Solar electricity generation using a photovoltaic-thermoelectric system operating in Nigeria climate

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Abstract. This paper presents the performance evaluation of a hybrid photovoltaic-thermoelectric (PV-TE) system operating under practical conditions in Nigeria climate. The thermoelectric generator (TEG) is directly attached to the back plate of the PV cell and is used to regulate the cell temperature while increasing its overall efficiency. A three-dimensional finite element model is developed in ANSYS 2020 R1 commercial software and is utilised in studying the temperature and electric distribution of the hybrid system operating under practical conditions. Temperature dependent material properties are also considered. The simulation is carried out for 24 h to encompass both day and night operation of the hybrid system. Results indicate that power output obtained from the hybrid PV-TE set up is higher than that harvested from the stand-alone PV system. Furthermore, the TEG acts as a heat sink by converting the waste infrared radiation from the PV to electricity. Hence, the incorporation of TEGs to PV systems is highly encouraged since this will result in better system performance at relatively low cost. The results obtained from this study will provide a reference for the design of hybrid photovoltaic-thermoelectric systems operating in Nigeria.

Keywords: photovoltaic-thermoelectric systems; solar power generation; finite element analysis; Nigeria solar radiation.

1. Introduction
The adverse effects of fossil fuels on the environment has, in recent times, led to the rapid increase in the exploration of renewable energy sources like photovoltaic (PV) systems [1,2]. These systems are characterised by peculiar merits such as: low maintenance cost, zero environmental pollution and noiseless device operation [3]. However, the efficiency of PV systems is still limited by the increasing cell temperature during power generation [4]. The peak efficiency obtainable from a monocrystalline cell is approximately 18% [5]. This value is relatively low; hence, the PV cell efficiency needs to increase in order to increase its relative advantage over present-day fossil fuel sources. Thus, encouraging its large-scale adoption in global power generation systems.

Since PV cells use a fraction of the solar spectrum, the infrared component of sunlight which is not utilized by the cell reduces its efficiency by heating it up. Hence, incorporating a thermoelectric generator (TEG) which utilizes the infrared component of sunlight would lead to the complete utilization of the broad solar spectrum [6]. The effective incorporation of a TEG in a PV system would establish a notable advance in the utilisation of solar energy [7]. A TEG is a device which converts thermal energy directly to electricity using the Seebeck effect [8]. Thus, using a TEG in conjunction with a PV achieves a double purpose of cooling the PV cell and producing extra electrical power using the cell waste heat.

Several authors have investigated the performance of a hybrid PV-TE system using finite element method (FEM). Kiflemariam et al. [9] used this method to carry out a two-dimensional (2-D) study of a PV-TE system. They reported that increasing the concentration ratio results in a higher electrical power output from the TEG. Beeri et al. [10] validated their experiment on a hybrid PV-TE system using this method. Their results demonstrated that a maximum efficiency of about 30% was obtained for a concentration ratio \( \leq 200 \). Furthermore, Teffah et al. [11] utilised this method in evaluating the
performance of a hybrid system consisting a: triple junction solar cell (TJSC), thermoelectric cooler (TEC) and TEG, respectively. Also, Li et al.[12] used FEM to determine the optimum geometry required to maximise the power generated by the TEG in the PV-TE system.

Hence, this paper presents the transient analysis of a concentrated PV-TE system subject to practical weather conditions – in Enugu, Nigeria – using FEM. This research is aimed at investigating the effects of transient and fluctuating heating on the thermal and electrical performance of a concentrated PV-TE system. The uni-couple TE model is used in order to accelerate computation time while obtaining accurate results from which substantial variation techniques can be implemented. The effects of the rising heat sink temperature on the TEG temperature gradient is also investigated and temperature dependent material properties are considered. A three-dimensional model is developed in ANSY 2020 R1 software and FEM is used to analyse the model. To the best of our knowledge, this study predicated others and would provide useful information on the design of PV-TE operating under actual meteorological conditions in Enugu, Nigeria. The only similar previous study was carried out by ref. [13]. However, in their study, the hourly solar radiation data used was peculiar to the United Kingdom (UK). In addition, the concentration ratio was assumed constant while the heat sink convective heat transfer coefficient was varied from 200-700 W/m²K. Furthermore, the effect of the TEG solder paste and the PV-TEG interface conductive layer on the temperature distribution was neglected. However, in this study, the effect of varying concentration ratio and solar radiation on the overall system performance; while accounting for the TEG solder paste and copper conductive layer, is investigated. Additionally, this analysis is implemented under matched load power conditions and the equations of heat transfer are modelled using FEM. The merits of using FEM are: it offers an easy interface for modelling and analysing results while maintaining high accuracy [14]. Also, the application of FEM solvers, like ANSYS, permits the incorporation of different physical models (Multiphysics) thus facilitating a more detailed study.

