Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

A Review on Thermoelectric Generators: Structural Optimization and Economic Analysis

Raja Nur Atikah Raja Azam Shah[1], Farah Liana Mohd Redzuan[1,*], Sheikh Ahmad Zaki[1], Ahmad Faiz Mohammad[1], Fitri Yakub[1]

[1] Malaysia–Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 14 December 2022
Received in revised form 9 April 2023
Accepted 15 April 2023
Available online 2 May 2023

Keywords:
Waste heat recovery; thermoelectric generator; structural optimization; economic analysis

ABSTRACT

The interest in recovering waste heat has resurged in recent years due to growing concerns about the energy crisis and global warming. A thermoelectric generator (TEG) is regarded as an environmentally-friendly technology for capturing and recovering waste heat by directly converting heat to electrical energy via the Seebeck effect. The critical challenge in improving this technology is the low conversion efficiency of the TEG device, thus limiting its application to a niche area. The structural optimization of TEG has been the subject of extensive research over the past few years. Nonetheless, there is currently a lack of review studies focusing on TEG structural optimization, and to the best of our knowledge, only one review paper associated with this key area is available in the literature. This work presents an analysis of the ongoing research progress of TEG structural optimization with a focus on the thermoelectric leg length, leg cross-sectional area, angle of the legs, and leg shape. In addition, the economic analysis of the application of TEG in recovering waste heat is also presented to rationalize the economic feasibility of this technology compared to other existing technologies.

1. Introduction

The increasing trend of energy demand over the past decades is due to fast population growth and increasing living standards. With the rising concerns of the energy crisis and global warming, the engineering industries are obligated to reduce greenhouse gas emissions and optimize their sites' efficiency [1]. As such, the application of waste heat recovery systems in industrial processes is necessary as it will reduce fuel consumption, improve overall process efficiency, and lower the emissions of harmful substances into the atmosphere [1-3].

Industrial waste heat is the energy produced in industrial processes that are not being used and wasted, dumped, or lost into the environment [1]. Waste heat can be categorized into high, medium, and low-temperature grades. According to Jouhara *et al.,* [1] the strategy of how to recover the heat loss will differ based on the heat grade and the economics involved. High-temperature waste heat

---

[*] *Corresponding author*
E-mail address: farahliana@utm.my

https://doi.org/10.37934/arfmts.105.2.99114

recovery is recovering the waste heat with a temperature higher than 400°C and usually comes from a direct combustion process. The medium temperature grade is between 100 to 400°C and is generated from combustion units' exhaust. Meanwhile, the low-temperature waste heat has a temperature of less than 100°C, and this type of heat is generally produced from parts, products, and the equipment of process units [4]. As indicated by Men *et al.,* [5], medium- to high-temperature waste heat has high quality, and is thus easier to recover and utilize.

There are several waste heat recovery technologies commonly used nowadays which include regenerative and recuperative burners, economizers, waste heat boilers, air preheaters, plate heat exchangers, heat pipe systems, heat recovery steam generators, Organic Rankine Cycle, and others [1,2,6-8]. Most of these technologies use the energy in a similar way it is discharged, which is as thermal energy. Nevertheless, there are other options available to transform this energy into electrical power. These technologies include the utilization of thermoelectric, piezoelectric, thermo-photo- voltaic, and thermionic devices for electricity production [1,9-11]. Accordingly, this paper will discuss the thermoelectric generator (TEG) and the optimization of its structure.

TEG is built by connecting a large number of thermocouples, and each thermocouple is formed by p- and n-type semiconductor legs [12-15]. The p-type leg has a positive Seebeck coefficient and an excess of holes [16]. Meanwhile, the n-type leg has a negative Seebeck coefficient and an excess number of free electrons. TEG will convert thermal energy into electricity through the Seebeck effect when there is a temperature gradient between the thermocouples [17,18]. The temperature difference will lead to an electrical production when charge carriers, i.e., electrons or holes move from the hot side towards the cold side of a circuit [19].

Thermoelectric technology offers several advantages including zero-emission, high reliability, compact design, quiet, has no moving parts, prolong service life, etc. [20-22]. Despite these advantages, a big deterrent to its practical application is due to relatively low conversion efficiency. Consequently, this technology is only utilized in a niche area where its solid-state nature supersedes its poor efficiency [23]. On top of that, the cost of thermoelectric material is too high to rationalize its low conversion efficiency. Thus, the current direction of this technology is to increase its efficiency at a minimal cost [24].

There are two key approaches to improving the efficiency of TEG while keeping the thermoelectric material cost low; the approaches are material optimization and structural optimization [25]. Research on thermoelectric material aims to develop new materials which have a high figure of merit (ZT). On the other hand, the purpose of structural research is to enhance the structure and geometry of the thermoelectric generator to attain the highest conversion efficiency from this device [24]. Since there are abundant review papers that had discussed thermoelectric material, therefore this research paper will focus on the structural optimization of the thermoelectric generator in which the thermoelectric leg length, leg cross-sectional area, angle of the legs, and leg shape will be conferred. Although there is one existing literature that conferred on this research area, the lack of analysis from an economic perspective has led to the production of this review paper. Therefore, this work will also include the economic analysis of the application of TEG for recovering waste heat to justify the applicability of this technology as compared to other existing technologies.

2. Thermoelectric Structural Optimization

Thermoelectric materials optimization has become the conventional method for enhancing the efficiency of TEGs. Nonetheless, researchers can opt for another option which is optimizing the structure of this device. Accordingly, numerous researchers had proposed several ways of designing the modules where the focus is directed towards the overall leg length, the cross-sectional area of the legs, the angle of the thermoelectric leg, and the shape of the TEG legs. Consequently, this section presents the studies of the four geometries leg being researched up to this date.

2.1 Leg Length

The optimization of leg length was first proposed by Swanson *et al.,* [26] wherein the authors modified the length of segmented TEG legs to attain maximum efficiency of the modules. Following the fruitful outcome of this novel concept, numerous studies had been carried out by other researchers. Fan and Gao [3] investigated the effects of geometric dimensions on the thermoelectric and mechanical performance of annular thermoelectric generators (ATEGs). The numerical analysis indicates that when the length of the thermocouple legs increases, the thermoelectric performance of the device will reduce, yet it will enhance the mechanical reliability of the ATEG. As shown in Figure 1(a) and Figure 1(b), when the length (L) of the thermocouple legs fixed at 1 mm, the ATEG can produce a maximum output power density of 11.489 × 10^6 W/m^3, and its maximum conversion efficiency was 4.69%. Meanwhile, as seen in Figure 1(c), the value of von Mises stress is the lowest for any legs length when the angle ratio (θ) was 0.7. Nonetheless, the lowest von Mises stress can be attained by having a longer leg, i.e., L = 5 mm.

