irradiation and, therefore, reducing temperature and heat flux of the PV cell, the voltage increases. The slight increase in the PV power generation shown in area (2) is due to this temperature drop. A different electrical response of the PV cell can be seen in area (3), where the solar concentration, temperature, and heat flux increase. Therefore, the PV power generation decreases in area (4), and the two main parameters affecting the PV power generation in this study are solar irradiation and the operating temperature. The impact of the solar concentration is more significant and causes a stepwise variation in electrical power. The influence of temperature on the output electrical power is smaller than that of solar irradiation as can be observed in areas (2) and (4) in Figures 4b and 5b.

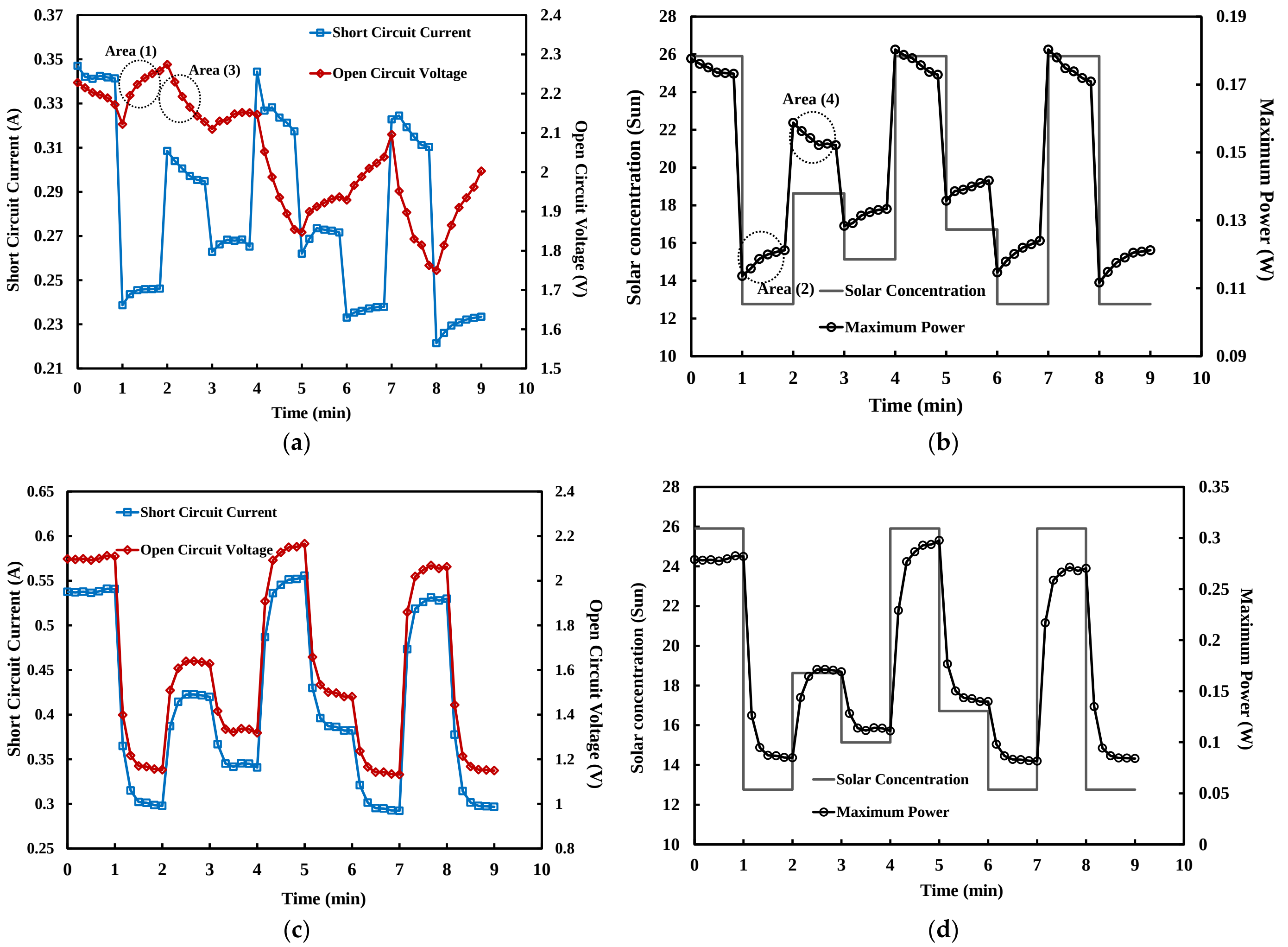


Figure 4. Maximum power, solar concentration, open-circuit voltage, and short-circuit current by (**a**,**b**) PV cell in PV-only system and (**c**,**d**) TE module in TE-only system.

The maximum output power, the short-circuit current, and the open-circuit voltage of the TE module in the TE-only and TE-PV-BS hybrid systems are shown in Figure 4c,d and Figure 5c,d, respectively. The temperature difference across the TE module and its figure of merit are two of the key parameters affecting the TE module's performance. Since the variation in the figure of merit in the studied range of the temperature is insignificant [33], the most critical parameter in this study is the operating temperature. Higher solar concentrations cause higher temperature differences across the TE module and vice versa. Therefore, as shown in Figure 4c,d and Figure 5c,d, the parameters of the electrical response follow the solar irradiation variation.

PV power generation in the PV-only and TE-PV-BS systems is displayed in Figure 6a. The significant influence of the spectral splitting management on PV performance can be seen in this figure. The parts of the solar spectrum with shorter or longer wavelengths than visible light are not favorable for the PV cell [34]. These parts of the spectrum are converted into heat and decrease the performance of the PV. This happens for the PV-only system, where the whole solar spectrum reaches the cell and reduces the PV conversion performance by increasing its operating temperature. Reflecting only the visible light onto the PV cell, however, leads to considerable enhancement in the cell's performance in the TE-PV-BS hybrid system.