2. Methodology
The three-dimensional model and assigned materials are depicted in Figs. 1 (a) and (b), respectively. A polycrystalline silicon-based PV module comprises, from top to bottom: glass, ethylene vinyl acetate (EVA), polycrystalline silicon-based cell, EVA, tedlar polyester tedlar (TPT) and copper conductive layer. The top glass cover offers system mechanical integrity and rigidity while providing high light transmissivity and low reflection. The EVA is an encapsulant that is utilised in binding the solar cell, the cell top surface and the TPT, respectively. The solar cell converts incident solar radiation to electricity using the PV effect, while the TPT protects the cell back surface. Since the model is designed using the direct coupling method, it becomes crucial to specify a copper conductive layer which enhances heat transfer between the cell back plate (TPT) and the TEG. The specified thicknesses of the EVA, solar cell, TPT and conductive layer are 0.5 mm, 0.15 mm, 0.3 mm and 0.5 mm, respectively. The TEG uni-couple is directly attached to the copper conductive layer. A typical uni-couple comprises, from top to bottom: ceramic plates, copper conductor pads, solder paste and thermoelectric materials. The thermoelectric material used is a bismuth telluride, which is suitable for low temperature application, with material properties as specified by ref. [15]. The top and bottom ceramic plates provide module mechanical integrity, the copper conductor pads enhance electrical conductivity through the thermoelectric legs, the solder paste joins the cooper conductor pads to the thermoelectric legs while reducing the thermal stresses in the legs. The thicknesses of the ceramic plates, conductor pads and solder paste are 0.8 mm, 0.1 mm and 0.05 mm, respectively.
The following equations are used to govern the behavior of the TEG and PV systems:

The TEG power output obtained under matched load conditions \( R = R_L \) is given as \([16,17]\)

\[
P_{TE} = \frac{\alpha^2 (T_h - T_c)^2}{4R_L}
\]

where \( \alpha \), \( T_h \), \( T_c \) and \( R_L \) are the temperature dependent Seebeck coefficient, hot junction temperature, cold junction temperature and external load resistance, respectively.

The PV power output is given by \([18]\)

\[
P_{PV} = CG\alpha_{PV}A_{PV}\eta_{ref} \left[ 1 - \beta_{PV} \left( T_{PV} - T_r \right) \right]
\]

where \( C \), \( G \), \( \alpha_{PV} \), \( A_{PV} \), \( \eta_{ref} \), \( \beta_{PV} \), \( T_{PV} \) and \( T_r \) are the concentration ratio (1-10), transient solar radiation, PV light transmissivity (0.9 \([19]\)), area of the PV panel (0.0001 m\(^2\) \([20]\)), PV reference efficiency (0.15 at 298 K \([21]\)), PV thermal expansion coefficient of (0.004 K\(^{-1}\) \([21]\)) and reference temperature (298 K \([22]\)), respectively.

Hence, the PV efficiency is deduced from Eq. (2) as

\[
\eta_{PV} = \eta_{ref} \left[ 1 - \beta_{PV} \left( T_{PV} - T_r \right) \right]
\]

Finally, the efficiency of the hybrid PV-TE system is given as \([23]\)

\[
\eta_{PV-TE} = \frac{P_{PV} + P_{TE}}{CG\alpha_{PV}A_{PV}}
\]
3. Results and Discussions
The all-day simulation of a hybrid PV-TE system is implemented using the commercial ANSYS 2020 R1 software. A transient heat flux boundary condition, corresponding to Enugu, Nigeria weather conditions, is imposed on the PV top glass cover, while a temperature dependent heat transfer coefficient is placed on the TEG heat sink. The ambient temperature is specified as 298 K. Furthermore, the effects of convective and radiative heat losses on the PV glass surface are also considered. The effect of the aluminium alloy heat sink on the temperature distribution is considered for increasing concentration ratios within different time intervals. The numerical model implemented in this study is verified by comparing the results obtained with that of ref. [23]. Hence, the results obtained can be deemed accurate.

