Analysis of a Two-Stage Variable Leg Geometry Solar Thermoelectric generator

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Abstract

Varying thermoelectric leg geometry and utilizing multiple thermoelectric modules (cascading) can greatly affect the performance of solar thermoelectric generators (STEGs), which utilize concentrated solar radiation in generating electricity. Hence, this conference paper presents a three-dimensional analysis of a two-stage variable leg solar thermoelectric generator (STEG) using ANSYS 2020 R2 software. The first-stage STEG utilizes the conventional rectangular leg geometry while the second-stage STEG comprises of the X-leg variable geometry. The hybrid two-stage STEG is subjected to varying concentrated solar radiation, and the performance parameters of the first-stage STEG, second-stage STEG and two-stage STEG are evaluated simultaneously. Results indicate that under the same operating conditions, the second-stage STEG generates a higher temperature gradient, power output density and efficiency compared to the first-stage STEG. Results further reveal the inefficiency of the conventional rectangular leg in handling thermal energy in STEG systems. Finally, results indicate that the use of variable leg geometry in the second-stage STEG greatly improves the overall performance of the hybrid-two stage system. The results obtained in this paper could provide insightful information in the design of cascaded solar thermoelectric generators operating under varying solar radiation.

Keywords
Variable leg geometry, X-leg, Solar thermoelectric generator, Cascaded thermoelectric generators, Finite element method.

1. Introduction
Research into the potential of the solar thermoelectric generators (STEGs) as a viable and promising renewable energy alternative for harnessing solar energy has gained significant attention in recent times (Sundarraj et al., 2014). This is because STEGs have several attractive features like being solid state devices & thus frictionless, noiseless, compact, and having little maintenance requirements. More so, they effectively convert thermal energy (solar irradiance or heat) into electricity through Seebeck effect (Zheng et al., 2014).

However, to improve their efficiencies, several studies have been conducted, one of which is on the effect of thermoelectric (TE) leg geometry. For instance, Al-Merbati et. al 2013 used finite element analysis (FEA) to study the effect of varying pin-leg geometry on the thermal stress, thermal efficiency and power output of a TEG and found that changing the pin geometry improves the efficiency of the device while reducing the maximum stress levels in the pin. Thus, they concluded that the efficiency and durability of TEGs can be increased using pin geometry. (Ali et al., 2015) carried out an exergy analysis on a TEG and studied the effect of bi-tapered pin geometry, defined by a dimensionless shaped parameter, on the first and second law efficiencies as well as the power output of the device. They discovered that the dimensionless shape parameter significantly affects the second-law efficiency but only slightly affects the first-law efficiency and that the power output increases with increasing and decreasing values of the shape parameter. Thermodynamic analysis of a TEG was also carried out by (Lamba et al., 2017) in which they investigated the effect of leg geometry configuration and Thompson effect on the power output and efficiency of the device. Their results showed a trapezoidal shaped TEG gives a 2.32% and 2.31% increase in energy and exergy efficiency, respectively, as compared to conventional TEG geometry (i.e. rectangular legs). More so, the power output was enhanced. Validation of these results has also been done by a comparison of simulation results with these and other previous studies in which (Yilbas et al., 2016) demonstrated a good agreement between their simulation results and results from previous studies. In their study, they simulated the effect of varying temperature at the cold-side of n-type and p-type pins on the efficiency and power output of a TEG with extended pin configuration. The simulation was done using the finite element numerical code ABAQUS. They reported that thermal stress developed in tapered pin configuration attains lower values than that of rectangular pin configuration.