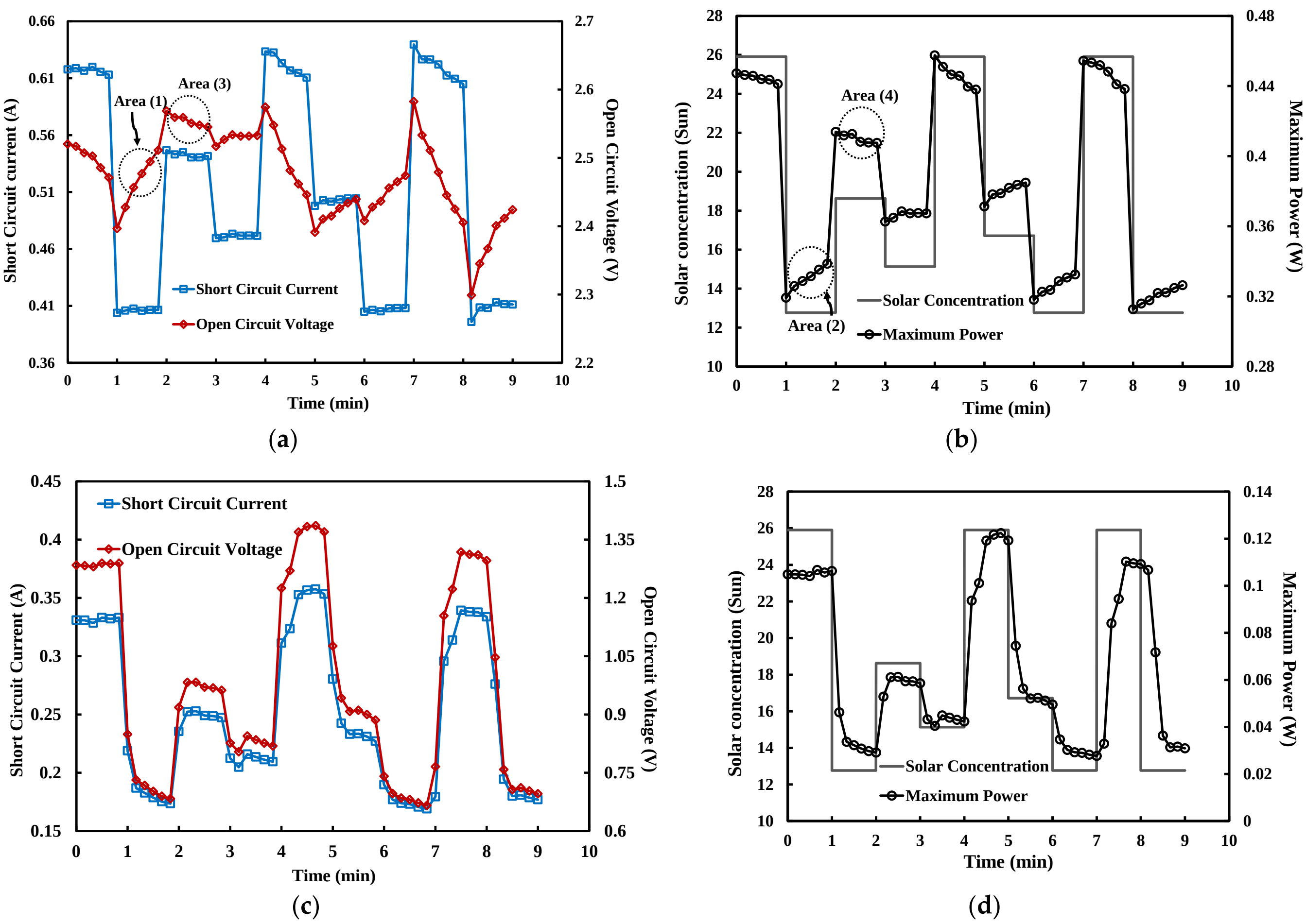


Figure 5. Maximum power, solar concentration, open-circuit voltage, and short-circuit current by (**a**,**b**) PV cell and (**c**,**d**) TE module in TE-PV-BS system.

