



**HAL**  
open science

## Boosting diesel generators power with thermoelectric generators and integrated oil tank – Thermal modeling and parametric study

Jalal Faraj, Wassim Salameh, Ahmad Al Takash, Hicham El Hage, Cathy Castelain, Mehdi Mortazavi, Rani Taher, Mahmoud Khaled

### ► To cite this version:

Jalal Faraj, Wassim Salameh, Ahmad Al Takash, Hicham El Hage, Cathy Castelain, et al.. Boosting diesel generators power with thermoelectric generators and integrated oil tank – Thermal modeling and parametric study. *International Journal of Thermofluids*, 2024, 22, pp.100632. 10.1016/j.ijft.2024.100632 . hal-04529526

**HAL Id: hal-04529526**

**<https://hal.science/hal-04529526>**

Submitted on 2 Apr 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Boosting Diesel Generators Power with Thermoelectric Generators and Integrated Oil Tank – Thermal Modeling and Parametric Study

Jalal Faraj<sup>1,2</sup>, Wassim Salameh<sup>1,2</sup>, Ahmad Al Takash<sup>1,2</sup>, Hicham El Hajj<sup>1</sup>, Cathy Castelain<sup>3</sup>, Mehdi Mortazavi<sup>4</sup>, Rani Taher<sup>5</sup>, and Mahmoud Khaled<sup>1,6,\*</sup>

<sup>1</sup>Energy and Thermo-Fluid Group, Lebanese International University LIU, Bekaa, Lebanon.

<sup>2</sup>Energy and Thermo-Fluid Group, The International University of Beirut BIU, Beirut, Lebanon.

<sup>3</sup>Nantes Université, CNRS, Laboratoire de thermique et energie de Nantes, LTeN, UMR6607, 44000 Nantes, France.

<sup>4</sup>Department of Mechanical and Materials Engineering, Worcester Polytechnic Institute, Worcester, MA 01609, USA.

<sup>5</sup>College of Engineering and Technology, American University of the Middle East, Kuwait.

<sup>6</sup>University Paris Diderot, Sorbonne Paris Cite, Interdisciplinary Energy Research Institute (PIERI), Paris, France.

\*Correspondence: [mahmoud.khaled@liu.edu.lb](mailto:mahmoud.khaled@liu.edu.lb)

## Abstract

In this paper, a unique method for using thermoelectric generators (TEGs) to generate electricity is introduced, a technique that makes use of a cold oil tank and hot exhaust gases from generators. A set of TEGs and an integrated cold oil tank are connected to the diesel generator as part of the suggested design. A pertinent thermal modeling was designed and a thorough parametric study was carried out to show the validity of this innovative concept. The parametric study has demonstrated that when the generator power and the thickness to thermal conductivity ratio of each TEG in the system are increased, the temperature differential in each TEG module and the power produced by the assembly of TEGs both exhibit linear increases. The length of the TEG plate and the height of the exhaust gas duct cause an exponential increase in the temperature differential across each TEG module. The TEG assembly's power output increases linearly with TEG surface length and decreases exponentially with exhaust gas duct height. Using an exhaust gas duct height of 0.05 m, and a TEGs plate length of 1 m, the parametric study showed that power generation of up to 2778 W is feasible under the predetermined circumstances of a diesel generator with an output of 125 kW. When compared to a conventional setup, the new hybrid generator in this scenario may be able to increase power generation by up to 2.22%.

**Keywords:** Diesel Generators; Thermoelectric Generators; Power; Oil tank; Thermal Modeling; Parametric Analysis.

---

## Nomenclature

$A$	Area of the gas duct
$A_{af}$	Air to fuel ratio
$C_{p,g}$	Specific heat of gas
$D_h$	Hydraulic diameter
$F_{ex}$	Fraction of exhaust gas energy from total energy
$H$	Duct height
$h_c$	Convective heat transfer coefficient of the cold oil
$h_h$	Convective heat transfer coefficient of the exhaust gas
$k$	Thermal Conductivity of each TEG module
$L$	TEG Plate length
$\dot{m}_f$	Fuel mass flow rate
$\dot{m}_g$	Gas mass flow rate
$Nu$	Nusselt number
$P$	Duct perimeter
$P_{generator}$	Power generated by the generator
$Pr$	Prandtl number
$q_c$	Fuel heat of combustion
$\dot{Q}_{combustion}$	Heat rate of combustion
$\dot{Q}_{ex}$	Power lost in the exhaust gases
$Re$	Reynolds number
$S$	TEG surface area
$t$	Thickness of each TEG module
$T_{amb}$	Ambient temperature
TEG	Thermoelectric Generator
$T_{\infty c}$	Cold oil tank temperature
$T_{\infty h}$	Temperature of the exhaust gas exiting the generator
$u_{\infty}$	Hot gas velocity
$\dot{V}_g$	Gas volumetric flow rate

## Symbols

$\eta_g$	Efficiency of generator
$\rho_g$	Exhaust gas density
$\mu_g$	Gas dynamic viscosity

## 1- Introduction

Numerous researchers have focused on enhancing the utilization of renewable energy sources and managing energy due to the necessity of energy for daily activities such as powering

computers, transportation, communications, cutting-edge medical equipment, and much more [1-8]. However, the energy research community has been encouraged by governments in industrialized nations to give priority to scientific solutions targeted at lowering energy use and reducing carbon dioxide emissions [9-11]. Extensive study in the areas of renewable energy and energy management is required to accomplish this goal [12-13]. Indeed, meeting the global desire to conserve energy and cut operating costs requires careful attention to energy management. It entails the methodical preparation of energy-saving strategies, ongoing monitoring of energy consumption, efficient management methods, and conservation initiatives. The recovery of waste heat has also become a crucial element in the field of energy management, driven by the limitations set by the second law of thermodynamics. This procedure makes it easier to produce new energy sources, which raises the overall effectiveness of energy systems [14-17]. The use of thermoelectric generators is one of the techniques for heat recovery, and as a result, thermoelectric technology has become widely used in heat recovery applications. A variety of heat sources, including internal combustion engines [18-21], stoves [22-24], cars [25-28], biomass gasifiers [29], chimneys [30], diesel engines [31-34], and fuel cells [35], have effectively adopted it. Thermoelectric generators are simple and quick ways to generate electricity and recover heat everywhere there is or can be a temperature gradient, despite their relatively low conversion efficiency [36-37]. Thermoelectric generators also represent a crucial component for integration into hybrid heat recovery systems since they can be rapidly connected with various heat recovery heat exchangers wherever a temperature gradient can be created [38-41].

Models of two-stage serial and parallel thermoelectric generators were constructed in 2014 by Sun et al. [42]. The models use medium-temperature skutterudite and low-temperature bismuth telluride thermoelectric materials, while the exhaust gas from internal combustion engines serves as the heat source. It is discovered that the thermoelectric materials' characteristics rely on temperature. The heat transfer coefficient between the hot and cold sides, as well as the temperatures of the heat and cold sources, affect performance metrics such as output power, conversion efficiency, and exergy efficiency.

In 2015, Shixue et al. [43] presented an advanced mathematical model of a thermoelectric generator that includes the effect of the temperature gradient in the flow direction. Engine operating conditions might cause variations in the exhaust gas parameters. Therefore, the impact of these variations on the best thermoelectric performance—achieved with the help of Fortran—was taken into consideration in order to maximize the overall power output. It was discovered that the exhaust gas flow rate had a significant impact on the ideal module areas that corresponded to the maximum power output, but not the gas temperature. In the same year, In et al. [44] presented a study that provides useful information on optimization of the TEG system, including optimization of the system layout, and configuration of TEG. Furthermore, a theoretical analysis was used to forecast the heat transfer characteristics of thermoelectric modules, and these predictions were compared to experimentally determined heat transfer characteristics.

