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Thermoelectric Generators: A comprehensive review of characteristics and applications

Farzad Tohidi [a], Shahriyar Ghazanfari Holagh [b], Ata Chitsaz [a,*]

[a] Department of Mechanical Engineering, School of Engineering, Urmia University, Urmia, Iran
[b] School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran

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ABSTRACT

Energy crisis and associated environmental issues are the main challenges in today's changing world, where there is a growing demand for electricity. To address such challenges, modern-day energy conversion systems for which, reliability and scalability are the two most desired features, are in need. Thermoelectric generators are a kind of heat engines capable of offering solutions for these challenges if they reach their expected potentials. The advantages for such technologically advanced devices are manifold; they are environmentally friendly, highly scalable, reliable, and have long lifespan. Additionally, by applying thermoelectric generators, one can improve the existing systems' efficiency or supply the electricity demand of different systems with high flexibility. Nonetheless, the low conversion efficiency of thermoelectric generators has impeded their wide application, restricting them to an academic subject. Yet, recent advancements in thermoelectric materials and devices are pushing the technology to find its place among state-of-the-art energy conversion systems. The present review explores the recent literature to present a comprehensive and realistic perspective of the state of the technology. Furthermore, this review carefully investigates the feasibility of integrating thermoelectric generators into different systems and applications, and eventually, provides an in-depth analysis with recommendations for future studies.

1. Introduction

Nowadays, the ever-growing electricity consumption, fossil fuel reservoirs depletion, global warming, and environmental issues are among the most well-known challenges humanity has ever faced. According to a recent report by International Energy Agency (IEA), energy sector is responsible for about three-quarters of the greenhouse gas emissions today, and to reduce the global CO_2 emission to net zero by 2050, a huge transition in energy supply and conversion is crucial [1]. Hence, most studies conducted on energy systems have mainly focused on either improving the efficiency of existing systems or introducing novel systems with higher efficiencies and flexibilities towards using renewable sources. Over the past decades, the development and improvement of industries, transportation systems, and in general, humans' lifestyle, have mostly relied on converting fossil fuels' chemical energy into thermal, mechanical, and electrical forms. However, to reach net zero emission by 2050, the share of electricity should increase to almost half of the total energy consumption, and more importantly, this electricity should be supplied from renewable sources rather than fossil fuels [1]. Additionally, although the energy demand is predicted to increase, a huge part of this demand can be reduced by improving the energy efficiency of energy systems [2]. Altogether, with the growing demand, necessity of employing low-intensity renewable sources like solar, and the advent of new technologies requiring access to electricity onboard and on a more permanent basis than what batteries offer, are some of the reasons that add new dimensions to energy systems. Therefore, energy systems seem to be in urgent need of high-performance devices with new capabilities such as robustness, scalability, compatibility, and reliability.

To this goal, there is ongoing research towards developing such devices although it is not as straightforward as one may assume. One of these devices that have gained massive attention over the recent decades is thermoelectric generator (TEG). Thermoelectric generator is a kind of heat engine that can produce an electromotive force via the Seebeck effect when exposed to a temperature difference. TEGs enjoy numerous advantageous characteristics like direct energy conversion, solid-state with no moving parts, high reliability, scalability, and lifespan, and compatibility with different systems and environment, making them as

* Corresponding author.
E-mail address: A.chitsaz@urmia.ac.ir (A. Chitsaz).

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an attractive energy conversion device. However, the low efficiency of TEGs has been the most significant obstacle impeding their practical application in a vast manner [3,4]. Nevertheless, TEGs are potentially suitable for many applications where efficiency is not the primary concern; applications including either or both of a free heat source (like waste heat) and a requirement for the unique characteristics of TEGs (like deep space missions).

Although thermoelectric devices are capable of operating in cooling, heating, and power generation modes, the latter is the main concern of the current review. Over the past decades, countless research has been conducted on thermoelectricity, and the review papers have been published, expounding different aspects of the subject. Generally speaking, conducted research on thermoelectricity can be categorized into three interdependent domains as follows. (a) Material science, concentrating on new thermoelectric material and engineering techniques to improve the nominal performance of the existing thermoelectric materials [5-9]. (b) Device-level design, concerned with assessing new solutions to design and improve thermoelectric devices regarding the roles they could adapt with the lowermost possible degradation compared to their nominal performance [10-12]. And (c) system-level design and engineering, mostly dealing with the applications and routes to improve the TEG systems considering the demands and characteristics of those applications [13-18].