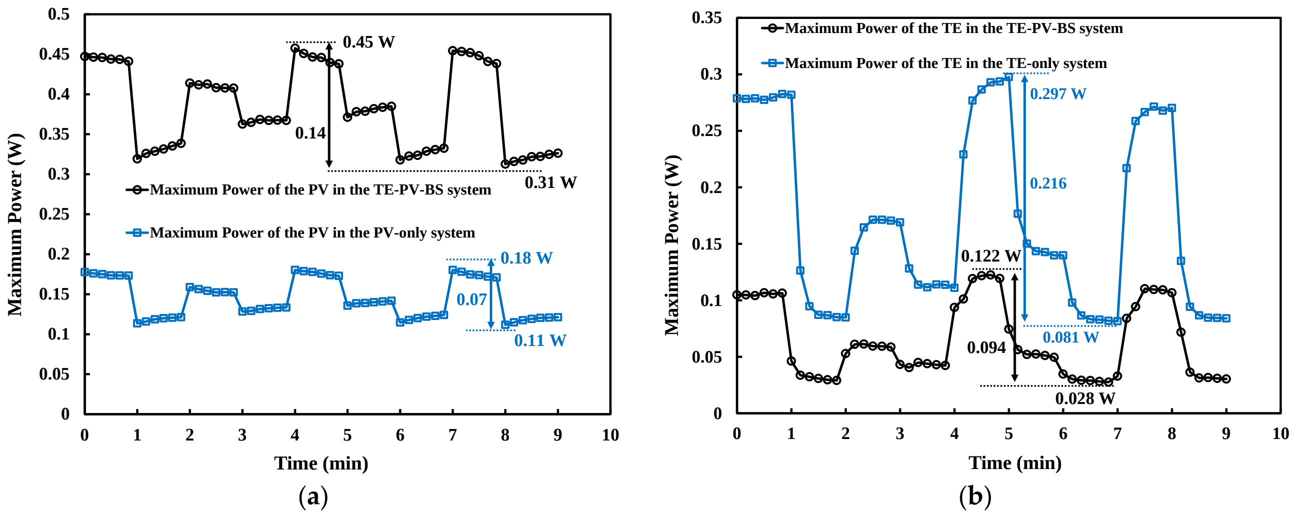


Figure 6. Maximum power comparison between (**a**) PV cell in the PV-only and TE-PV-BS systems, and (**b**) TE module in the TE-only and TE-PV-BS systems.