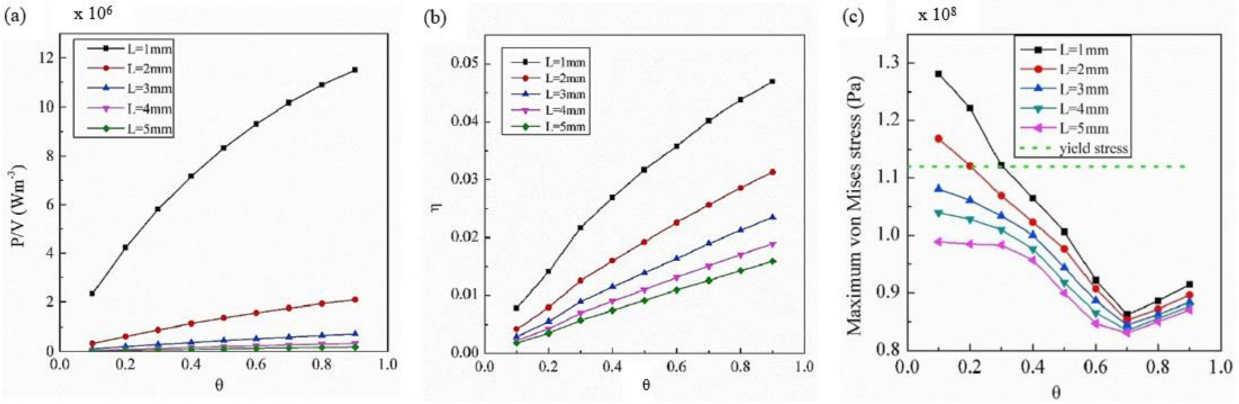

Fig. 1. The effect of L on the (a) output power density (b) conversion efficiency, and (c) maximum von Mises stress [3]

Likewise, Shittu *et al.,* [25] performed an analysis of the effect of leg length on the thermoelectric and mechanical performance of a segmented annular thermoelectric generator (SATEG). The result of the study demonstrated that the peak electrical performance i.e., conversion efficiency and output power of the device can be attained by having a shorter TE leg. When the length of the leg was 2 mm, the device's efficiency is 35.7% higher than when the length was 5 mm. Similarly, the device's output power when L = 2 mm is 73.1% higher than the output power when L = 5 mm. Nevertheless, the mechanical performance of the SATEG deteriorated when shorter legs were used wherein the highest von Mises stress was observed when L = 2 mm. This validates the result obtained from Fan and Gao [3], in which increases in the TEG leg length will improve its mechanical reliability, yet it will reduce the device's electrical performance.

On the other hand, Pandel *et al.,* [27] reported a contrary result from the preceding works mentioned above. A TEG system built with Mg_2(Si-Sn) was analyzed via a numerical model to investigate the output power and efficiency of the module. By keeping the leg cross-section area constant at 2.5 × 2.5 mm^2, the thermoelectric leg length was varied from 0.5 mm to 4 mm. The result of the analysis shows that under the temperature difference of 400 K, the output power will decrease alongside the increment of thermoelectric leg length. Nevertheless, the conversion efficiency of the module increases as the leg length increases (see Figure 2(a)). With a leg length of 0.5 mm, the output power and conversion efficiency were 61.04 W and 7.22%, respectively. Meanwhile, when the leg length was 4 mm, the output power and conversion efficiency were 9.04 W and 9.32%, respectively. As stated by Pandel *et al.,* [27], the output power decreases drastically due to the increases in electrical resistance when the leg length increases. On the other hand, the increase in thermoelectric leg length will increase the temperature gradient of the module, thereby resulting in a higher conversion efficiency value. From the graph in Figure 2(a), it is acknowledged that 1.4 mm can be taken as the optimized leg length [27].

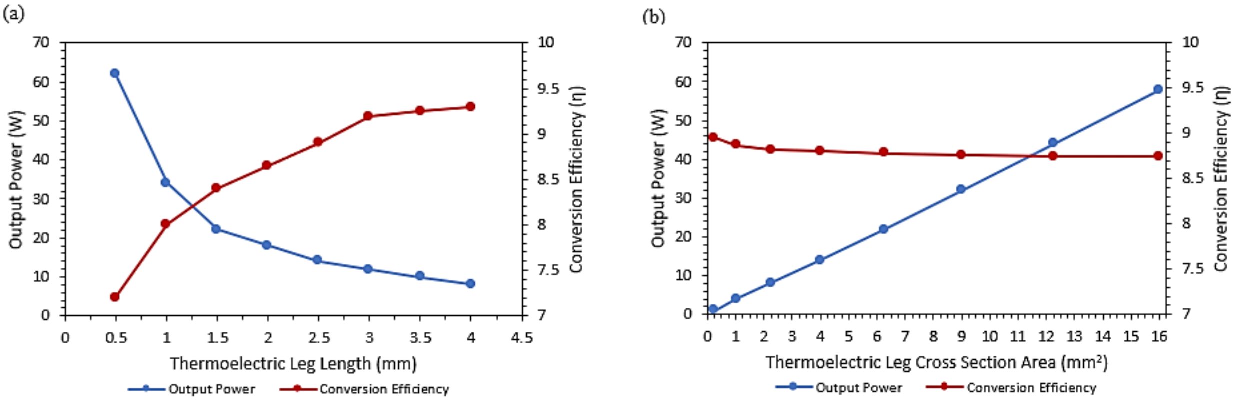

Fig. 2. The effect of (a) leg length, and (b) cross-section area on the output power and conversion efficiency of the Mg_2(Si-Sn) TEG module [27]

2.2 Leg Cross-sectional Area

It is worth noting that thermoelectric legs are commonly designed in cuboid shape with a constant cross-sectional area along the leg length [28]. Nevertheless, in 1928, Thacher suggested the idea of designing legs with variable cross-sections to improve the performance of TEG. Subsequently, this novel design received a huge deal of attention wherein numerous studies recognized that TEG modules with variable cross-section legs can achieve larger output power and conversion efficiencies as compared to the conventional legs [29,30]. Since n-type materials are generally weaker than p-type materials, hence the top performance of the devices can be achieved when the cross-sectional area of p-type legs (A_P) is greater than the n-type legs (A_N). Accordingly, Ouyang and Li [31] employed an asymmetrical geometry with $A_N < A_P$ in their study and identified that the TEG modules could attain higher efficiency and higher output power per unit area. This result validates that the implementation of uniform cross-sectional areas for both legs is not beneficial. While it is acknowledged that this design can enhance the module's performance, it also poses detrimental effects, for instance, increases in the cost of the modules and also developed significant stress on one end of the TEG modules [28].

Liu *et al.,* [28] conducted a theoretical analysis to investigate the performance of a TEG by randomly varying cross-sections of TEG legs via a one-dimensional energy equilibrium approach. The analysis was done under eight combinations of thermal boundary conditions. The simulated modules are shown in Figure 3 wherein one conventional TEG and two variable cross-section TEGs are chosen. Figure 3(a) depicts the TEG with a larger cross-sectional area on the hot end (referred to as Variable cross-section 1), while Figure 3(c) shows the TEG with a larger cross-sectional area on the cold end (Variable cross-section 2). On the other hand, Figure 3(b) is the conventional TEG design having a constant cross-sectional area. Based on the result of the analysis, is it known that the variable cross-section legs will enhance the maximum conversion efficiency of the TEG. Nonetheless, this geometry structure may increase or decrease the maximum output power, depending on the type of boundary conditions being introduced to the system. Besides, variable cross-section legs will affect the maximum working current of the TEG where it may remain unchanged or reduced.