In 2017, Vale et al. [45] reported a parametric study and optimization approaches of a thermoelectric generator (TEG) for the recovery of energy from the exhaust gas in Diesel vehicles used in freight transport. A heavy-duty vehicle (40 tonnes) and a commercial vehicle (3.5 tonnes) have the TEG fitted in their tailpipes. The cooling water serves as the heat sink and the exhaust gas as the heat source. Plain fins and offset strip fins are the two heat exchanger layouts that are

taken into consideration. Plain fins, which produce a maximum electrical power of 188 W for the commercial vehicle and 886 W for the heavy-duty vehicle, are the best option based on the study's criteria. For the light-duty vehicle, the best recovery efficiency is roughly 2%, with an average thermoelectric material efficiency of about 4.4%.

In 2018, Mostafavi and Mahmoudi [46] presented a study that deals with the general modeling of a thermoelectric generator system, including the modeling of the cooling system for the cold side of thermoelectric generator, system of heat transfer from smokestack to the hot side of thermoelectric generator and also the modeling of the thermoelectric modules themselves. Next, an experimental prototype of this thermoelectric generator is built, and the theoretical and empirical results are compared for nominal voltage, current, and power of the manufactured system. This is done to validate the obtained equations. This contrast, particularly at low temperatures, demonstrates the viability of the modeling that is being provided and the strong agreement between the theoretical and real results. In the same year, Nour Eddine et al. [47] investigated using analytical and experimental methods how engine exhaust gas pulsations affect a thermoelectric generator's ability to recover wasted heat. The findings verify that engine exhaust gas composition and engine exhaust gas pulsation are the two primary engine exhaust gas features that influence TEG performance.

Massaguer et al. [48] proposed a novel method in 2020 for automotive thermoelectric generators to address the cold-start problem and lower NO<sub>x</sub>, HC, and CO emissions. The authors suggest using an exhaust gas heater in conjunction with a thermoelectric generator. The autonomous system's purpose is to convert waste heat into electric heat, which can swiftly boost the temperature of exhaust gases to the ideal level. According to the results, it is possible to boost the catalyst's efficiency by up to 94%. Furthermore, in a WLTC operating cycle with a threshold exhaust gas temperature of 350 °C, the system may reduce pollutant emissions of NO<sub>x</sub>, HC, and CO by up to 94%, 91%, and 97%, respectively.

In 2022, Gurbuz et al. [49] presented a series of tests that are performed on the exhaust waste heat recovery using a thermoelectric generator (TEG) in a propane-fueled spark-ignition (SI) engine. Two engine coolant exchangers (Ec\_hex) are positioned on both surfaces of the rectangle exhaust heat exchanger (Ex\_hex) to form a three-layer TEG. To let propane pass through the TEG, copper serpentine pipes are inserted into each Ec\_hex, creating a unique design. The paper's findings show that, in the engine's 1500–5000 rpm range, the DC electrical power of the TEG with propane is greater than that of the TEG without propane, with a difference of 11.5–12.1%.

In 2023, Lan et al. [50] suggested a system of recovery of waste heat from exhausted gas of a proton exchange membrane fuel cell (PEMFC) to produce hydrogen using thermoelectric generators. A water electrolysis cell, thermoelectric generator (TEG) modules, and a PEMFC are all part of the system. A sensitivity analysis has been used to examine the effects of the cooling technique, electrical array arrangement, and PEMFC outlet temperature on the system efficiency, output power, rate of hydrogen production, and payback period. In particular, the findings indicate that the water-cooling method produces hydrogen at a rate 31.4–44.8% higher than the air-cooling method.

To regard the fluctuations of exhaust heat in practical situations, Luo et al. [51] presented a study in 2024 that adopts a transient fluid-thermal-electric multiphysics model to investigate the dynamic performance of the thermoelectric generator. The findings indicate that variations in exhaust temperature have a more significant impact on the dynamic properties than variations in exhaust mass flow rate. A decrease in exhaust heat improves the thermoelectric generator's dynamic performance; an increase in exhaust heat has the opposite effect.

In conclusion, the difficulties encountered in practical applications of thermoelectric generators (TEGs) are mostly related to the capacity to generate significant temperature changes rather than finding hot and cold sources. Stated differently, the hurdles lie in optimizing temperature gradients among TEGs and subsequently in producing power through more suitable means of coupling the hot and cold sources in a matched arrangement. In particular, the following deficiencies are apparent even though exhaust gas and water are excellent hot and cold supplies in the literature:

1. Configurations that use TEGs as a wall to directly divide the hot flow from the cold flow are rare. When TEGs are used for direct separation, the temperature differentials between them will be greater than when they are adhered to the surface of the exhaust pipe;
2. The research that employ TEGs as a separator of plane walls are few. By using the TEGs as a plane wall separator, it will be possible to install more TEGs, decrease the additional pressure losses caused by pasting TEGs on surfaces, and allow the exhaust gas to travel farther, increasing the convective capacity between the hot exhaust gas and the hot surfaces of the TEGs;
3. The use of cold tanks as sources of cold fluid without the need for pumping power has not advanced. Studies that use oil as a cold source are also rare. In comparison to water, oil has two main advantages: it is lighter, especially in applications where weight is a critical consideration, like small portable Diesel generators; it can also heat up to higher temperatures than water, especially in confined geometry like those of Diesel generators (which increases the time of power generation).

In light of the above results of the literature review and to address the research gaps indicated, the current study proposes an innovative concept for power generation by using hot exhaust gas from generators in conjunction with a cold oil tank in order to increase the temperature differential while using thermoelectric generators (TEGs) as direct separation in a plane wall between the exhaust gas and oil. A diesel generator is connected to a number of TEGs and an integrated cold oil tank in the desired design. This configuration is distinguished by a flow of diesel generator's exhaust gas and cold oil in a tank, separated by a plate with several series-connected TEGs. As a result, the hot exhaust gas flow will heat the upper surface of each TEG module while the cold oil will cool the lower surface. This temperature difference will thus be created, permitting the production of electrical energy. A thermal model of the required design has been prepared to validate the aforementioned novel concept. This model predicts the performance of the power production based on a variety of parameters, including the power output of the diesel generator, the thickness and conductivity of each TEG module, the height of the exhaust gas duct, and the length of the TEGs plate.

The work's uniqueness lies not only in the benefits mentioned above but also in its ability to combine TEG power generation with diesel generator power, increasing the diesel generator's output and thereby lowering fuel usage. Additionally, the current work offers a streamlined

theoretical thermal technique that can be applied to comprehensive parametric studies for evaluating the viability of novel TEG power production systems and/or configurations for any fluids used as hot and cold sources.

The remaining parts of this document are organized as follows: The concept of the new system is introduced in Section 2, and the accompanying thermal modeling and calculations are thoroughly explained in Section 3. The observations, conclusions, and analysis of the findings are presented in Section 4. Finally, based on the findings, conclusions are offered in Section 5.