The range of the maximum power variation in the PV-only system for the selected solar concentration pattern is between 0.11 W and 0.18 W. This range is between 0.31 W and 0.45 W for the TE-PV-BS hybrid system. These values indicate the substantial impact of using the spectral splitting concept. It is worth noting that the variance between the lowest and highest values of power generation of the PV-only and TE-PV-BS hybrid systems are 0.07 W and 0.14 W, respectively.

Figure 6b displays the time-dependent variation in the maximum power in the TE-PV-BS and TE-only systems. Due to the TE module's heat capacity, the electrical response is not stepwise and is similar to the PV cell, where the variations are gradual. Since the TE-only module is exposed to the whole spectrum of solar irradiance, it absorbs the photons' energy not only in the infrared band but also in the visible range. In fact, in the TE-only system, all the solar spectrum's energy arrives at the TE module, while in the TE-PV-BS system, part of the spectrum, which is visible light, is reflected onto the PV. Consequently, all of the energy of the photons does not reach the TE. Therefore, the temperature difference in the TE-only system and power generation significantly increase. For the TE-only system, the lowest and highest levels of the maximum power generation are 0.081 and 0.297, respectively. For the TE-PV-BS system, these values are 0.028 and 0.122. Although the power generated by the TE-only system is higher than that generated by the TE-PV-BS system, the range of variation is also higher. The variation range of power in the TE-only system is 0.216, while this value is 0.094 in the TE-PV-BS system.

To show the effect of the beam-splitting technique, the overall maximum power generation in the TE-PV-BS system was compared with the aggregation of the maximum power in the TE-only and PV-only systems. The results in Figure 7 show that the solar spectrum management technique has a substantial effect on the hybrid system's power generation. The power generated by the hybrid system varies between 0.35 W and 0.56 W, and the summation of powers in the TE-only and PV-only systems varies between 0.20 W and 0.46 W. Not only does the power generation increase, but also the range of variation of the power in the hybrid system (0.21 W) is smaller than the aggregation of the powers in the PV-only and TE-only systems (0.26 W). This indicates that the TE-PV-BS system provides more stable and steady output power.