As mentioned above, there are some great reviews on each research areas for thermoelectric generators; however, it seems there exists a disconnection between the applications of thermoelectric generators and thermoelectric materials and module designs. In other words, no review works have given an all-around and comprehensive perspective of the thermoelectric generators. Yet, it is crucial to have some background information on the materials, modelling approaches, and design processes in order to analyze and assess the feasibility of employing thermoelectric generators in corresponding applications, and clearly understand the directions through which thermoelectric technology can flourish. Therefore, the present review aims at introducing an overall view of the characteristics of TEGs, and recognizing the advantages, challenges, and restrictions of employing this technology. To this goal, a brief, but all-around view of the theoretical background, advancements in thermoelectric materials, and important characteristics of TEGs at device-level and system-level designs are presented at the first five sections of this paper. Having established this foundation, in the main body of the present review, a detailed assessment of TEGs' most common applications is provided. Unlike similar reviews on this topic, in the current review, the previous research and their results are thoroughly discussed, highlighting their important outcomes and comparing them to the similar research. Moreover, to make the context of applications of thermoelectric generators more intelligible, the potentials and restrictions of the applications are briefly introduced at the beginning of each section and then, advantages, challenges, and in general, the feasibility of employing TEGs in these applications are expounded. Overall, the present review provides a unique and comprehensive view of the thermoelectric generators in the context of today's energy market, and tries to present a clear and realistic prospect of the TEGs' characteristics and applications. In the end, such a prospective sheds light on hidden aspects of the thermoelectric generators applications and provides outlook for the future directions of thermoelectric generators.

2. Thermoelectric fundamentals

Thermoelectric (TE) phenomenon is the direct conversion of a temperature difference between two dissimilar materials into electricity. The phenomenon was discovered by Thomas Seebeck in 1821 and is known as the Seebeck effect. He showed that heating the junction of two dissimilar conductors can produce an electromotive force. Fig. 1 schematically shows how the Seebeck effect occurring in a unicouple of thermoelectric materials; the change in the distribution of free charge careers (holes and electrons) under the influence of temperature gradient leads to a voltage difference at the two open ends of the unicouple. The Seebeck coefficient (α) is defined as the ratio of the produced electric potential difference (V) to the temperature difference (ΔT) between the two junctions:

$$\alpha = \frac{V}{\Delta T} \tag{1}$$

Later in 1834, J. Peltier discovered the second thermoelectric effect. He found that when an electric current pass through a thermocouple, a heating/cooling effect, depending on the current direction, appears in the junctions so that one gets hotter, while the other one gets colder. This effect is known as the Peltier effect. The Peltier coefficient (π) is defined as the ratio of the heating/cooling rate ($\mathring{q}$) to the current (I) passing through a specimen:

$$\pi = \frac{\mathring{q}}{I} \tag{2}$$

In 1855, W. Thomson (later Lord Kelvin) recognized that the Peltier and Seebeck effects are interdependent. Applying the theory of thermodynamics, he demonstrated a relation between the Seebeck and Peltier coefficients. He also discovered a third thermoelectric effect; reversible heating or cooling in the concurrent presence of an electric current and a temperature gradient in a homogeneous conductor. Thomson coefficient (τ) is defined as the heating rate per unit length caused by the transition of unit current through a conductor in which there is a unit temperature gradient.

The first Kelvin relation expresses the Peltier coefficient in terms of the Seebeck coefficient:

$$\pi = \alpha . T \tag{3}$$

And the second one connects the Seebeck and Thomson coefficients:

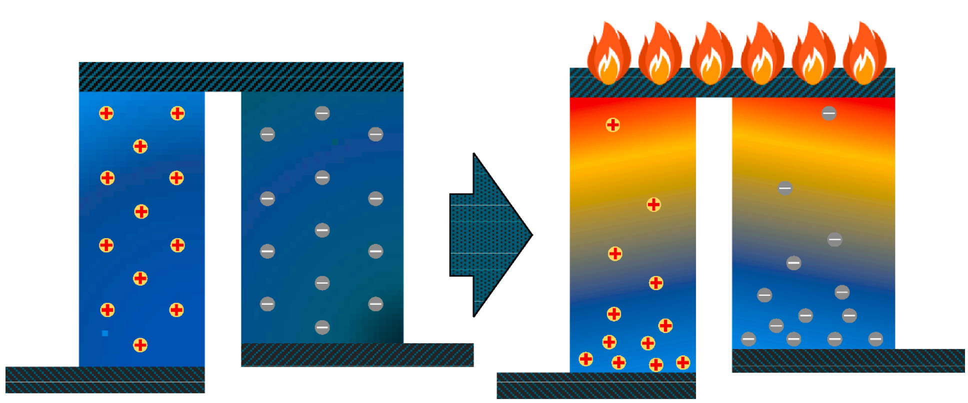

Fig. 1. Schematic visualization of the Seebeck effect in a thermoelectric unicouple.

$$\tau = \left(\frac{d\alpha}{dT}\right)T \tag{4}$$

Another effect, which is also applied in thermocouples, is the well-known Joule heating effect. This effect, caused by an electric current in an electrically resistant conductor, was discovered by J. Joule in 1840. The irreversibly lost energy as heat is:

$$\mathring{q}_j = R.I^2 \tag{5}$$

Thomson's work revealed that a thermocouple can be a kind of heat engine, i.e., one can utilize the Seebeck effect to generate electricity from temperature difference or the Peltier effect to create a temperature difference between the two junctions. However, because of irreversible phenomena like thermal conduction and Joule heating, thermocouples are relatively inefficient [3].