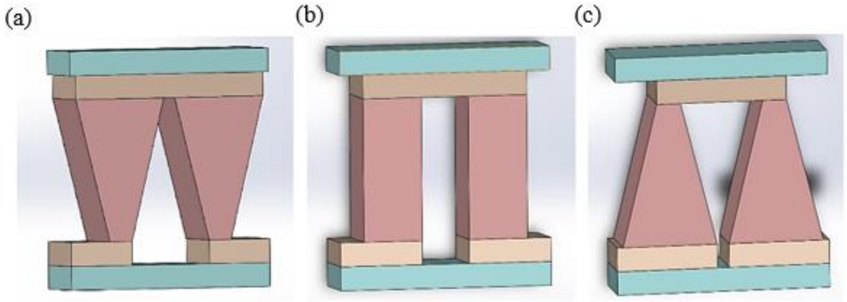

Fig. 3. Schematics of the simulated TE module. (a) Variable cross-section 1 (b) Conventional design (c) Variable cross-section 2 [28]

Additionally, according to Lavric [32], there exists an optimum leg length to maximize the power output per area, and this can be further maximized when the legs have a larger cross-sectional area. Nonetheless, cross-sections that are too large are undesirable as they may negatively affect the thermo-mechanical performance of the device. For that reason, Pandel *et al.,* [27] had run an analysis to find the optimum leg cross-section area value that can maximize the thermoelectric performance of the Mg_2(Si-Sn) module. Similar to the analysis result for the leg length presented in the preceding subsection, the output power and conversion efficiency follow an inverse trend, wherein the output power will increase while the efficiency decreases in respect to increasing in the thermoelectric leg cross-section area. The result can be referred from Figure 2(b). At leg cross-section area of 0.5 × 0.5 mm^2, the output power and efficiency were 0.96 W and 8.95%, respectively. Whereas, at leg cross-section area of 4 × 4 mm^2, the output power and efficiency were 57.32 W and 8.74%, respectively. The intersection between output power and conversion efficiency in Figure 2(b) is considered as optimum value. Consequently, the authors concluded that a TEG module having cross-section area of 2.75 × 2.75 mm^2 will generate the best value in terms of output power and efficiency.

2.3 Angle of Thermoelectric Legs

Aside from the investigation of the effect of leg length on the ATEG performance, Fan and Gao [3] also analyze the influence of leg angle on the electrical and mechanical performance of the power generation device. From the result of the study, it was identified that the output power density and conversion efficiency will increase when the total leg angle increases. In other words, the ATEG having a total leg angle (θ) equal to 6° will produce a greater power density and has better efficiency compared to ATEG having a total leg angle of 2°. On the other hand, the analysis of the device's mechanical performance shows that the maximum von Mises stress will decrease first but then increase with the increment of the leg angle ratio (Φ). Additionally, the analysis demonstrates that for legs with a total angle of 6°, the maximum von Mises stress in the thermoelectric legs will surpass the yielding stress when the angle ratio (Φ) is less than 0.2 or more than 0.7. This indicates that the ATEG is prone to damage when the angle ratio is too small or too large. Based on the result of the analysis, the authors conclude that the optimum geometry for mechanical performance enhancement was $\Phi = 0.7$, $\theta = 3°$, and L = 1 mm as the maximum von Mises stress achieves the minimum value when these structural parameters were incorporated into the ATEG design.

In a subsequent year, Shittu *et al.,* [25] examined the performance of SATEG by modifying the angle of the thermoelectric legs. It is worth mentioning that there are three variations of leg angle being focused on in this study which are θ_1, θ_2, θ_3, and θ which represent the angle of a single thermoelectric leg, half of the angle between two legs, the angle between the outer copper and the thermoelectric legs, and total leg angle, respectively (see Figure 4). The analysis of the device performance was done by modifying the θ_2 and its result can be seen in Figure 5. From both Figure 5(a) and Figure 5(b), it is known that the efficiency and output power of the SATEG decreases when θ_2 increases. This indicates that a small angle between the n- and p-type legs were desirable as it can enhance the thermoelectric performance of the device. Additionally, as discussed in section 2.1, shorter thermoelectric legs offer the best performance with regard to conversion efficiency and output power. At an optimal length of 2 mm, the efficiency and output power were improved by 17.8% and 55.5%, respectively just by reducing the θ_2 from 5° to 2°. On the contrary, the maximum von Mises stress decreases as the leg angle increases, and the highest von Mises stress is identified when $\theta_2 = 2°$. This demonstrates that the thermoelectric and mechanical performance of the device has an inverse relationship when the leg angle is altered. Based on the result of the analysis, the authors conclude that the optimum geometry for the maximum thermoelectric performance of the device was when $\theta_2 = 2°$, θ = 8°, and L = 2 mm.

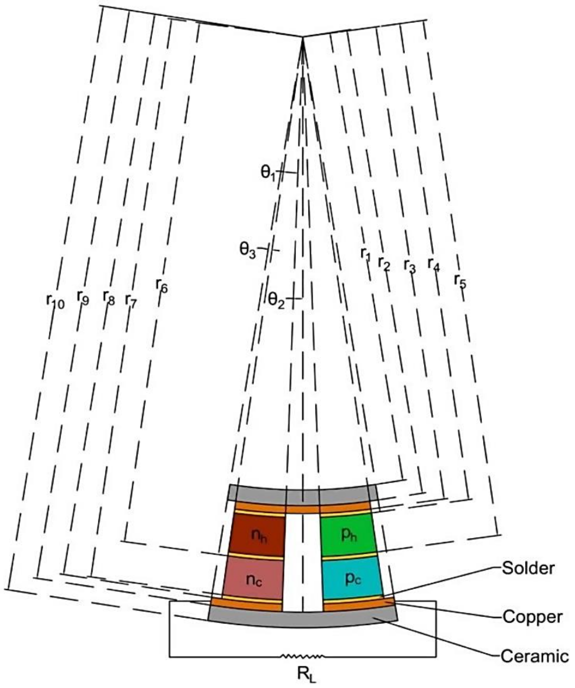

Fig. 4. Schematic diagram of SATEG geometry [25]

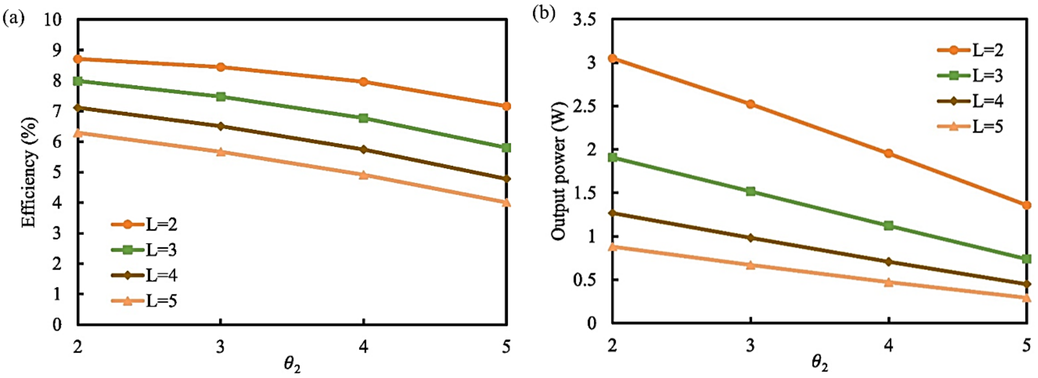

Fig. 5. The effect of leg angle towards SATEG performance (a) efficiency (b) output power when θ = 8° [25]

Additionally, Tian *et al.,* [33] investigated the thermal, exergetic, and economic analysis of the SATEG. By using the 3D numerical simulation method, the impacts of several main parameters, e.g., height ratio of segments, load ratio, and angle ratio of the legs on the performance of segmented and non-segmented annular TEG were analyzed. The result of the analysis can be referred from Figure 6. As seen in the figure, the angle ratio (ϕ_n/ϕ_p) was varied between 1 and 10 with various hot side temperatures. From Figure 6(a), it is known that the maximum output power is achieved when the $\phi_n/\phi_p = 1$. Then, the value begins to drop. Figure 6(b) and Figure 6(c) demonstrate that the conversion efficiency and exergy efficiency follow the trend of the output power wherein the value increases at first, and decreases when the angle ratio exceeds 1. On the contrary, the cost per unit output power decreases when the angle ratio increases from 0.1 to 1. However, the unit cost of output power will increase with the further increment of the angle ratio.