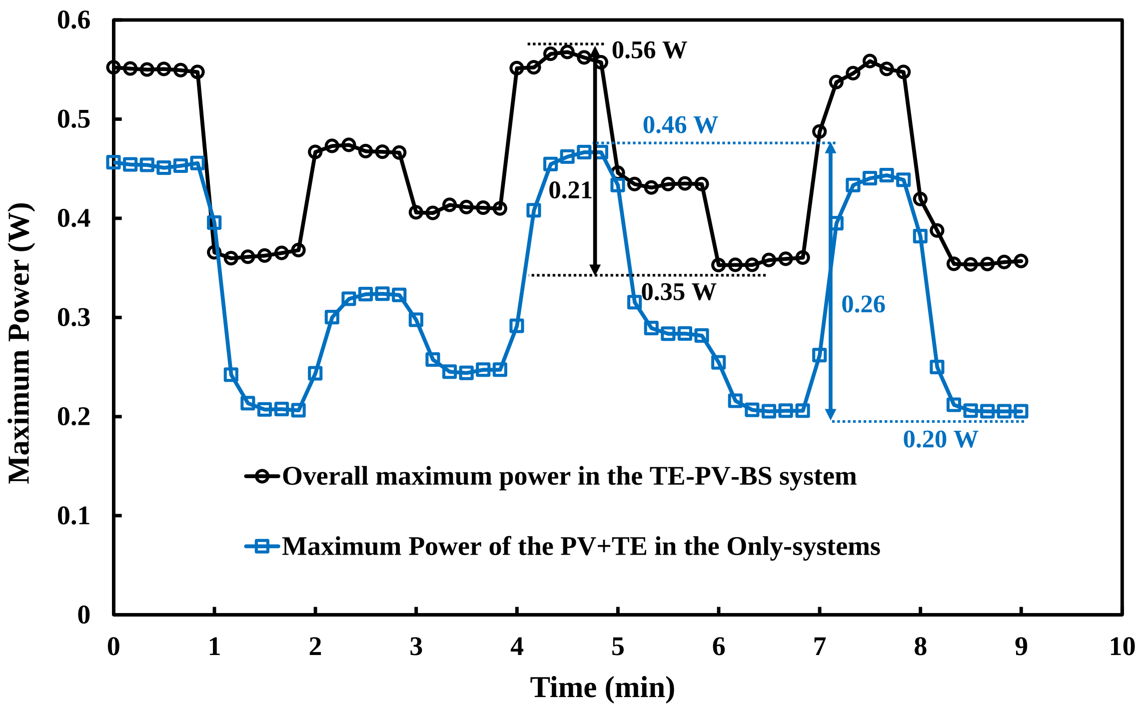


Figure 7. Overall maximum power generated by the hybrid system and the aggregation of the maximum powers in the PV- and TE-only systems.

Table 1 summarizes the results for the highest and lowest maximum power generation by the PV cell and TE module in each system.

Table 1. Comparison of the maximum power generated by each system.

System	Lowest Maximum Power Generated by PV Cell	Highest Maximum Power Generated by the PV Cell	Difference between the Lowest and Highest Maximum Power
PV-only system	0.11 W	0.18 W	0.07 W
TE-PV-BS hybrid system	0.31 W	0.45 W	0.14 W
System	**Lowest Maximum Power Generated by the TE Module**	**Highest Maximum Power Generated by the TE Module**	**Difference between the Lowest and Highest Maximum Power**
TE-only system	0.081 W	0.297 W	0.216 W
TE-PV-BS hybrid system	0.028 W	0.122 W	0.094 W
System	**Lowest Maximum Power Generated by the PV Cell and TE Module**	**Highest Maximum Power Generated by the PV Cell and TE Module**	**Difference between the Lowest and Highest Maximum Power**
Overall maximum power generated by the hybrid system	0.35 W	0.56 W	0.21 W
Aggregation of the maximum powers in the only-systems	0.20 W	0.46 W	0.26 W

As mentioned, the power generated by the PV cell in the TE-PV-BS system is higher than that generated by the PV-only system due to the spectrum management and the direction of the favorable range of the solar spectrum toward the PV cell in the hybrid system. Figure 8 shows that the ratio of the maximum power generation in the PV-only system over the TE-PV-BS hybrid system increases as solar irradiation increases. This value changes between 0.356 to 0.401 for solar concentration equal to 12.8 suns and 25.9 suns, respectively. The ratio of the maximum power in the TE-only system over the TE-PV-BS system also has the same trend. That is, it increases with solar irradiation. As shown, the electrical power in the TE-only system is greater than the power in the TE-PV-BS system. Figure 8 indicates that the ratio of the maximum power ratio of the TE-only system over the TE-PV-BS system increases from 2.03 to 2.89 for irradiation input of 12.8 suns to 25.9 suns, respectively.