(Kaushik et al., 2015) modeled an annular TEG (ATEG) considering Thompson, Peltier, Joule and Fourier heat conduction effects and did energy and exergy analysis on the model. Their analysis revealed that ATEG systems have lower energy/exergy efficiencies as well as power output than conventional TEGs. However, they went on to conclude that ATEG will be more viable in power generation from waste/exhaust heat and solar energy due to its annular shape and higher heat transfer area at its cold-side. This agreed with the recommendation of (Shen et al., 2015), especially for practical applications with round-shaped heat source/sink. (Erturun et al., 2014) did a comparative investigation on the thermomechanical and power generation performances of four (4) TEG geometries namely: rectangular, trapezoidal, cylindrical and octagonal geometries. Finite element analysis for two different temperature gradients was done using ANSYS. They reported significant differences in the temperature distributions, power outputs and conversion efficiencies of the models due to varying leg geometries thus demonstrating that varying TE leg geometry can improve the performance of TEGs. Furthermore, their results revealed that cylindrical geometries give less thermal stress while rectangular geometries give the highest. (Ibeagwu, 2019) performed a numerical modelling of the performance of five (5) leg geometries on COMSOL Multiphysics. The geometries had rectangular, trapezoidal, I, Y, and X cross-sectional areas. He also discovered that varying cross-sectional area significantly influences the performance of conventional rect-leg with X-leg being the most efficient and showing a 19.13% increase in power density of the rect-leg. In addition, the X-leg showed the least thermal stresses, while results for the Y and trapezoidal leg predicted possible structural failures before other models.

Despite the improvements resulting from modification of TEG geometries, further improvements in TEG performance can be achieved by using two or more stages of TEGs (Chen et al., 2005). (Asaadi et al., 2019) did a 3D simulation of a two-stage annular TEG and used it to investigate the thermodynamic and exergoeconomic performance of the device. Their results indicated that for a range of heat-source temperatures, the power output, energy and exergy efficiency of two-stage ATEG was higher than for single-stage. However, the single stage ATEG was seen to be more economical for all heat source temperature. They concluded that the optimal height ratio for a cascaded TEG to attain maximum thermodynamic and exergoeconomic efficiencies is directly influenced by the heat source temperature. (Manikandan et al., 2016) used exergy analysis to investigate the combined effects of Thomson, Pelletier, Joule and Fourier heat conduction on an exoreversible and irreversible two-stage TEG (TTEG). They demonstrated that there is an optimum number of thermocouples for the first and second stage of the TTEG. Multi-objective optimization of a two-stage TEG in series and parallel electrical configuration, to simultaneously optimize thermal efficiency, entropy generation, and power output of the device was done by (Arora et al., 2016). Optimal values for design variables including electrical current and number of TE elements was presented. (Xiao et al., 2012) presented 3D finite element models of two-stage and three-stage STEG and used them to examine the effect of input energy on STEG performance. They reported that the total conversion efficiency of the STEG cell increases gradually as number of stages increases. Also, for the three-stage model, they achieved a total conversion efficiency of 10.52%.

From the reviews done so far, it has been demonstrated that varying TE leg geometry and cascading TEGs, each resulted in an improvement in the performance of TEGs. However, the possibility of employing thermoelectric legs with variable leg geometries in cascaded TEG systems is yet to be investigated. This study is crucial because the use of variable leg TEGs will provide a significant improvement in the performance of cascaded systems. This paper seeks to investigate a cascaded TEG comprising of variable leg geometry thermoelements using ANSYS 2020 R2 software.

2. System Description

A pictorial representation of the two-stage variable leg solar thermoelectric generator (STEG) without the solar concentrator is shown in Figure 1. From the figure, it is seen that the two-stage thermoelectric generator (TEG) comprises of a first-stage TEG, made up of rectangular legs, and a second-stage TEG, comprising of variable legs

(X-legs). As shown in Figure 1a, the two-stage STEG comprises of ceramic plates, copper electrodes, solder paste and thermoelectric legs. The ceramic plate material is specified as alumina 96%, and is used to maintain temperature gradient across the thermoelectric module (TEM) while ensuring module mechanical integrity. The copper conductor pad material is specified as copper alloy, and is utilized in ensuring continuous current flow throughout the module. The solder paste material is specified as Sn-Pb (60-40%) alloy, and is used to join the thermoelements to the copper conductor pads. Bismuth telluride is used as the thermoelectric material due to its commercial availability and its optimum performance for the specified operating temperature range. The thermoelements comprise of two unlike metals, *p-type* and *n-type* bismuth telluride, connected electrically in series and thermally in parallel, which generate voltage in the presence of a temperature gradient across the top and bottom ceramic plates. This is made possible by the Seebeck effect. Finally, a solar selective absorber is placed at the top ceramic plate to facilitate absorption of incident solar radiation.