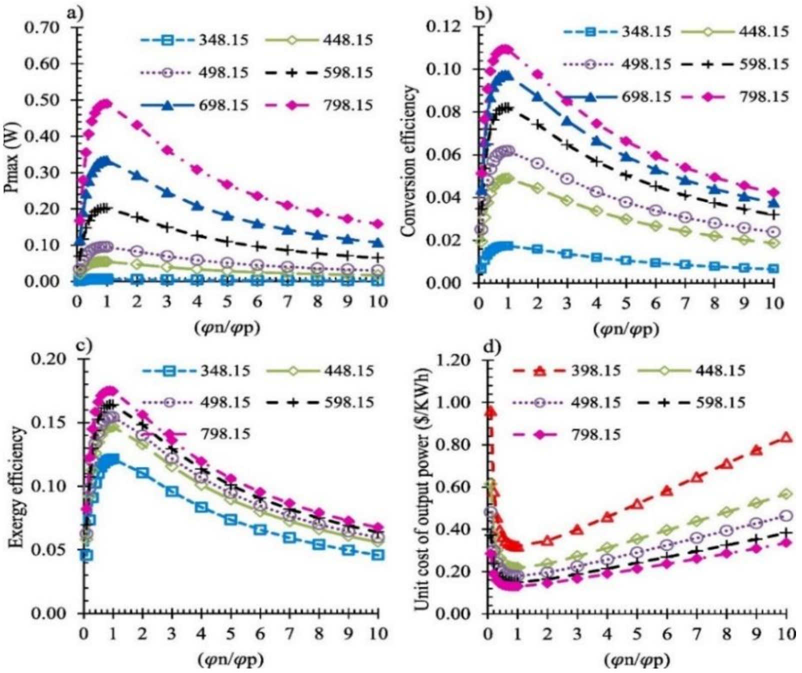

Fig. 6. The effect of angle ratio ϕ_n/ϕ_p, on the (a) maximum output power (b) conversion efficiency (c) exergy efficiency, and (d) cost per unit output power on the performance of SATEG [33]

2.4 Leg Shape

Generally, thermoelectric legs are designed to be in a rectangular and symmetrical shape. Nonetheless, the interest in asymmetrical thermoelectric legs has upsurged due to the need in enhancing the heat transfer in the legs and improving the module performance. Compared to the conventional thermoelectric legs, the asymmetrical legs provide a greater temperature gradient due to the reduction of the TEG overall thermal conductance [24,34].

Ibeagwu [35] performed a comprehensive analysis of the performance of thermoelectric generators by varying the cross-sectional area of the module's legs. Several leg geometries considered in his study are two existing leg geometry (i.e., trapezoidal and rectangular legs) and three newly proposed leg geometry (i.e., 2-truncated pyramids fitted together, 3-fitted rectangular prism, and a truncated pyramid fitted to a rectangular prism). For simplicity, the novel geometries are referred to as X-leg, I-leg, and Y-leg, respectively (see Figure 7). Results from the study showed that the leg geometries strongly influenced the performance of the power generation device wherein the

X-leg geometry produced the highest power density of 4.8975 × 10^5 W/m^3, which is approximately 19.13% higher than the rectangular leg. With a conversion efficiency of 4.989%, the X-leg proved to be the most efficient design compared to the other leg geometries in this study. Additionally, all novel geometries are shown to have lower von Mises stresses as compared to the trapezoidal and rectangular legs.

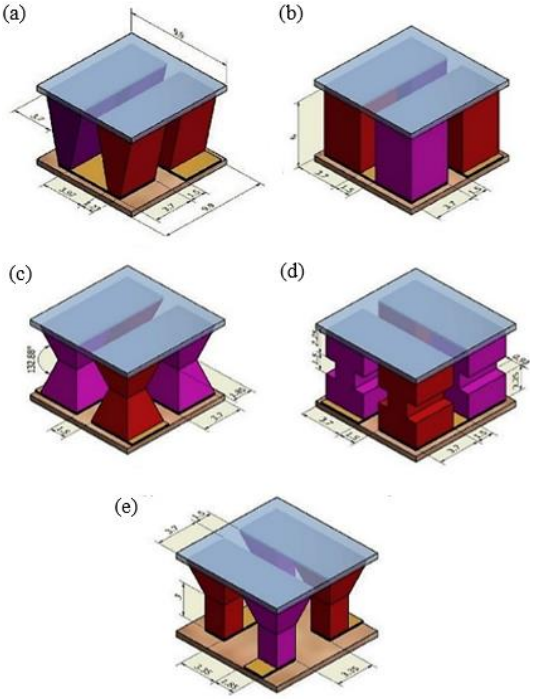

Fig. 7. Schematic diagram of the conceptual models (a) Trapezoidal leg (b) Rectangular leg (c) X-leg (d) I-leg (e) Y-leg [35]

In a study by Fabián-Mijangos *et al.,* [23], the authors fabricated a "proof-of-concept" TE module wherein they experimentally demonstrated the enhanced performance of thermoelectric modules having asymmetrical legs. The authors compared the performance of a module having truncated square pyramid legs with the conventional TE module having rectangular legs. Based on the result of the study, they identified that asymmetrical legs could help in harnessing the Thomson effect and lowering the overall thermal conductance of the device, which in turn will increase the temperature gradient in the legs. The asymmetrical TE module shows to have almost twofold the thermoelectric figure of merit as compared to its counterpart rectangular module. Moreover, thermal analysis unveils an upsurge in the temperature gradient and Seebeck voltage across the asymmetrical module, which validates that the thermoelectric enhancement is due to the harnessing of the Thompson effect. This study proves that the geometrical configuration of the TEG legs can improve the performance of the module.

Furthermore, Luo and Cheng [34] performed a three-dimensional finite element analysis to examine the influence of geometry on the thermoelectric and mechanical performance of the segmented asymmetric thermoelectric generator. Two TEGs structures, segmented pyramidal TEG (SPTEG) and segmented cone TEG (SCTEG) were analyzed in this study. Based on the result of the analysis, it is known that the thermoelectric performance of both structures was similar since they possess the same cross-sectional area and volume. Nonetheless, the thermal stress developed in SCTEG was distributed more dispersive, while thermal stress in SPTEG concentrates on the four corners. Consequently, the maximum von Mises stress in SCTEG was reduced by approximately 10%

compared to the von Mises stress in SPTEG. Furthermore, Sahin and Yilbas [36] conducted a theoretical analysis wherein the influence of leg geometry on the efficiency and power generation of the thermoelectric device was analyzed. Based on the result of the analysis, it is known that increasing or decreasing the shape parameter has a positive effect on the TEG efficiency. Nevertheless, the shape parameter has an unfavorable effect on the output power of the thermoelectric generator.