To play a significant role in the quest for sustainability, thermoelectric devices performance must be improved. To this goal, materials with a high Seebeck coefficient (α) and electrical conductivity (σ) and low thermal conductivity (k) should be selected. For thermoelectric materials, these conditions are summarized in the figure of merit (z), $z = \alpha^2\sigma/k$, where z has the dimension of inverse temperature. Specifying the dimensionless figure of merit, which is equal to zT at a given temperature, is more common. For practical applications, one would like zT to be in the order of unity or larger. However, this is difficult to achieve as the mentioned transport coefficients are incompatible [4]. Nowadays, commercial thermoelectric materials possess a zT value around unity, and new developments could push this value up to around 2–3.

2.1. Mathematical modelling of thermoelectric generators

Due to the interdependence of local temperature and transport properties of thermoelectric materials, precisely solving the differential equations governing the phenomena in a TEG can be a complex process [19]. Therefore, numerous approximate methods have been developed to simulate the performance of TEGs, including numerical [20] and simplified analytical [21] models. Numerical techniques can predict TEG's performance with high accuracy, but this is achieved at the expense of long processing times and high computational costs. On the other hand, analytical models, using temperature-averaged values for thermoelectric properties, can be beneficial for parametric study and optimization purposes; however, they can also be highly inaccurate, especially under huge temperature differences. P. Ponnusamy et al.[22] investigated the reason behind the failure of temperature-averaged method for certain materials, and found it to be the strong dependency of thermal conductivity to temperature in these materials. They introduced the spatial averaging method for these materials, and showed it to be accurate as much as a finite element method. Furthermore, regardless of the approach, a complete model should take the effect of heat source, heat sink, and thermal contact resistances into account. L. Catalan et al.[23] developed a comprehensive numerical model based on electrical analogy between heat transfer and electricity, and considering phase change heat exchangers on both sides of the thermoelectric modules. Sh. Qing et al.[24] used an analytical model to optimize the performance of a TEG under the influence of different heat transfer coefficients on each side of a TEG. Altogether, based on the level of accuracy and pace of analysis, different types of modelling approaches can be utilized to simulate the performance of TEGs. Nevertheless, the main purpose of the current review is to introduce the concept and basis of modelling a TEG, which can be achieved using a simplified analytical model.

Fig. 2 schematically illustrates the structure of a single pair of thermocouples for power generation. A common type of thermoelectric unicouple is composed of a pair of semiconductors to make an excessiveness (N-type) or a deficiency (P-type) of electrons in response to the heat flux. These elements are then connected to a load R_L in an electrical loop, where the current (I) flows. The connection is established by an appropriate electrical and thermal conductor (generally copper). The thermocouple is sandwiched between two ceramic plates, which are good thermal conductors and electrical insulators. Practical devices usually use modular TEs composed of several thermocouples connected thermally in parallel and electrically in series. In this arrangement, they can be used between a heat source and sink to produce a reasonable voltage. The supposed thermocouple has the properties of Seebeck coefficient (α_p and α_n), electrical resistance (R_p and R_n), and thermal conductance (K_p and K_n). Note that the thermal conductance (K) and electrical resistance (R) are dependent on thermal and electrical conductivities (k,σ) and the ratios of length (L) to cross-section areas (A) of branches:

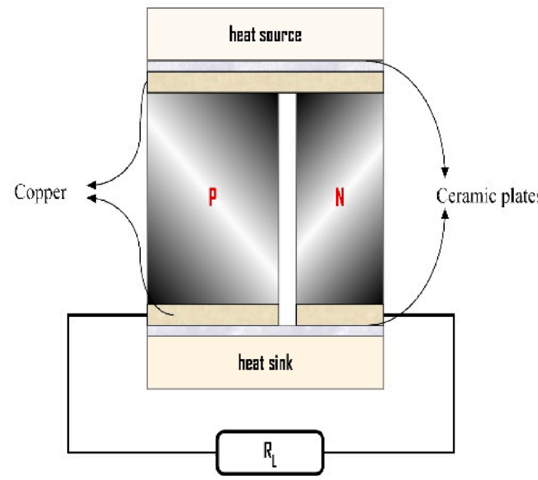

Fig. 2. Schematic view of a single pair of thermocouples.

$$R = \frac{L}{A\sigma} \tag{6}$$

$$K = \frac{kA}{L} \tag{7}$$

In the general theory outlined here, below listed simplifying assumptions are used [3]:

1. The thermal resistance between the thermocouple and heat source, and sink is neglected.
2. The transport coefficients (α, σ, k) are assumed to be constant with temperature, i.e., the Thomson effect disappears by this assumption, according to the second Kelvin relation (*Eq. (4)*).
3. Thermal losses are negligible, and heat transfer occurs only through the two branches.
4. The cross-sectional areas of the two branches are constant.
5. The flow is under steady-state conditions.
6. Heat transfer is one-dimensional.