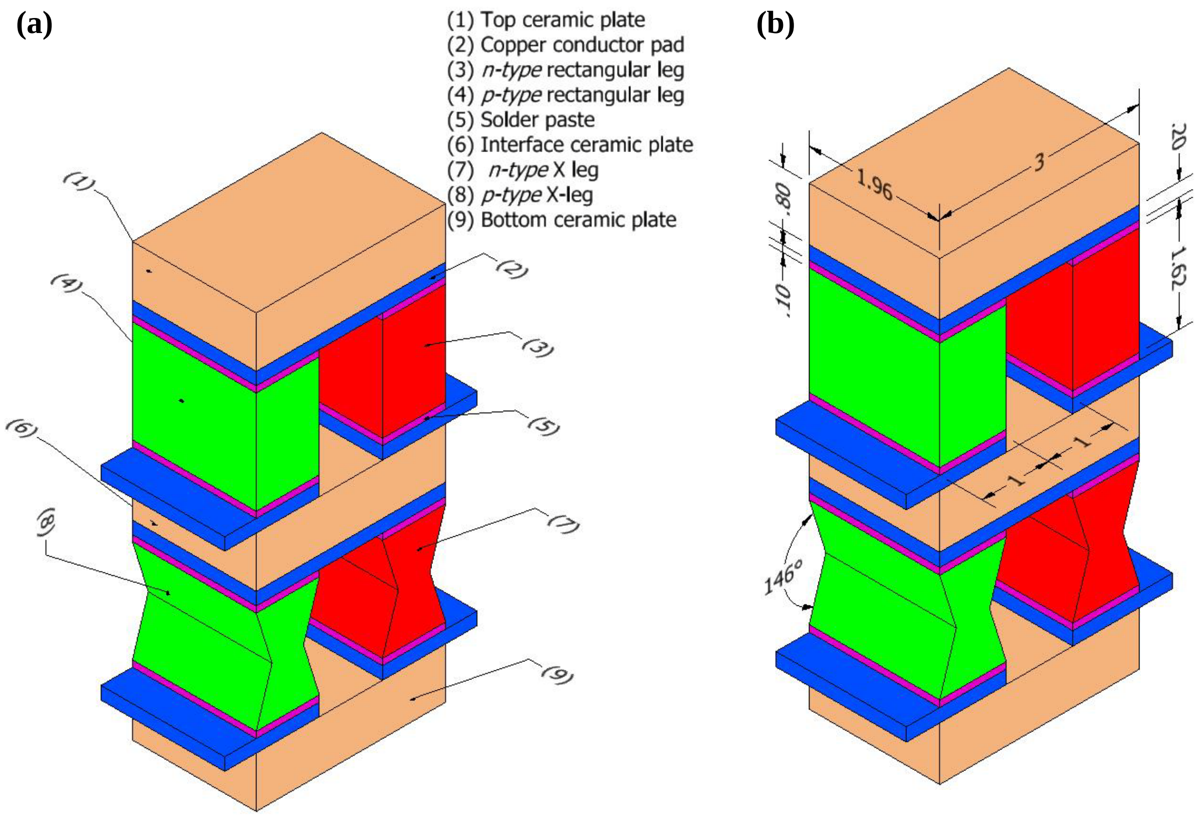

Figure 1: Two-stage variable leg STEG **(a)** Exploded view **(b)** Dimensioned diagram.