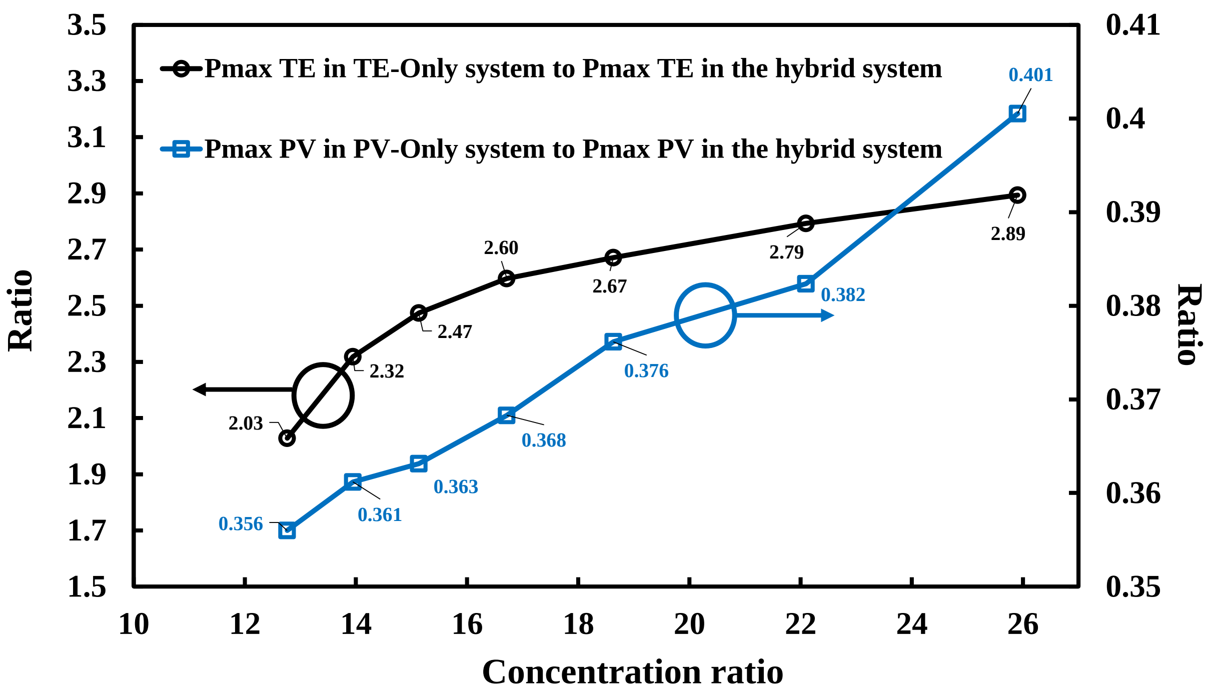


Figure 8. Ratio of power generation by the PV cell and TE module in the PV-only and TE-only systems over the TE-PV-BS hybrid system.

4. Conclusions

The transient response of a TE module and PV cell in three different systems was evaluated under time-dependent solar irradiation in this experimental study. The variation in electrical outputs was obtained and discussed for the studied systems. The results indicated that the spectral management concept and use of a proper predesigned BS are useful tools to enhance the utilization of solar energy. It was found that the concentration ratio of the solar irradiation and the operating temperature are the two main parameters affecting the performance of the TE module and PV cell. The PV cell generated more power when it was used in the TE-PV-BS hybrid system compared to the PV-only system. However, the TE-only system generated higher power than the TE module in the hybrid system. Since the PV cell contributed more to the total output power in the TE-PV-BS system, the hybrid system's efficiency showed an inverse proportional relationship with the variation in solar irradiation. The results of this study showed that using the solar spectrum technique not only increased the utilization of solar energy but also provided a more stable and steady electrical power delivery.

Author Contributions: Conceptualization, L.R. and A.R.; methodology, S.M., P.A.C., D.T.C., E.J.H.S. and A.R.; software, S.M. and P.A.C.; validation, S.M., P.A.C., D.T.C. and E.J.H.S.; formal analysis, S.M. and P.A.C.; investigation, S.M., D.T.C., E.J.H.S. and A.R.; resources, K.P. and L.R.; data curation, S.M. and P.A.C.; writing—original draft preparation, S.M., P.A.C., D.T.C., E.J.H.S. and A.R.; writing—review and editing, S.M., D.T.C., E.J.H.S. and A.R.; visualization, S.M. and E.J.H.S.; supervision, K.P., L.R. and A.R. All authors have read and agreed to the published version of the manuscript.

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