3. Economic Analysis

The research development on the application of thermoelectric technology to recover waste heat has shown significant progress throughout these years. Nevertheless, little attention has been paid to the economic analysis of the waste heat recovery system. As indicated by Araiz *et al.,* [37] the performance analysis of the TEG systems is considered partial when they did not include any economic analysis or when they disregard any alteration on the hot source. Albeit there is the existence of former studies which do include economic assessment in their work, most of them only analyze the cost by estimating the ratio of fuel-saving, or they only take into account the cost of the thermoelectric materials used in their works [38-40]. Hence, there is a need to execute a comprehensive economic assessment to reflect the economic feasibility of the TEG system as compared to other waste heat recovery technologies. To top that, the establishment of more inclusive economic studies associated with TEGs would enhance the employment of such a system in the industry [41].

3.1 Levelized Cost of Electricity

There are several approaches to performing the economic analysis of the TEG system and one of them is the Levelized Cost of Electricity (LCOE). This index, also known as the Levelized Cost of Energy, is extensively used in the energy field and allows the evaluation of diverse power generation technologies. Additionally, this parameter portrays the required price that the electricity gained from a power plant should have to attain a break-even point [37]. Besides, LCOE was also used to assess the performance and feasibility of the proposed renewable power plants in contrast to the existing fossil fuel plants [42]. As reported by Araiz *et al.,* [37] the LCOE can be estimated as follows:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t + D_t}{(1+k)^t}}{\sum_{t=1}^{n} \frac{E_{year\_t}}{(1+k)^t}} \tag{1}$$

where I_t represents the total installation cost, M_t is the cost associated with operation and maintenance, F_t is the price of fuel, D_t is the plant dismantling costs, and E_{year_t} denotes the electrical energy produced every t-period. On the other hand, k and n are the discount rate and the expected lifetime of the generators, respectively.

One of the preceding studies which had employed the LCOE was by Araiz *et al.,* [37]. The authors claimed that while LCOE was commonly used in other waste heat recovery technologies nonetheless, it was the first time it is used to economically analyze the application of TEGs to recover industrial waste heat. In their work, a computational study and optimized design of a thermoelectric generator were proposed for a waste heat recovery system in a real manufacturing plant in Navarre, Spain. The study has been carried out from two perspectives: the first one was to maximize the electrical power output, and the second one was to minimize the TEG installation cost. The result of the study depicts that the production of electrical energy was affected by the occupancy ratio (δ) wherein the net power output will increase as the occupancy ratio increases from δ = 0.08 to δ = 0.40. However, the power output will decline when δ > 0.40 (see Figure 8(a)). By referring to Figure 8(b), it is known that the minimum installation costs were attained when δ is between 0.24 to 0.40. With 10 mm fin spacing and δ = 0.40, a maximum net power output of 45,838 W was achieved, whereas the installation cost was minimized to 10.6 €/W when δ = 0.24. In both cases, the LCOE is predicted to be around 15 c€/kWh which is within the range of prices of other renewable energy sources such as concentrated solar power plants or offshore wind turbines. This result proves the feasibility of TEG as one of the waste heat recovery technologies.

Bellos and Tzivanidis [43] performed the energy and economic analysis of a solar-driven TEG where the system operates by absorbing incident solar irradiation and then converting it partially to electrical energy. The annual electrical energy generated was 5,415 kWh for a solar potential per area of 1,695 kWh/m^2. For a specific capital system cost of 1000 €/kW and a 2% discount factor, the LCOE was found to be around 0.0441 €/kWh and its payback period is about 4.5 years. As indicated by International Renewable Energy Agency [44], the concentrating solar power plants lead to an LCOE of 0.15 €/kWh, while the photovoltaic panels lead to an LCOE of 0.07 €/kWh. These results demonstrate that the proposed system by Bellos and Tzivanidis [43] presents lower LCOE, therefore it is a more feasible choice compared to other technologies mentioned above.

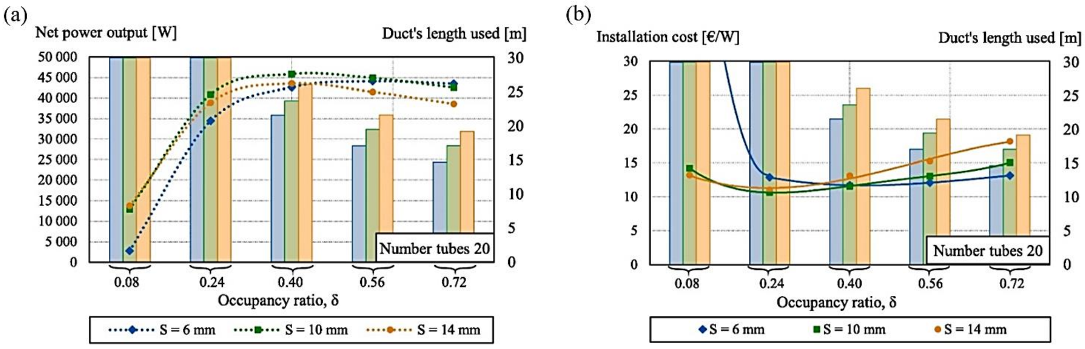

Fig. 8. (a) Net power output (b) Installation cost of the TEGs as a function of different occupancy ratios, δ and fin spacing, S [37]

In a former work by Farhangian Marandi *et al.,* [45], an economic assessment was done to analyze the economic feasibility of a novel solar PV-TEG hybrid module embedded in a cavity receiver. The performance of the hybrid cavity PV-TEG was compared with the conventional system, i.e., the flat plate PV-TEG system. In the study, the LCOE was assessed via Eq. (2) wherein the degradation rate (d) which was not considered by Araiz *et al.,* [37] was included in this study. Other parameters such as initial investment cost including construction (I_t), maintenance costs (M_t), operation costs (O_t), yearly energy output (S_t), and discount rate (r) were also included in the expression. It is important to note that the I_t is at the beginning of the first year, therefore it should not be discounted during the system's lifetime. Accordingly, the LCOE was estimated by utilizing the following formula [46,47]

$$LCOE = \frac{\sum_{t=0}^{T} \frac{I_t + O_t + M_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{S_t (1-d)^t}{(1+r)^t}} \qquad (2)$$

By assuming the discount rate as 8%, the degradation rate as 0.5%, and the expected lifetime (T) as 30 years, the sum of electrical energy generated over the lifetime and LCOE of the system were shown in Table 1. Even though cavity PV-TEG generated a larger amount of electrical energy compared to flat PV-TEG, nonetheless the system also possesses a higher LCOE which is 67% greater than the flat plate PV-TEG.