## 2- New Suggested Concept

Under varying heat flux, temperature, and convection boundary conditions, TEG to convection at the top and lower sides was determined to be one of the most effective layouts for thermoelectric generators [52–53]. As a result, in this arrangement, the bottom side is exposed to cold convection and the upper side to hot convection [52–53]. Thermoelectric generators that are intentionally exposed to convection on both sides are suggested as a unique method for producing electricity in this study (Fig. 1).

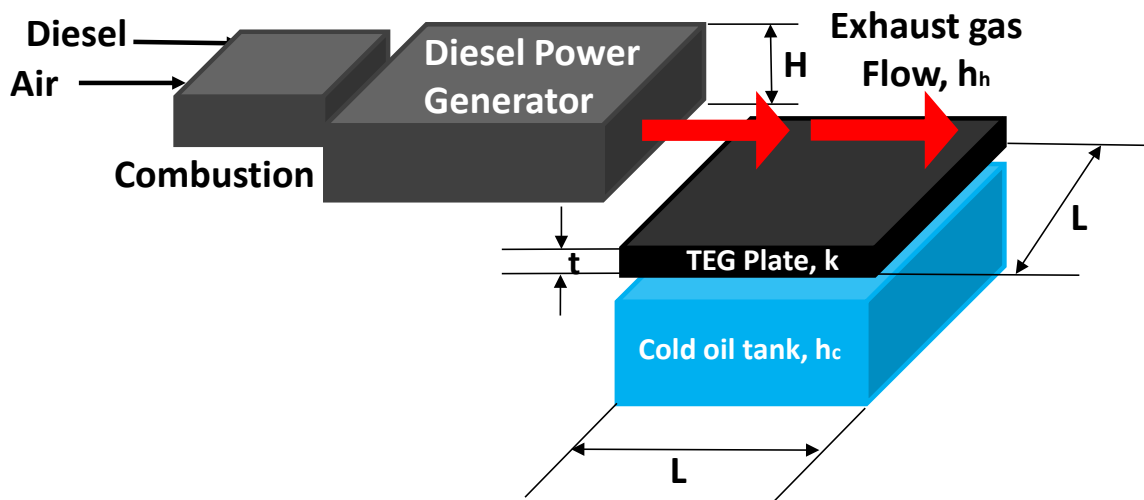


Figure 1. Schematic of the proposed system of power generation.

In the new design, the TEGs' put in series in the plane plate have their upper surfaces exposed to the hot exhaust gas from the generators, while their lower surfaces are in contact with relatively cold oil placed in a tank. According to this layout, the oil tank at the bottom of the TEG plate provides the cold convection condition, while the larger flow of hot exhaust gas provides the hot convection condition for the TEGs plate. As a result, a temperature differential may be produced across the thickness of each TEG in the plane plate placed between the hot exhaust gas and relatively cold oil and then used to produce power.

## 3- Thermal Modeling and Calculations

The thermal modeling is demonstrated in Figure 2, where the TEGs are shown as a planar wall with convection on both sides.

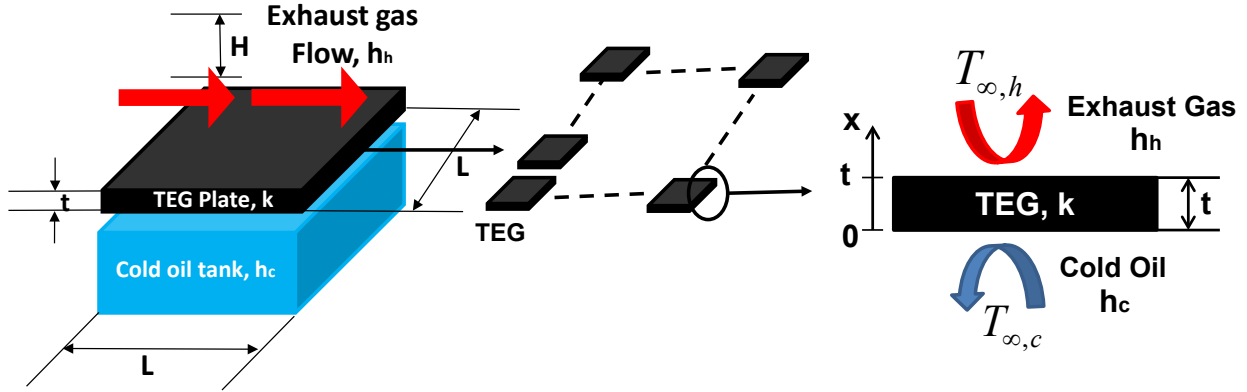


Figure 2. Thermal representation of the TEGs plate situation.

The top side is where hot convection occurs, and the bottom side is where cold convection takes place. As a result, from this point forward, the term "TEGs plate" will refer to the entire surface area of the TEGs because it is essential to keep in mind that the TEGs are positioned closely next to one another on the same plane.

The temperature distribution is initially estimated using the heat diffusion equation, and the temperature difference in the system is then determined. The heat diffusion equation can be simplified to the following form [54] by treating the TEGs plate as a planar wall and assuming a steady-state condition with no heat generation:

$$\frac{d^2T}{dx^2} = 0 \quad (1)$$

By applying the below boundary conditions at the upper and lower surfaces of the TEG [54]:

$$-k \left. \frac{dT}{dx} \right|_{x=0} = h_c (T_{\infty,c} - T(0)) \quad (2)$$

$$-k \left. \frac{dT}{dx} \right|_{x=t} = h_h (T(t) - T_{\infty,h}) \quad (3)$$

The temperature distribution and the temperature gradient within the TEGs can be calculated by integrating equation (1) and applying the boundary conditions stated in equations (2) and (3) as follows:

$$T(x) = \frac{h_c h_h (T_{\infty,h} - T_{\infty,c})}{k(h_c + h_h) + h_c h_h t} x + T_{\infty,c} + \frac{k h_h (T_{\infty,h} - T_{\infty,c})}{k(h_c + h_h) + h_c h_h t} \quad (4)$$

$$\Delta T = \frac{h_c h_h (T_{\infty,h} - T_{\infty,c})}{k(h_c + h_h) + h_c h_h t} t \quad (5)$$

Where  $T_{\infty,c}$  represents the cold oil temperature and  $T_{\infty,h}$  represents the generator exhaust gas temperature,  $h_c$  and  $h_h$  are the convective heat transfer coefficients of respectively the cold oil and the exhaust gas, and  $t$  and  $k$  are respectively the thickness and thermal conductivity of each TEG module.