3. Numerical model

3.1 Thermoelectric generator

The coupled equations of thermoelectricity are expressed as (Maduabuchi and Mgbemene 2020; Maduabuchi et al. 2020)

$$\vec{\nabla}.\left(k\vec{\nabla}T\right)+J^2\rho-\tau\vec{J}\vec{\nabla}T=0 \quad (1)$$

$$\vec{\nabla}.\left(\xi\vec{\nabla}\frac{\partial\phi}{\partial t}\right)+\vec{\nabla}.\left(\frac{1}{\rho}\vec{\nabla}V\right)+\vec{\nabla}.\left(S\vec{\nabla}T\right)=0 \quad (2)$$

where S , ρ , k and τ are the temperature dependent Seebeck coefficient, electrical resistivity, thermal conductivity and Thomson coefficient, respectively. $\vec{J}$ is the current density vector. ξ and ϕ are the electric permittivity of the medium and scalar potential of the electric field, respectively.
The power output density generated by the ith stage thermoelectric generator is given as

$$P_{TE,i} = \frac{I_{TE,i}{}^2 R_L}{V_i} \tag{3}$$

where $I_{TE,i}$ is the current generated by the ith stage TEG, R_L is the external load resistance and V_i is the volume of the thermoelement in the ith stage TEG.
The efficiency of the ith stage TEG is expressed as

$$\eta_{TE,i} = \frac{P_{TE,i}}{Q_{in,i}} \tag{4}$$

3.2 Solar thermoelectric generator

The heat absorbed at the hot junction of the ith stage STEG is given as (Li et al., 2010)

$$Q_{in,i} = CGA_s \alpha_s \eta_{opt} \tag{5}$$

where C and η_{opt} are the concentration ratio and optical efficiency of the solar concentrator, respectively. G is the global incident solar radiation, A_s and α_s are the area and absorptivity of the solar selective absorber.
The efficiency of the ith STEG is given as (Xiao et al., 2012)

$$\eta_i = \eta_{TE,i} \alpha_s \eta_{opt} \tag{6}$$

4. Results and discussions

The results obtained from the analysis of the cascaded variable leg solar thermoelectric generator are presented in Figure 2. The figure shows the effect of concentration ratio on the STEG performance parameters such as temperature gradient, power output density and efficiency, respectively. It is clearly seen that the first-stage STEG, made up of conventional rectangular thermoelements, yielded the lowest performance parameters. It is further observed that despite the placement of the X-leg geometry TEG in the second-stage STEG, the temperature gradient obtained from the second-stage TEG was still greater than that of the first-stage STEG. This is due to the relatively lower thermal resistivity of the rectangular leg compared to the X-leg geometry. This demerit consequently led to a higher heat dissipation capacity in the rectangular leg, resulting in the harvesting of a relatively low temperature gradient and consequently, power output and efficiency. This basically implies that the rectangular leg geometry, placed in the first-stage STEG, is very inefficient in handling thermal energy, hence, the use of X-leg geometry STEGs is highly encouraged. It is further seen that the two-stage STEG generated the highest performance parameter values. This is due to the increase in system performance offered by the X-leg geometry. These results clearly demonstrate the merits of utilizing X-leg geometries in two-stage TEG systems.