Table 1
Cost assessment of different PV systems [45]

System	Sum of electrical energy generated over the lifetime, kWh/lifetime	LCOE, $/kWh
Flat PV-TEG	6.74	5.65
Cavity PV-TEG	20.22	9.432

3.2 Cost-performance Ratio

Aside from LCOE, another method to assess the economic feasibility of the TEG is by measuring the cost-performance ratio (CPR) of the module. According to Ouyang and Li [48], the widespread implementation of such technology not only depends on its high performance but is also related to the cost performance of the system. The CPR of a TEG can be expressed as the fraction of the overnight capital cost (C_{total}) and the power generation capability (P) of the module [48]. The expression is shown in Eq. (3). The C_{total} is the summation of several costs in consideration which include the cost of thermoelectric materials ($C_{materials}$), manufacturing costs of the TEG module ($C_{manufacturing}$), and the cost of heat exchangers on both sides (C_{HE}). On the other hand, the P is the product of the TEG efficiency (η), the cross-sectional area of the TE module (A_{TE}), and the heat flux (q) absorbed at the hot segment. Accordingly, Eq. (3) can expand to Eq (4). In the case of unknown prices of thermoelectric materials, it is best to assume their prices by taking the most similar materials as a reference, which will still produce a fairly accurate result [48].

$$CPR = \frac{C_{total}}{P} \tag{3}$$

$$CPR = \frac{C_{materials} + C_{manufacturing} + C_{HE}}{\eta A_{TE} q} \tag{4}$$

In 2018, Ouyang and Li [48] built several STEG modules by combining different thermoelectric materials which were chosen based on their high performance. In this study, the researchers evaluated the cost-performance of the modules wherein they compared the economic feasibility of STEG having high-ZT TE materials with STEG having high-power factor TE materials. It is worth mentioning that for a segmented TEG, the price of each material is calculated first, then the summation presents the total material cost for the STEG. The results depict that the successful segmentation of high-ZT materials can offer a CPR of ~0.86 $/W, while the STEG with the segmentation of high-power factor TE materials can only offer a CPR of ~1.11 $/W. Since the commercially desired cost-effectiveness of TEG is 1.0 $/W, therefore it is highly suggested to choose the TE materials with a high figure of merit over their counterparts [48].

3.3 Payback Coefficient

In a study by Omer *et al.,* [49], an electric- and water-saving smart thermoelectric waste heat generator (STWHG) which was intended to be installed in the industrial establishment was produced. The research was carried out by focusing on the design, simulation, and cost assessment. The economic feasibility of the module was evaluated by computing the payback coefficient (K). As reported by Omer *et al.,* [49], the Payback Coefficient can be defined as the ratio of power sales revenue produced throughout the warranty phase (G) to the total cost of the thermoelectric generator (M). To conclude that a thermoelectric waste heat power plant is profitable, a condition of $K = G/M > 1$ must be met. Based on the result of the study, the aforementioned condition was met thus the SWTHG was identified as a promising technology for recovering waste heat from the industrial establishment. At a temperature difference of 100 °C, the proposed system able to produce 150 W power and the payback period of the system was estimated to be 6 years. The payback time may further decrease up to 2 years when the temperature differences of the system was increased to 200 °C.

4. Recommendation for Future Works

The enhancement of TEG performance by altering its geometry and structure has garnered a lot of attention recently. Regarding the thermoelectric leg length, it has been reported that the thermoelectric and mechanical performance of the TEG has an inverse relationship wherein a shorter leg is desirable for higher conversion efficiency and output power, yet it has an adverse effect on the device's mechanical reliability. Nonetheless, other studies reported contrary results in which the conversion efficiency and output power have a linear and inverse relationship, respectively with the leg length. This suggests that the device's efficiency will increase while its output power will decrease when the length of the thermoelectric leg increases. Consequently, enhancing the leg length for linear improvement of both conversion efficiency and output power of the TEG is the key issue and ought to be dealt with seriously in the future. In addition, it was reported that the implementation of constant cross-sectional areas for both n- and p-type legs is not beneficial. This has to do with the fact that the n-type materials are commonly weaker in comparison with the p-type materials. Therefore, the peak performance of the TEG can be attained when the leg geometry with the cross-sectional area of $A_N < A_P$ was employed. Nevertheless, this geometry design might introduce other issues such as a higher module cost and significant stress induced on one end of the device. For that reason, a comprehensive analysis is required before adopting this design. Besides, attention should be paid to the thermal boundary conditions as it was reported that it can affect the maximum conversion efficiency, output power, and working current of the TEG device.

Likewise, the adjustment of the thermoelectric leg angle can have a significant effect on the TEG performance. It was reported that a wider total leg angle will result in higher conversion efficiency and output power density. Nonetheless, it will deteriorate the mechanical performance of the device. Therefore, a thorough analysis should be done by researchers who opt for this design to find the optimum geometry that can enhance both the electrical and mechanical performance of the TEG. Additionally, it was reported that if both n- and p-type legs have a similar angle (angle ratio = 1), hence the device could attain the maximum conversion efficiency while keeping the module cost low. Although several studies were performed to analyze the effect of leg angle on the performance of TEG, there is still a lack of studies conducted to validate the outcome of the existing studies. Thus, more experimental research should be performed to increase the opportunities for the commercialization of TEG with diverse leg angles. Furthermore, the interest in asymmetrical legs has increased due to better heat transfer in this type of leg compared to conventional rectangular legs. Accordingly, numerous leg shapes had been proposed and the performance of this novel design proved to be more efficient and has better mechanical reliability. This is owing to the fact that asymmetrical legs could facilitate harnessing the Thomson effect and decreasing the overall thermal conductance of the TEG. Though varying the leg shape able to enhance the efficiency of the TEG, nonetheless it was reported that the shape parameter has an adverse effect on the device output power.

The economic assessment of the thermoelectric device is very vital to evaluate the viability of the technology in recovering waste heat. LCOE, CPR, and Payback Coefficient are some of the methods that have been done by researchers to analyze the economic feasibility of current waste heat recovery technologies. The LCOE has been used extensively in various power generation technologies. Though there is a formula to compute the LCOE, nonetheless it is not consistent wherein each researcher might include some parameters but disregard other parameters. As reported in preceding studies, LCOE computation intends to compare the feasibility of current or novel power generation technologies as compared to fossil fuel plants. Hence, dissimilarity in calculation methods may make it difficult for researchers and industrial practitioners to make comparisons between these technologies. Consequently, a standardized formula of LCOE should be proposed and utilized from this time forth. Aside from that, other economic analysis methods such as CPR and Payback Coefficient should be further studied to justify their suitability in analyzing the viability of the relevant technologies.

5. Conclusions

The concerns about the energy crisis and the environmental issue have led to an increase in interest to recover waste heat. One of the technologies that can convert unusable waste heat to utilizable energy is the TEG. Though this technology offers numerous benefits for instance quiet, has no moving part, high reliability, environmentally friendly, etc., nonetheless, the relatively low conversion efficiency of this device had hindered its practical application in various areas. Hence, there are tremendous efforts from many parties to enhance the performance of a thermoelectric generator particularly by increasing its conversion efficiency and output power. This can be done either by optimizing the thermoelectric materials or the structure of the device. As the research area of material optimization has progressed significantly throughout these years, therefore this review paper had focused on structural optimization where up to this date, only one review paper relevant to this research area can be found in the literature.

Accordingly, this review paper presented the state-of-the-art TEG structural optimization wherein the modification of thermoelectric legs i.e., length, cross-sectional area, angle, and shape were validated as the parameters that can significantly influence the performance of a thermoelectric generator. The results attained from these geometries were included and discussed. Besides, preceding works that studied on economic analysis of TEG in recovering waste heat were also presented in this review paper. Finally, recommendations for future works were included to offer guidance for other researchers to extend the studies, particularly on the structural enhancement of the thermoelectric generator as well as on the economic assessment of the device.