The convective heat transfer coefficient of the cold oil ( $h_c$ ) may be found from the heat transfer



references used in natural convection for oil [54] while  $T_{\infty c}$ , will be assumed as the ambient temperature. Moreover, the intended parametric study will use the values of  $t$  and  $k$  as input parameters for the calculations. The operational parameters of the generator determine the values of  $T_{\infty, h}$  and  $h_h$ . Applying energy balances within the generator's operational mode is now required to determine the gas mass flow rate ( $\dot{m}_g$ ) and exhaust gas temperature ( $T_{\infty h}$ ). The ratio between the output and the input of the generator is defined as efficiency. The input power represents the heat rate due to the combustion of the fuel while the output power represents the electrical power generated. The efficiency may be defined as [55]:

$$\eta_g = \frac{P_{generator}}{\dot{Q}_{combustion}} \quad (6)$$

A fraction of the heat produced during combustion is lost in the form of power in the exhaust gases ( $\dot{Q}_{ex}$ ), normally this fraction ( $F_{ex}$ ) between 30% and 40% [55]. The power lost within the exhaust gases may be expressed as follows [55]:

$$\dot{Q}_{ex} = F_{ex} \dot{Q}_{combustion} \quad (7)$$

The result of combining equations (6) and (7) is:

$$\dot{Q}_{ex} = F_{ex} \frac{P_{generator}}{\eta_g} \quad (8)$$

Likewise, the rate of energy transferred by exhaust gases can be expressed as follows [54]:

$$\dot{Q}_{ex} = \dot{m}_g C_{p,g} (T_{\infty, h} - T_{amb}) \quad (9)$$

The rate of heat generated from the combustion of the fuel ( $\dot{Q}_{combustion}$ ) depends on the mass flow rate of the diesel ( $\dot{m}_f$ ) and the heat of combustion of the fuel ( $q_c$ ). The mass flow rate of the fuel (diesel) may be calculated as follows [55]:

$$\dot{m}_f = \frac{\dot{Q}_{combustion}}{q_c} = \frac{P_{generator}}{\eta_g q_c} \quad (10)$$

The mass flow rate of the gas may be calculated based on the air to fuel ratio ( $A_{af}$ ) of each fuel (diesel in this case). It can be expressed as follows [55]:

$$\dot{m}_g = (A_{af} + 1) \dot{m}_f = (A_{af} + 1) \frac{P_{generator}}{\eta_g q_c} \quad (11)$$

Based on the fraction of the heat lost within the exhaust gas, the energy within the fuel and the ambient temperature, the temperature of the exhaust gas may be evaluated. This hot temperature may be found by combining the equations (8), (9) and, (11):

$$T_{\infty, h} = T_{amb} + \frac{F_{ex} q_c}{(A_{af} + 1) C_{p,g}} \quad (12)$$

It is possible to calculate the hot convective heat transfer ( $h_h$ ) using established heat transfer correlations found in reference [54] once the mass flow rate of exhaust gas is known. The velocity of the hot gas is related to the gas mass flow rate as follows [54]:

$$u_\infty = \frac{\dot{V}_g}{A} = \frac{4\dot{m}_g}{\rho_g \pi D_h^2} \quad (13)$$

The hydraulic diameter of the duct ( $D_h$ ) may be calculated using the following relation [54]:

$$D_h = \frac{4S}{P} = \frac{2HL}{H+L} \quad (14)$$

As mentioned previously, the convective heat transfer ( $h_h$ ) at the upper surface of the TEG may be calculated using the suitable correlations based on the type of the flow. The type of the flow is determined by calculation the Reynolds number using the following relation [54]:

$$Re_L = \frac{\rho_g u_\infty L}{\mu_g} \quad (15)$$

The flow is assumed to be laminar for a Reynolds number less than  $5 \times 10^5$ . However, it is assumed to be mixed flow (laminar then turbulent) if the Reynolds number is above the critical value ( $5 \times 10^5$ ). The convection coefficient is calculated using the following correlation of the Nusselt number ( $Nu$ ) if the flow is considered laminar [54]:

$$Nu_h = \frac{h_h L}{k} = 0.664 Re_L^{0.5} Pr^{1/3} \quad (16)$$

If the flow is found to be mixed, the following correlation of the Nusselt number may be used to calculate the convection coefficient of the hot gas [54]:

$$Nu_h = \frac{h_h L}{k} = (0.037 Re_L^{4/5} - 871.32) Pr^{1/3} \quad (17)$$

As many thermal modeling reported in the literature [56-57], the thermal modeling used in this manuscript is a simplified thermal modeling that possesses the minimum components to perform a detailed parametric analysis that permits to come out with appropriate conclusions related to the feasibility of the suggested concept.

Beyond that, the effects of design parameters will be examined like generator power, each TEG's thickness to thermal conductivity ratio, exhaust gas duct height, and TEG plate length. Thus, using initial calculations with the height of exhaust gas duct ( $H$ ) of 0.05 m, the TEG plate dimensions (length and width) assumed to 0.4 m, the cold oil temperature maintained ( $T_{\infty,c}$ ) at 25°C, and the ambient temperature ( $T_{amb}$ ) held at 20°C, the influence of generator power and the ratio of thickness to thermal conductivity for each TEG was examined. The convective heat transfer coefficient of the cold oil was found at a value of  $200 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$  for the aforementioned parametric investigation [54]. A total of 25 computations were performed in all, with each calculation corresponding to a unique configuration determined by the generator's power and the ratio of TEG thickness to thermal conductivity. Five generator power values 25 kW, 50 kW, 75

kW, 100 kW, and 125 kW as well as five distinct ratio values 0.002, 0.004, 0.006, 0.008, and 0.01 were specifically evaluated. Previous researches have shown that the ratio ( $t/k$ ) normally ranges from 0.002 to 0.005 [58-59]. As part of the parametric testing procedure, larger ratios for this parameter have been selected with the intention of examining the potential for recommending new ratios to improve temperature gradients. If future production becomes feasible, such improvements might eventually result in higher power output. The relation between the power generated from the TEG and the difference of temperature presented in [58] will be considered. A second set of computations was performed with a constant generator power of 125 kW, the cold oil temperature at 25°C, and the ambient temperature at 20°C in order to examine the effects of exhaust gas height and the length of the TEG plate. The higher ratio ( $t/k$ ) is used. Similar to this, a series of 25 calculations were performed, each one corresponding to a unique configuration determined by the height of the exhaust gas and the length of the TEG plate. The TEG plate's width and length were assumed to be equivalent in these computations. In particular, five distinct TEG plate lengths 0.2 m, 0.4 m, 0.6 m, 0.8 m, and 1 m as well as five different exhaust gas duct heights 0.05 m, 0.1 m, 0.15 m, 0.2 m, and 0.25 m were taken into consideration.

#### 4- Results and Analysis

Figure 3a shows the variation in temperature differential across each TEG module for different thickness to conductivity ratio. Figure 3b shows the total power attained by the suggested TEG generators based on the intended design, which is the sum of the power created by each TEG module for different thickness to conductivity ratio.

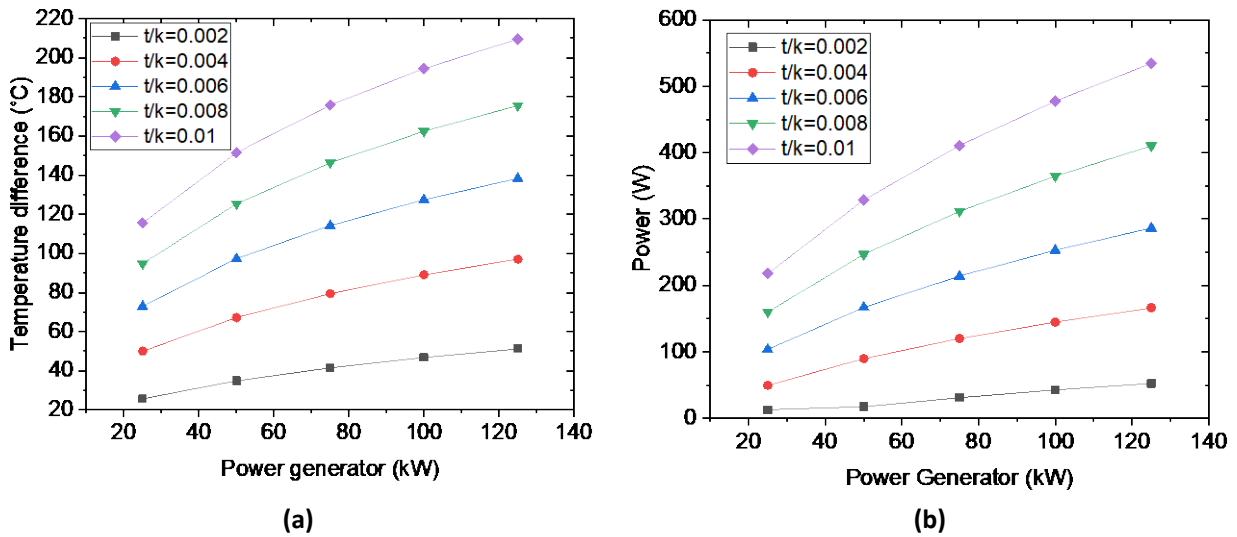


Figure 3. The variation of (a) temperature differential across each TEG module and (b) the power generated by the assembly of TEG modules as a function of the generator power for various ratios  $t/k$ .