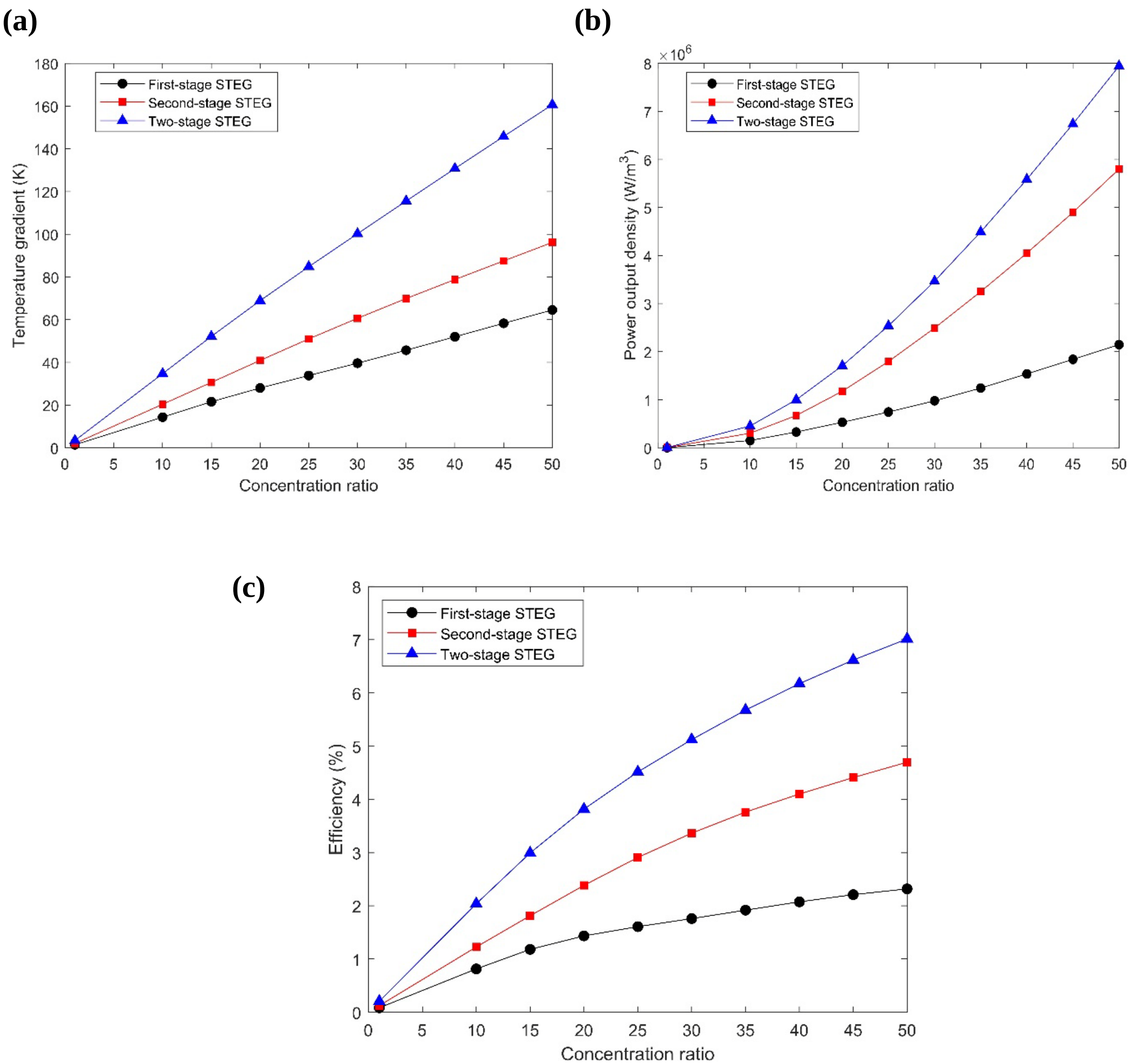

Figure 2: Effect of concentration ratio, **(a)** Temperature gradient, **(b)** Power output density and **(c)** Efficiency.

5. Conclusion

The three-dimensional modelling and subsequent performance evaluation of a two-stage variable leg solar thermoelectric generator was conducted in this study. ANSYS 2020 R2 software was used in solving the coupled thermoelectric field equations based on the finite element method. The effect of concentration ratio on performance parameters of the first-stage solar thermoelectric generator, using conventional rectangular geometry, and second-stage solar thermoelectric generator, using X-leg geometry was studied. Also, the performance evaluation of the hybrid two-stage solar thermoelectric generator was carried out. The following conclusions are drawn from this study:

- The X-leg geometry solar thermoelectric generator provided a higher temperature gradient compared to the conventional rectangular leg solar thermoelectric generator.
- The temperature gradient, power output density and efficiency generated by the X-leg solar thermoelectric generator was 67%, 82% and 75% higher than that of the conventional rectangular solar thermoelectric generator.

- Although the X-leg solar thermoelectric generator was placed below the conventional rectangular solar thermoelectric generator, it still offered a relatively higher performance compared to the conventional rectangular leg solar thermoelectric generator.
- The use of variable X-leg geometry in two-stage solar thermoelectric generators can ensure higher performance parameters under the same operating conditions.

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Biographies

Chika Maduabuchi is a researcher at the Department of Mechanical Engineering, University of Nigeria Nsukka. He obtained B.Eng. in Mechanical Engineering from the Department of Mechanical Engineering, University of Nigeria Nsukka. He has published journals and conference papers. His research interests include renewable energy, energy storage and computational analysis.

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