Acknowledgement

This research was not funded by any grant.

References

[1] Jouhara, Hussam, Navid Khordehgah, Sulaiman Almahmoud, Bertrand Delpech, Amisha Chauhan, and Savvas A. Tassou. "Waste heat recovery technologies and applications." *Thermal Science and Engineering Progress* 6 (2018): 268-289. https://doi.org/10.1016/j.tsep.2018.04.017

[2] Xu, Qi, Saffa Riffat, and Shihao Zhang. "Review of heat recovery technologies for building applications." *Energies* 12, no. 7 (2019): 1285. https://doi.org/10.3390/en12071285

[3] Fan, Shifa, and Yuanwen Gao. "Numerical simulation on thermoelectric and mechanical performance of annular thermoelectric generator." *Energy* 150 (2018): 38-48. https://doi.org/10.1016/j.energy.2018.02.124

[4] Brückner, Sarah, Selina Liu, Laia Miró, Michael Radspieler, Luisa F. Cabeza, and Eberhard Lävemann. "Industrial waste heat recovery technologies: An economic analysis of heat transformation technologies." *Applied Energy* 151 (2015): 157-167. https://doi.org/10.1016/j.apenergy.2015.01.147

[5] Men, Yiyu, Xiaohua Liu, and Tao Zhang. "A review of boiler waste heat recovery technologies in the medium-low temperature range." *Energy* 237 (2021): 121560. https://doi.org/10.1016/j.energy.2021.121560

[6] Cuce, Pinar Mert, and Saffa Riffat. "A comprehensive review of heat recovery systems for building applications." *Renewable and Sustainable Energy Reviews* 47 (2015): 665-682. https://doi.org/10.1016/j.rser.2015.03.087

[7] Mardiana-Idayu, Ahmad, and S. B. Riffat. "Review on heat recovery technologies for building applications." *Renewable and Sustainable Energy Reviews* 16, no. 2 (2012): 1241-1255. https://doi.org/10.1016/j.rser.2011.09.026

[8] Nawi, Zalina Mat, Siti Kartom Kamarudin, and Siti Rozaimah Sheikh Abdullah. "Improve Waste Heat Recovery and Performance of Organic Rankine Cycle Analysis for Exhaust Gas from A Marine Diesel Engine Using Biofuel from Algae." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 29, no. 3 (2023): 1-20. https://doi.org/10.37934/araset.29.3.120

[9] Roy, Rhitankar Saha, Lim Chong Lye, Lim Chin Guan, and Nor Mariah Adam. "ANSYS Simulation Study to Generate Pressure from Various Water-Wind Flow Conditions to Calculate Electricity Generated Using Piezoelectric Cells." *CFD Letters* 12, no. 9 (2020): 27-35. https://doi.org/10.37934/cfdl.12.9.2735

[10] Smoker, J., M. Nouh, O. Aldraihem, and A. Baz. "Energy harvesting from a standing wave thermoacoustic-piezoelectric resonator." *Journal of Applied Physics* 111, no. 10 (2012): 104901. https://doi.org/10.1063/1.4712630

[11] Ferrari, Claudio, and Francesco Melino. "Thermo-photo-voltaic generator development." *Energy Procedia* 45 (2014): 150-159. https://doi.org/10.1016/j.egypro.2014.01.017

[12] Markowski, Piotr M. "Multilayer thick-film thermoelectric microgenerator based on LTCC technology." *Microelectronics International* 33, no. 3 (2016): 155-161. https://doi.org/10.1108/MI-05-2016-0038

[13] Strasser, M., R. Aigner, C. Lauterbach, T. F. Sturm, M. Franosch, and G. Wachutka. "Micromachined CMOS thermoelectric generators as on-chip power supply." *Sensors and Actuators A: Physical* 114, no. 2-3 (2004): 362-370. https://doi.org/10.1016/j.sna.2003.11.039

[14] Jaziri, Nesrine, Ayda Boughamoura, Jens Müller, Brahim Mezghani, Fares Tounsi, and Mohammed Ismail. "A comprehensive review of Thermoelectric Generators: Technologies and common applications." *Energy Reports* 6 (2020): 264-287. https://doi.org/10.1016/j.egyr.2019.12.011

[15] LeBlanc, Saniya. "Thermoelectric generators: Linking material properties and systems engineering for waste heat recovery applications." *Sustainable Materials and Technologies* 1 (2014): 26-35. https://doi.org/10.1016/j.susmat.2014.11.002

[16] Von Lukowicz, Marian, Elisabeth Abbe, Tino Schmiel, and Martin Tajmar. "Thermoelectric generators on satellites-An approach for waste heat recovery in space." *Energies* 9, no. 7 (2016): 541. https://doi.org/10.3390/en9070541

[17] Rowe, D. M. "Thermoelectrics, an environmentally-friendly source of electrical power." *Renewable Energy* 16, no. 1-4 (1999): 1251-1256. https://doi.org/10.1016/S0960-1481(98)00512-6

[18] Mat Noh, Nor Amelia Shafikah, Baljit Singh Bhathal Singh, Muhammad Fairuz Remeli, and Amandeep Oberoi. "Experimental Study On Waste Heat Recovery from an Internal Combustion Engine Using Thermoelectric Generator." *Journal of Advanced Research in Applied Mechanics* 72, no. 1 (2020): 25-36. https://doi.org/10.37934/aram.72.1.2536

[19] Enescu, Diana. "Thermoelectric energy harvesting: basic principles and applications." *Green Energy Advances* 1 (2019). https://doi.org/10.5772/intechopen.83495

[20] Zhang, Guobin, Linhao Fan, Zhiqiang Niu, Kui Jiao, Hai Diao, Qing Du, and Gequn Shu. "A comprehensive design method for segmented thermoelectric generator." *Energy Conversion and Management* 106 (2015): 510-519. https://doi.org/10.1016/j.enconman.2015.09.068

[21] Liu, Changwei, Pingyun Chen, and Kewen Li. "A 500 W low-temperature thermoelectric generator: Design and experimental study." *International Journal of Hydrogen Energy* 39, no. 28 (2014): 15497-15505. https://doi.org/10.1016/j.ijhydene.2014.07.163

[22] Karana, Dhruv Raj, and Rashmi Rekha Sahoo. "Influence of geometric parameter on the performance of a new asymmetrical and segmented thermoelectric generator." *Energy* 179 (2019): 90-99. https://doi.org/10.1016/j.energy.2019.04.199

[23] Fabián-Mijangos, A., Gao Min, and J. Alvarez-Quintana. "Enhanced performance thermoelectric module having asymmetrical legs." *Energy Conversion and Management* 148 (2017): 1372-1381. https://doi.org/10.1016/j.enconman.2017.06.087

[24] Shittu, Samson, Guiqiang Li, Xudong Zhao, and Xiaoli Ma. "Review of thermoelectric geometry and structure optimization for performance enhancement." *Applied Energy* 268 (2020): 115075. https://doi.org/10.1016/j.apenergy.2020.115075