As is obviously shown in Figure 3, when the space heating load and the ratio ( $t/k$ ) both rise at the same time, there is an almost linear increase in the temperature difference across each TEG module and the resulting power produced by the assembly of TEGs. As an example of a ratio ( $t/k$ ) of 0.002, when the generator's output is increased from 25 kW to 125 kW, the temperature differential across

each TEG module rises from 26°C to 51°C and the power generated by the assembly climbs from 13 W to 52 W. When the generator power is increased from 25 kW to 125 kW, the accompanying power provided by the assembly changes from 218 W to 534 W, and the temperature difference between each TEG component varies from 116°C to 210°C for a ratio of 0.01. In conclusion, it is clear that the increase in temperature difference and the resulting increase in power generation become more important as the thickness to thermal conductivity (ratio) ratio rises and as the generator power is raised. The temperature differential grows from 51°C to 210°C when the ratio is increased from 0.002 to 0.01, and the resulting power generation rises from 52 W to 534 W when the power output of the generator is fixed at 125 kW.

According to the length ( $L$ ) and duct height ( $H$ ), Figure 4 depicts the variations in the temperature difference across each TEG module as well as the overall power produced by the suggested TEG generators. These variations are plotted as functions of TEG plate length for various exhaust gas duct heights.

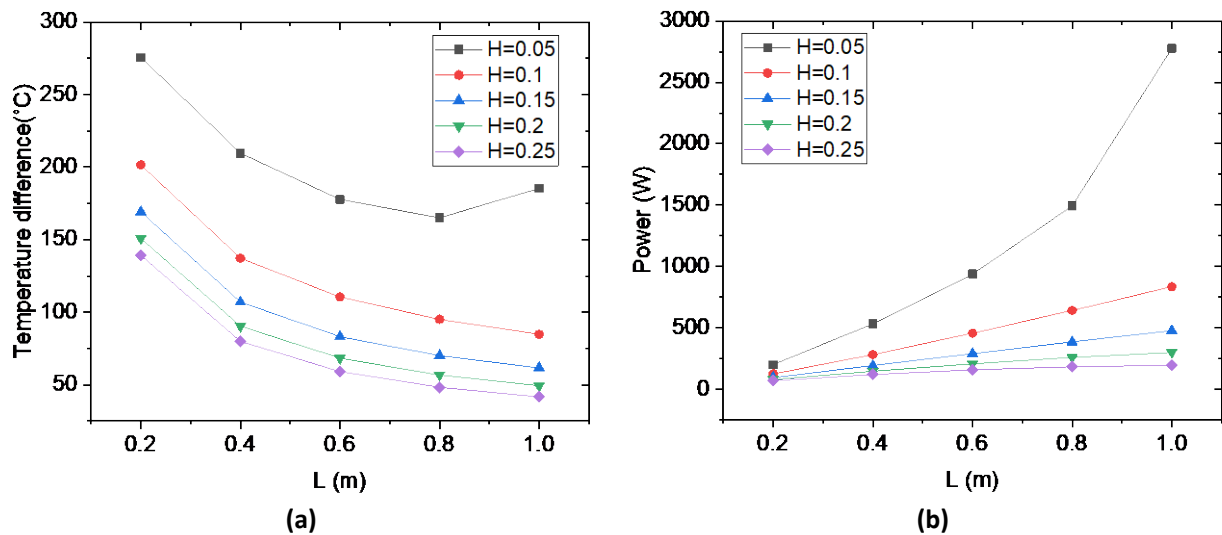


Figure 4: The fluctuation of (a) temperature differential within each TEG component and (b) power generated by the assembly of TEGs as a function of  $L$  for varied  $H$ .

Figure 4-a highlights how the temperature differential across each TEG module diminishes exponentially as the TEG surface length  $L$  rises. Similar to this, when  $H$  increases, the temperature disparity similarly decreases exponentially. As an example, at  $H$  of 0.05 m, the temperature differential across each TEG module falls from 276°C to 185°C as the TEG surface length increases from 0.2 m to 1.0 m. As the TEG plate length increases from 0.2 m to 1 m, the temperature differential across each TEG module decreases from 139°C to 42°C for an exhaust gas duct height of 0.25 m. It should be noted that the temperature difference grows as length  $L$  increases, which is an exception to the aforementioned tendencies for lengths of 0.8 and 1. These phenomena happens as a result of the TEG plate length exceeding 0.8 m, which causes the flow in some areas to become turbulent, creating a mixed boundary layer surrounding the TEG plate. Comparing the situation with full laminar flow, the convective coefficient is improved by this mixed boundary layer. As a result, the variation in temperature across each TEG module is observed to diminish as the plate length grows as a result of this turbulence and boundary layer

mixing.

Indeed, as shown by equations 16 and 17, once the length of the flow grows, the Reynolds number rises, which in turn causes the Nusselt number to rise. It is crucial to remember that although the Nusselt number could rise, the corresponding heat transfer might paradoxically fall. This may be caused by the intricate interaction of convective heat transfer components, including modifications to flow patterns and the formation of boundary layers as flow lengthens. Equations 14 and 15 show that as  $H$  grows, so does the hydraulic diameter. Consequently, the  $Re$  will fall for the same exhaust gas flow rate. The average convective heat transfer coefficient is decreased along with the Reynolds number. As a result, the temperature difference across each TEG module is reduced as a result of the decline in the convective heat transfer coefficient. These connections are crucial to comprehending how variations in geometrical parameters, such as the height of the exhaust gas duct, can affect convective heat transfer and temperature differences in the TEG system.

Figure 4-b illustrates how the power produced by the combined set of TEGs increases practically linearly as the length of the TEG plate increases while decreasing exponentially as the height of the exhaust gas duct rises. These findings demonstrate how these two parameters have a substantial impact on the TEG system's ability to generate power. As an illustration, the power grows from 202 W to 2778 W for  $H$  of 0.05 m as  $L$  increases from 0.2 m to 1.0 m. This demonstrates the important influence of TEG surface length on energy production. The power produced for  $L$  of 0.2 m declines exponentially from 202 W to 72 W when  $H$  rises from 0.05 m to 0.25 m. This demonstrates how variations in exhaust gas duct height can have a big effect on the TEG system's power output. Additionally, since the average convective coefficient of exhaust gas lowers, the temperature difference diminishes as the TEGs plate length grows. The quantity of TEG components also grows along with the length of the TEG plate. When the TEG surface length is increased, the power output increases linearly because the increase in TEGs has a dominant effect that offsets the decline in temperature differential. The shift to turbulence that takes place along a segment of the TEG plate's length and the development of a mixed boundary layer are responsible for the quadratic increase in power variation that starts at a length of 0.8 m when  $H$  is 0.05 m.