The results obtained from the 24 h simulation of the hybrid PV-TE system is shown in Fig. 2. The hourly average solar radiation variation for Enugu, Nigeria is portrayed in Fig. 2 (a). From the plot, it is observed that from 0-6 am, the solar radiation recorded is zero. This is due to the fact that the sun is unavailable during this time frame. However, beyond 7 am, a sharp increase in the solar radiation is observed up till about 10 am. Beyond this time, the variation of solar radiation rises and falls steadily, accruable to various weather conditions such as cloud cover. Finally, beyond 6 pm, the solar radiation approaches zero, due to the setting of the sun.

The time varying power output obtained from PV, TE and hybrid PV-TE systems are depicted in Figs. 2 (b)-(d), respectively. Firstly, it is noticed that the power output plots demonstrate a similar trend with the solar radiation plot as depicted in Fig. 2 (a). This makes sense, since the temperature on a surface increases with increasing solar radiation. Furthermore, the TE and PV power output are directly proportional to the hot junction temperature and PV cell temperature, respectively as demonstrated by Eqs. (1) and (2), respectively. This implies that increasing the solar radiation intensity increases the temperature, thereby, increasing the power output obtained from the TE, PV and PV-TE systems, respectively. This explains why the highest power output is obtained during times of maximum solar radiation. In addition, the effect of increasing the concentration ratio is also illustrated in the plots. It is seen that increasing the concentration ratio further increases the solar radiation, thus, increasing the power output. Furthermore, a close comparison of the plots reveal that the PV generates a relatively larger power output than the TEG as evident in Figs. 2 (b) and (c). This
is due to the different inherent material properties, mode of device operation and temperatures harvested by these devices as a result of their varying placement as portrayed in Fig. 1. Additionally, the power output harvested from the hybrid PV-TE system, as shown in Fig. 2 (d), is relatively higher than that of the stand-alone PV system as depicted in Fig. 2 (b). This is due to the additional power output obtained from the TEG.

(b)

(c)
Then, the time dependent variation of the PV efficiency is shown in Fig. 2 (e). From the plot, it is seen that from 0-6 am when solar radiation is unavailable, the cell efficiency is slightly above 15%. This is because the reference efficiency of the silicon-based cell is specified as 15% at a standard reference temperature of 298 K. Hence, notwithstanding the unavailability of solar radiation during this time frame, the cell efficiency still maintains a steady temperature dependent on the prevailing temperature of the ambient. However, the slight increase beyond 15% is because the PV efficiency is a multiple of other factors as demonstrated by Eq. (5). It is also observed that increasing solar radiation and concentration decreases the PV and PV-TE efficiency. This is due to the heating up of the PV cell by the infrared radiation from the sun which increases the PV cell temperature. Finally, a relative comparison between Figs. 2 (e) and (f) reveal that the efficiency of the hybrid PV-TE system is higher than that of the stand-alone PV system. This is evident in the less steepness of the transient curve of Fig. 2 (f) compared to Fig. 2 (e). This is accruable to the PV cooling effect provided by the TEG, thus, reducing the PV cell temperature and consequently enhancing the hybrid PV-TE system efficiency.
4. Conclusions and Recommendations
This study investigated the performance of a hybrid photovoltaic-thermoelectric (PV-TE) system operating under transient conditions in Enugu, Nigeria climate. The PV was directly attached to the hot junction of the thermoelectric generator (TEG). The effect of the aluminium alloy heat sink and convective and radiative heat losses on the PV glass and TEG were also considered in the study. The
fluctuating non-steady weather variation was also considered. A three-dimensional model was developed in ANSYS 2020 R1 software and was utilised in solving the heat and current density continuity equations. The TEG temperature dependent material properties were also considered. The influence of fluctuating transient heat flux on the performance of the stand-alone PV and hybrid PV-TE systems were comprehensively analysed. The results showed that incorporating a TEG in a PV system improved the power output and efficiency of the stand-alone PV. In fact, the TEG served as a heat sink by cooling the PV back plate, thus, reducing the overheating of the PV cell. The TEG further assisted the PV in the utilisation of the full broad solar spectrum by converting the wasted incident infrared radiation into electricity. Therefore, incorporating TEGs in PV systems would go a long way in improving the overall performance of PV systems, thus, increasing their competitive merit over fossil fuel sources.

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