[25] Shittu, Samson, Guiqiang Li, Xudong Zhao, Xiaoli Ma, Yousef Golizadeh Akhlaghi, and Emmanuel Ayodele. "High performance and thermal stress analysis of a segmented annular thermoelectric generator." *Energy Conversion and Management* 184 (2019): 180-193. https://doi.org/10.1016/j.enconman.2019.01.064

[26] Swanson, B. W., E. V. Somers, and R. R. Heikes. "Optimization of a sandwiched thermoelectric device." *Journal of Heat Transfer* 83, no. 1 (1961). https://doi.org/10.1115/1.3680473

[27] Pandel, Divija, Amit Kumar Singh, Malay Kumar Banerjee, and Ritesh Gupta. "Optimization of Mg2 (Si-Sn) based thermoelectric generators using the Taguchi method." *Materials Today: Proceedings* 44 (2021): 4124-4130. https://doi.org/10.1016/j.matpr.2020.10.457

[28] Liu, Hai-Bo, Shuo-Lin Wang, Yan-Ru Yang, Wei-Hsin Chen, and Xiao-Dong Wang. "Theoretical analysis of performance of variable cross-section thermoelectric generators: Effects of shape factor and thermal boundary conditions." *Energy* 201 (2020): 117660. https://doi.org/10.1016/j.energy.2020.117660

[29] Ali, Haider, Ahmet Z. Sahin, and Bekir S. Yilbas. "Thermodynamic analysis of a thermoelectric power generator in relation to geometric configuration device pins." *Energy Conversion and Management* 78 (2014): 634-640. https://doi.org/10.1016/j.enconman.2013.11.029

[30] Yilbas, B. S., and H. Ali. "Thermoelectric generator performance analysis: Influence of pin tapering on the first and second law efficiencies." *Energy Conversion and Management* 100 (2015): 138-146. https://doi.org/10.1016/j.enconman.2015.05.005

[31] Ouyang, Zhongliang, and Dawen Li. "Modelling of segmented high-performance thermoelectric generators with effects of thermal radiation, electrical and thermal contact resistances." *Scientific Reports* 6, no. 1 (2016): 24123. https://doi.org/10.1038/srep24123

[32] Lavric, Elena Daniela. "Sensitivity analysis of thermoelectric module performance with respect to geometry." *Chemical Engineering Transactions* 21 (2010): 133-138.

[33] Tian, Man-Wen, Leonardus WW Mihardjo, Hazim Moria, Soheil Asaadi, Hamed Sadighi Dizaji, Shahram Khalilarya, and Phong Thanh Nguyen. "A comprehensive energy efficiency study of segmented annular thermoelectric generator; thermal, exergetic and economic analysis." *Applied Thermal Engineering* 181 (2020): 115996. https://doi.org/10.1016/j.applthermaleng.2020.115996

[34] Luo, H. C., and L. S. Cheng. "Numerical Study on Optimizing the Geometry of Segmented Asymmetrical Thermoelectric Generator." In *IOP Conference Series: Earth and Environmental Science*, vol. 701, no. 1, p. 012022. IOP Publishing, 2021. https://doi.org/10.1088/1755-1315/701/1/012022

[35] Ibeagwu, Onyebuchi Isreal. "Modelling and comprehensive analysis of TEGs with diverse variable leg geometry." *Energy* 180 (2019): 90-106. https://doi.org/10.1016/j.energy.2019.05.088

[36] Sahin, Ahmet Z., and Bekir S. Yilbas. "The thermoelement as thermoelectric power generator: Effect of leg geometry on the efficiency and power generation." *Energy Conversion and Management* 65 (2013): 26-32. https://doi.org/10.1016/j.enconman.2012.07.020

[37] Araiz, Miguel, Álvaro Casi, Leyre Catalán, Álvaro Martínez, and David Astrain. "Prospects of waste-heat recovery from a real industry using thermoelectric generators: Economic and power output analysis." *Energy Conversion and Management* 205 (2020): 112376. https://doi.org/10.1016/j.enconman.2019.112376

[38] Ebrahimi, Masood, and Ehsan Derakhshan. "Thermo-environ-economic evaluation of a trigeneration system based on thermoelectric generator, two-bed adsorption chiller, and polymer exchange membrane fuel cell." *Energy Conversion and Management* 180 (2019): 269-280. https://doi.org/10.1016/j.enconman.2018.10.093

[39] Anderson, Kris, and Nigel Brandon. "Techno-economic analysis of thermoelectrics for waste heat recovery." *Energy Sources, Part B: Economics, Planning, and Policy* 14, no. 4 (2019): 147-157. https://doi.org/10.1080/15567249.2019.1632976

[40] Khan, Mohd Quasim, S. Malarmannan, and G. Manikandaraja. "Power generation from waste heat of vehicle exhaust using thermo electric generator: A review." In *IOP Conference Series: Materials Science and Engineering*, vol. 402, no. 1, p. 012174. IOP Publishing, 2018. https://doi.org/10.1088/1757-899X/402/1/012174

[41] Junior, OH Ando, A. L. O. Maran, and N. C. Henao. "A review of the development and applications of thermoelectric microgenerators for energy harvesting." *Renewable and Sustainable Energy Reviews* 91 (2018): 376-393. https://doi.org/10.1016/j.rser.2018.03.052

[42] Abbasi, Hamid Reza, and Hossein Pourrahmani. "Multi-criteria optimization of a renewable hydrogen and freshwater production system using HDH desalination unit and thermoelectric generator." *Energy Conversion and Management* 214 (2020): 112903. https://doi.org/10.1016/j.enconman.2020.112903

[43] Bellos, Evangelos, and Christos Tzivanidis. "Energy and financial analysis of a solar driven thermoelectric generator." *Journal of Cleaner Production* 264 (2020): 121534. https://doi.org/10.1016/j.jclepro.2020.121534

[44] IRENA. "Renewable Power Generation Costs in 2017." *International Renewable Energy Agency*. Accessed April 7, 2020. https://www.irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017.

[45] Marandi, Omid Farhangian, Mohammad Ameri, and Behrouz Adelshahian. "The experimental investigation of a hybrid photovoltaic-thermoelectric power generator solar cavity-receiver." *Solar Energy* 161 (2018): 38-46. https://doi.org/10.1016/j.solener.2017.12.039

[46] Branker, Kadra, M. J. M. Pathak, and Joshua M. Pearce. "A review of solar photovoltaic levelized cost of electricity." *Renewable and Sustainable Energy Reviews* 15, no. 9 (2011): 4470-4482. https://doi.org/10.1016/j.rser.2011.07.104

[47] Hernández-Moro, J., and Jose Manuel Martinez-Duart. "Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution." *Renewable and Sustainable Energy Reviews* 20 (2013): 119-132. https://doi.org/10.1016/j.rser.2012.11.082

[48] Ouyang, Zhongliang, and Dawen Li. "Design of segmented high-performance thermoelectric generators with cost in consideration." *Applied Energy* 221 (2018): 112-121. https://doi.org/10.1016/j.apenergy.2018.03.106

[49] Omer, Gunay, Abdullah Hakan Yavuz, Rasit Ahiska, and Kagan Ekrem Calisal. "Smart thermoelectric waste heat generator: Design, simulation and cost analysis." *Sustainable Energy Technologies and Assessments* 37 (2020): 100623. https://doi.org/10.1016/j.seta.2019.100623