Now, the two generators (Diesel generator and TEG generator) are considered as one generator so that the enhancement in power generation and then efficiency of the original diesel generator can be tracked and the effect of boosting the power generation with TEG and oil tank integration can be measured. To proceed, the percentage enhancement in power generation when the TEG and cold oil tank are integrated into the diesel generator with respect to the power generation with an original power generator is calculated for different generator power,  $t/k$ , Duct height  $H$ , and Length  $L$ .

Figure 5 shows the variation of the percentage enhancement of power generation in function of the diesel generator power for different ratios ( $t/k$ ).

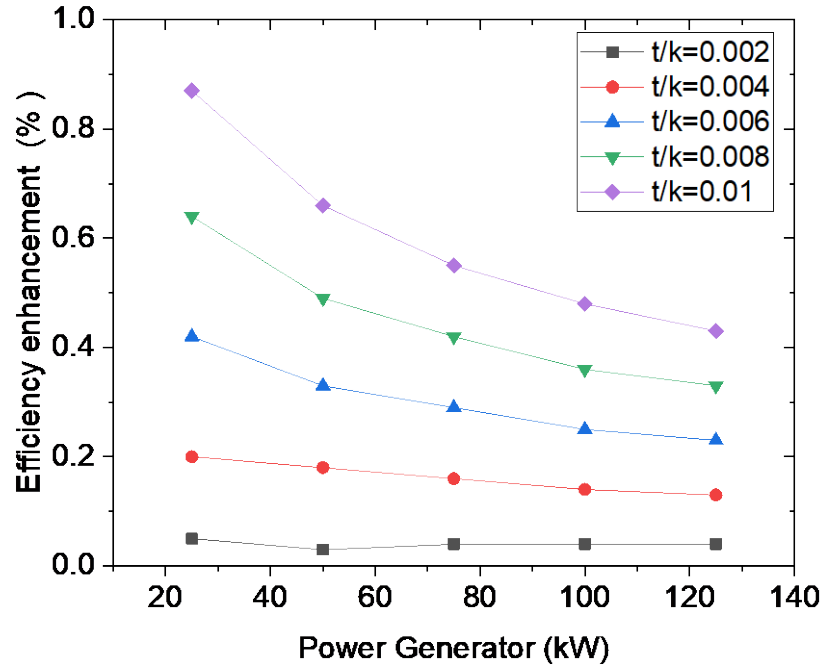


Figure 5: Variation of the diesel generator efficiency enhancement as function of the generator power for different ratios of thickness and thermal conductivity of each TEG.

As shown in Figure 5, the percentage enhancement in power generation decreases when the diesel generator power increases and increases when  $(t/k)$  increases. For a  $(t/k)$  of 0.002, if the diesel generator power is increased from 25 to 125 kW, the percentage enhancement of power generation decreases from 0.05 to 0.04%. For a  $(t/k)$  of 0.01, if the diesel generator power rises from 25 to 125 kW, the percentage enhancement decreases from 0.87 to 0.43%. Finally, for a diesel generator power of 25 kW, the percentage enhancement increases from 0.05 to 0.87% for  $(t/k)$  range of 0.002-0.01.

Figure 6 shows the variation of the percentage enhancement of power generation with  $L$  for different  $H$ .

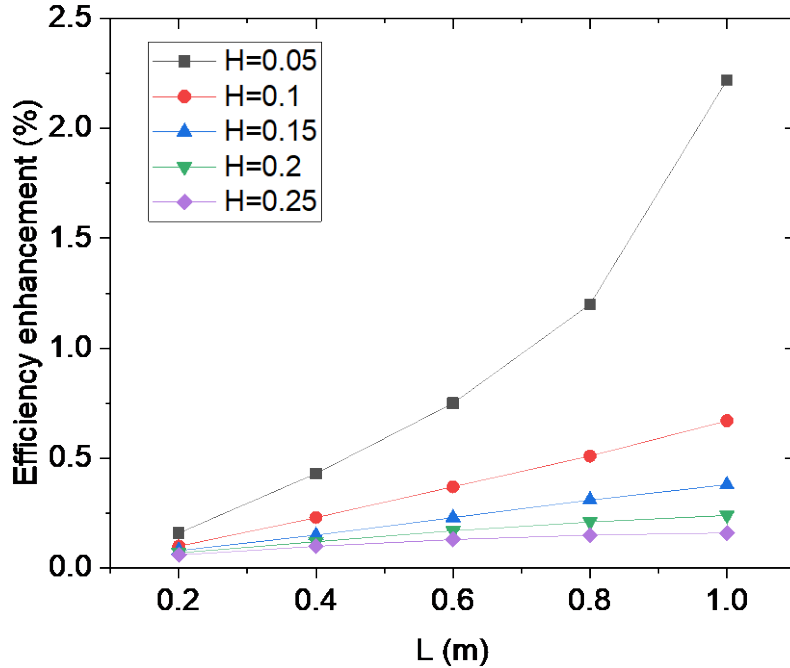


Figure 6: Variation of the diesel generator efficiency enhancement for different  $L$  and  $H$ .

Figure 6 illustrates how the improvement in power generation rises with increasing  $L$  and falls with increasing  $H$ . As an example, given a  $H$  of 0.05, the percentage increase in power generation increases from 0.16 to 2.22% when  $L$  is increased from 0.2 to 1 m. When  $L$  is increased from 0.2 to 1 m for  $H$  of 0.25 m, the percentage augmentation of power generation increases from 0.06 to 0.16%. The percentage enhancement for a TEG plate length of 1 m falls from 2.22 to 0.16% when  $L$  is increased from 0.2 to 1 m.

## 5- Conclusions, discussion, and future work

### 5.1. Conclusions

This study proposes a novel method for creating power with thermoelectric generators (TEGs) using hot generator exhaust gas and a cold oil tank. To verify the validity of this concept, a detailed thermal modeling approach is constructed, and an appropriate parametric analysis is conducted.

The parametric investigation has shown that:

1. The temperature differential in each TEG module and the resulting power generated by the assembly of TEGs both display linear increases as the generator power and the ratio of the thickness to thermal conductivity of each TEG are raised.
2. The temperature differential across each TEG module increases exponentially with both the length of the TEG plate and the height of the exhaust gas duct.
3. The power generated by the TEG assembly rises linearly with the TEG surface length and falls exponentially with the height of the exhaust gas duct.
4. Using an exhaust gas duct height of 0.05 m, and a TEGs plate length of 1 m, power generation of up to 2778 W is feasible under the predetermined circumstances of a diesel generator with an output of 125 kW. When compared to a conventional setup, the new

hybrid generator in this scenario may be able to increase power generation by up to 2.22%.

## 5.2. Discussion and future work

The co-authors' novel idea has not yet been used in an experimental setting. The purpose of this publication was to demonstrate the potential application of the proposed notion through theoretical and simplified modeling. Since the proposed idea appears to have practical applications, future articles (a future endeavor of the co-authors) can focus on experimental investigations, more accurate modeling, and literature comparisons. This work serves as a first baseline to validate the idea of using flat plates made entirely of TEGs and to identify the best configurations for applying this idea when hot or cold sources, such as exhaust gas and oil, are present. Drawing from the above indicated discourse, the subsequent areas of focus could be:

1. Create the identical parametric study using the same idea as described in the current manuscript through experimentation. In addition to providing an experimental database that may be utilized for the validation of numerical models, the goal will be to experimentally validate the notion proposed in this paper;
2. Create more precise numerical models that can improve the accuracy of the theoretical modeling described in this paper and/or account for transient characteristics. These models will be utilized to physically understand the system's electrical and thermal behavior under different circumstances. They can also be utilized to evaluate the viability of new ideas and/or improved system setups.

## References

- [1] Khaled, M., Harambat, F., El Hage, H., Peerhossaini, H. (2011). Spatial optimization of underhood cooling module – towards an innovative control approach. *Applied Energy*, 88, 3841-3849.
- [2] Khaled, M., Harambat, F., Peerhossaini, H. (2011). Towards the control of car underhood thermal conditions. *Applied Thermal Engineering*, 31, 902-910.
- [3] Khaled, M., Harambat, F., El Hage, H., Ramadan, M. (2015). Parametric analysis of heat recovery from exhaust gases of generators. *Energy Procedia*, 75, 3295-3300.
- [4] Wehbi, Z., Taher, R., Faraj, J., Castelain, C., Khaled, M. (2022). Hybrid Thermoelectric Generators-Renewable Energy Systems: A Review on Recent Developments. *Energy Reports*, 8, 1361-1370.
- [5] Wehbi, Z., Taher, R., Faraj, J., Ramadan, M., Castelain, C., Khaled, M. (2022). A Short Review of Recent Studies on Wastewater Heat Recovery Systems: Types and Applications. *Energy Reports*, 8, 896-907.
- [6] Murr, R., Faraj, J., Harika, E., Abdulhay, B., Khaled, M. (2020). Multi drain heat recovery system-Thermal modeling, parametric analysis, and case study. *Energy and Buildings*, 228, 1100447.



- [7] Habchi, C., Ghanem, A., Lemenand, T., Della Valle, D., Peerhossaini, H. (2019). Mixing performance in Split-And-Recombine Milli-Static Mixers—A numerical analysis. *Chemical Engineering Research and Design*, 142, 298–306.
- [8] Hassana, T., Habchi, C., Lemenand, T., Azizi, F. (2021). CFD simulation of creeping flows in a novel split-and-recombine multifunctional reactor. *Chemical Engineering and Processing - Process Intensification*, 162, 108353.
- [9] Herez, A., Ramadan, M., Abdulhay, B., Khaled, M. (2016). Short review on solar energy systems. *TMREES16 International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability*, Beirut, Lebanon.
- [10] Jaber, H., Ramadan, M., Lemenand, T., Khaled, M. (2018). Domestic Thermoelectric Cogeneration System: Optimization Analysis, Energy Consumption and CO<sub>2</sub> Emissions Reduction. *Applied Thermal Engineering*, 130, 279-295.
- [11] Zheng, J., Zheng, W., Chen, A., Yao, J., Ren, Y., Zhou, C., Wu, J., Ling, W., Bai, B., Wang, W., Zhang, Z. (2020). Sustainability of unconventional machining industry considering impact factors and reduction methods of energy consumption: A review and analysis. *Science of the Total Environment*, 722, 137897.
- [12] Razi, F., Dincer, I. (2022). Renewable energy development and hydrogen economy in MENA region: A review. *Renewable and Sustainable Energy Reviews*, 168, 112763.
- [13] Thirunavukkarasu, G.S., Seyedmahmoudian, M., Jamei, E., Horan, B., Mekhilef, S., Stojcevski, A. (2022). Role of optimization techniques in microgrid energy management systems—A review. *Energy Strategy Reviews*, 43, 100899.
- [14] Khaled, M., Ramadan, M. (2016). Heating fresh air by hot exhaust air of HVAC systems. *Case Studies in Thermal Engineering*, 8, 398-402.
- [15] Du, W.J., Yin, Q., Cheng, L. (2018). Experiments on novel heat recovery systems on rotary kilns. *Applied Thermal Engineering*, 139, 535-541.
- [16] Mahmoudi, A., Fazli, M., Morad, M. R. (2018). A recent review of waste heat recovery by Organic Rankine Cycle. *Applied Thermal Engineering*, 143, 660-675.
- [17] Akbari, A., Kouravand, S., Chegini, G. (2018). Experimental analysis of a rotary heat exchanger for waste heat recovery from the exhaust gas of dryer. *Applied Thermal Engineering*, 138, 668-674.
- [18] Shu, G., Zhao, J., Tian, H., Liang, X., Wei, H. (2012). Parametric and exergetic analysis of waste heat recovery system based on thermoelectric generator and organic rankine cycle utilizing R123. *Energy*, 45, 806–16.
- [19] Orr, B., Singh, B., Tan, L., Akbarzadeh A., (2014). Electricity generation from an exhaust heat recovery system utilising thermoelectric cells and heat pipes. *Applied Thermal Engineering*, 73,

586–95.

[20] Niu, Z., Diao, H., Yu, S., Jiao, K., Du, Q., Shu, G. (2014). Investigation and design optimization of exhaust-based thermoelectric generator system for internal combustion engine. *Energy Conversion Management*, 85, 85–101.

[21] He, W., Wang, S., Zhang, X., Li, Y., Lu, C. (2015). Optimization design method of thermoelectric generator based on exhaust gas parameters for recovery of engine waste heat. *Energy*, 91, 1–9.

[22] Champier, D., Bédécarrats, J., Kousksou, T., Rivaletto, M., Strub, F., Pignolet, P. (2011). Study of a TE (thermoelectric) generator incorporated in a multifunction wood stove. *Energy*, 36, 1518–26.

[23] Montecucco, A., Siviter, J., Knox, AR. (2017). Combined heat and power system for stoves with thermoelectric generators. *Applied Energy*, 185, 1336–42.

[24] Gao, H.B., Huang, G.H., Li, H.J., Qu, Z.G., Zhang, Y.J. (2016). Development of stove-powered thermoelectric generators: A review. *Applied Thermal Engineering*, 96, 297–310.

[25] Durand, T., Dimopoulos, P., Tang, Y., Liao, Y., Landmann, D. (2018). Potential of energy recuperation in the exhaust gas of state of the art light duty vehicles with thermoelectric elements. *Fuel*, 224, 271–9.

[26] Chinguwa, S., Musora, C., Mushiri, T. (2018). The design of portable refrigerator powered by exhaust heat using thermoelectric. *Procedia Manuf*, 21, 741–8.

[27] He, W., Wang, S., Yue, L. (2017). High net power output analysis with changes in exhaust temperature in a thermoelectric generator system. *Applied Energy*, 196.

[28] Li, B., Huang, K., Yan, Y., Li, Y., Twaha, S., Zhu, J. (2017). Heat transfer enhancement of a modularised thermoelectric power generator for passenger vehicles. *Applied Energy*, 205, 868–79.

[29] Ma, H., Lin, C., Wu, H., Peng, C., Hsu, C. (2015). Waste heat recovery using a thermoelectric power generation system in a biomass gasifier. *Applied Thermal Engineering*, 88, 274–279.

[30] Jaber, H., Khaled, M., Lemenand, T., Faraj, J., Bazzi, H., Ramadan, M. (2017). Effect of Exhaust Gases Temperature on the Performance of a Hybrid Heat Recovery System. *Energy Procedia*, 119, 775–82.

[31] Vale, S., Heber, L., Coelho, P.J., Silva, C.M. (2017). Parametric study of a thermoelectric generator system for exhaust gas energy recovery in diesel road freight transportation. *Energy Conversion Management*, 133, 167–77.

[32] Kim, T.Y., Negash, A.A., Cho, G. (2016). Waste heat recovery of a diesel engine using a thermoelectric generator equipped with customized thermoelectric modules. *Energy Conversion*

Management, 124, 280–6.

[33] In, B., Kim, H., Son, J., Lee, K. (2015). The study of a thermoelectric generator with various thermal conditions of exhaust gas from a diesel engine. *International Journal of Heat and Mass Transfer*, 86, 667–80.

[34] Shu, G., Zhao, J., Tian, H., Liang, X., Wei, H. (2012). Parametric and exergetic analysis of waste heat recovery system based on thermoelectric generator and organic rankine cycle utilizing R123. *Energy*, 45, 806–16.

[35] Gao, X., Andreasen, S., Chen, M., Kaer, S. (2012). Numerical model of a thermoelectric generator with compact plate-fin heat exchanger for high temperature PEM fuel cell exhaust heat recovery. *International Journal of Hydrogen. Energy*, 37, 8490–8.

[36] Tohidi, F., Holagh, S.G., Chitsaz, A. (2022). Thermoelectric Generators: A comprehensive review of characteristics and applications. *Applied Thermal Engineering*, 201, 117793.

[37] Shoeibi, S., Kargarsharifabad, H., Sadi, M., Arabkoohsar, A., Mirjalily, S. A. A. (2022). A review on using thermoelectric cooling, heating, and electricity generators in solar energy applications. *Sustainable Energy Technologies and Assessments*, 52, 102105.

[38] Haddad, A., Ramadan, M., Khaled, M., Ramadan, H., Becherif, M. (2020). Triple hybrid system coupling fuel cell with wind turbine and thermal solar system. *International Journal of Hydrogen Energy*, 45, 11484-11491.

[39] Aridi, R., Faraj, J., Ali, S., Lemenand, T., khaled, M. (2022). A comprehensive review on hybrid heat recovery systems: Classifications, applications, pros and cons, and new systems. *Renewable and Sustainable Energy Reviews*, 167, 112669.

[40] Zhang, F., Wang, X., Hou, X., Han, C., Wu, M., Liu, Z. (2022) Variance-based global sensitivity analysis of a hybrid thermoelectric generator fuzzy system. *Applied Energy*, 307, 118208.

[41] Gharzi, M., Kermani, A. M., Shamsabadi, H. T. (2023). Experimental investigation of a parabolic trough collector-thermoelectric generator (PTC-TEG) hybrid solar system with a pressurized heat transfer fluid. *Renewable Energy*, 202, 270-279.

[42] X. Sun, X. Liang, G. Shu, H. Tian, H. Wei, and X. Wang, Comparison of the two-stage and traditional single-stage thermoelectric generator in recovering the waste heat of the high temperature exhaust gas of internal combustion engine, *Energy*, 77 (2014) 489-498.

[43] W. He, S. Wang, X. Zhang, Y. Li, and C. Lu, Optimization design method of thermoelectric generator based on exhaust gas parameters for recovery of engine waste heat, *Energy*, 91 (2015) 1-9.

[44] B. D. In, H. I. Kim, J. W. Son, and K. H. Lee, The study of a thermoelectric generator with

various thermal conditions of exhaust gas from a diesel engine, *International Journal of Heat and Mass Transfer*, 86 (2015) 667-680.

[45] S. Vale, L. Heber, P.J. Coelho, and C.M. Silva, Parametric study of a thermoelectric generator system for exhaust gas energy recovery in diesel road freight transportation, *Energy Conversion and Management*, 133 (2017) 167-177.

[46] S. A. Mostafavi and M. Mahmoudi, Modeling and fabricating a prototype of a thermoelectric generator system of heat energy recovery from hot exhaust gases and evaluating the effects of important system parameters, *Applied Thermal Engineering*, 132 (2018) 624-636.

[47] A. Nour Eddine, D. Chalet, X. Faure, L. Aixala, and P. Chessé, Effect of engine exhaust gas pulsations on the performance of a thermoelectric generator for wasted heat recovery: An experimental and analytical investigation, *Energy*, 162 (2018) 715-727.

[48] A. Massaguer, T. Pujol, M. Comamala, and E. Massaguer, Feasibility study on a vehicular thermoelectric generator coupled to an exhaust gas heater to improve aftertreatment's efficiency in cold-starts, *Applied Thermal Engineering*, 167 (2020) 114702.

[49] H. Gürbüz, H. Akçay, and Ü. Topalçı, Experimental investigation of a novel thermoelectric generator design for exhaust waste heat recovery in a gas-fueled SI engine, *Applied Thermal Engineering*, 216 (2022) 119122.

[50] Y. Lan, J. Lu, L. Mu, S. Wang, and H. Zhai, Waste heat recovery from exhausted gas of a proton exchange membrane fuel cell to produce hydrogen using thermoelectric generator, *Applied Energy*, 334 (2023) 120687.

[51] D. Luo, Y. Yan, W. Chen, and B. Cao, Exploring the dynamic characteristics of thermoelectric generator under fluctuations of exhaust heat, *International Journal of Heat and Mass Transfer*, 222 (2024) 125151.

[52] Ramadan, M., Ali, S., Bazzi, H., Khaled, M. (2017). New hybrid system combining TEG, condenser hot air and exhaust airflow of all-air HVAC systems. *Case Studies in Thermal Engineering*, 10, 154-160.

[53] Faraj, A., Jaber, H., Chahine, K., Faraj, J., Ramadan, M., El Hage, H., Khaled, M. (2020). New Concept of Power Generation Using TEGs: Thermal Modeling, Parametric Analysis, and Case Study. *Entropy*, 22, 1-16.

[54] Incropera, F.P., DeWitt, D.P. (2007). *Fundamentals of heat and mass transfer*. Sixth Edition. John Wiley & Sons.

[55] Khaled, M., Murr, R., El Hage, H., Ramadan, M., Ramadan, H., Becherif, M. (2020). An iterative algorithm for simulating heat recovery from exhaust gas – Application on generators. *Mathematics and Computers in Simulations*, 167, 92-103.

[56] D. Luo, Z. Wu, Y. Yan, J. Cao, X. Yang, Y. Zhao, and B. Cao, Performance investigation and

design optimization of a battery thermal management system with thermoelectric coolers and phase change materials, *Journal of Cleaner Production*, 434 (2024) 139834.

[57] D. Luo, Z. Liu, Y. Yan, Y. Li, R. Wang, L. Zhang, and X. Yang, Recent advances in modeling and simulation of thermoelectric power generation, *Energy Conversion and Management*, 273 (2022) 116389.

[58] TEG Specification Sheet, Seedbeck Thermoelectric Generator, 2003. Available from: [https://customthermoelectric.com/media/wysiwyg/TEG\\_spec\\_sheets/1261G-7L31-04CQ\\_20140514\\_spec\\_sht.pdf](https://customthermoelectric.com/media/wysiwyg/TEG_spec_sheets/1261G-7L31-04CQ_20140514_spec_sht.pdf)

[59] Specifications TEG Module TEG1-12611-6.0, Available from: <https://thermoelectric-generator.com/wp-content/uploads/2014/04/SpecTEG1-12611-6.0Thermoelectric-generator1.pdf>