The model of a TE element under power generating condition is illustrated in Fig. 3. As can be seen, the thermocouple's hot surface is in contact with a high temperature (T_h) heat source, while the cold surface is connected to a low temperature (T_c) heat sink. As a power generator, the thermocouple absorbs heat from the heat source, a part of which is converted into electricity while the remaining part is rejected to the heat sink. When the condition is on open circuit (no-load), the generated electricity appears as a voltage difference (V_{NL}) across the TE's terminals. However, if a power absorbing device with an internal resistance of R_L is connected, the current (I) flows through the load and the power (P_L) is consumed.

As shown in Fig. 3, first, a differential element is drawn for one of the branches without considering the Peltier (or Seebeck) effect. Thus, at the first step, the differential element is just a simple conducting wall in

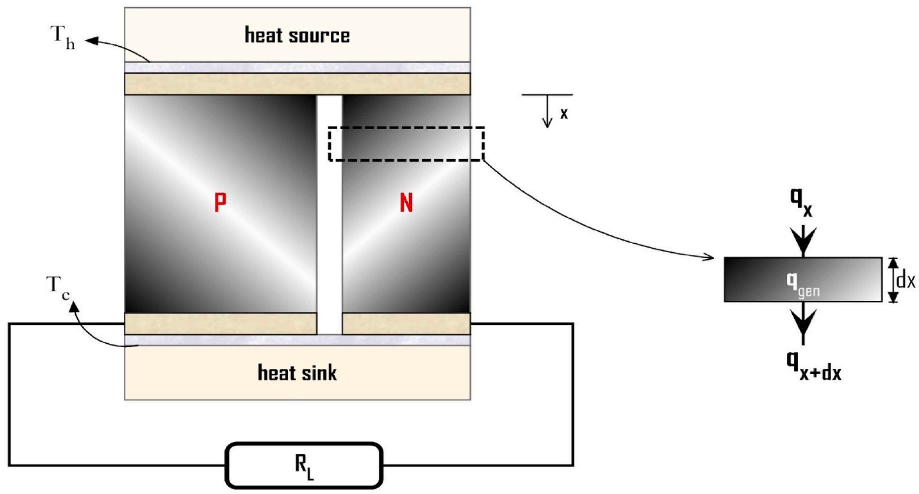

Fig. 3. A simple TE element under power generation condition, and a differential section of one of the branches and its energy distribution (without considering the Seebeck effect).

which energy generation occurs (Joule heating). Notice that as the two branches are under the same conditions, the general procedure will be done for one of the branches and then specified for each of them.

According to Fourier's law of heat conduction, the rate of the thermal energy entering the element at the positions, x and $x + dx$, are:

$$\mathring{q}_x = -kA\frac{dT}{dx} \tag{8}$$

$$\mathring{q}_{x+dx} = -kA\frac{dT}{dx}+\frac{\partial}{\partial x}\left(-kA\frac{dT}{dx}\right)dx \tag{9}$$

The heat generated in the differential element is:

$$\mathring{q}_J = RI^2 = \frac{I^2}{\sigma A}dx \tag{10}$$

Now, by applying the first law of thermodynamics, the summation of the energies entering the element and generated inside is equal to the leaving energy, that is,

$$\frac{d^2T}{dx^2}+\frac{I^2}{k\sigma A^2}=0 \tag{11}$$

Then, the integration of the above equation on x gives the following relation

$$T = -\frac{I^2}{2k\sigma A^2}x^2+C_1x+C_2 \tag{12}$$

The boundary conditions for the supposed model are:

$$\text{B.C.}\begin{cases} x=0 \rightarrow T=T_h \\ x=L \rightarrow T=T_c \end{cases}$$

Solving the equation at boundaries, the temperature distribution becomes:

$$T = -\frac{I^2}{2k\sigma A^2}x^2+\left[\frac{T_c-T_h}{L}+\frac{I^2}{2k\sigma A^2}L\right]x+T_h \tag{13}$$

The first objective is to calculate the heat absorbed from the heat source. For this purpose, the term dT/dx must be calculated and then, substituted into the Fourier's law (*Eq.* (8)), hence:

$$\frac{dT}{dx} = -\frac{I^2}{k\sigma A^2}x+\left[\frac{T_c-T_h}{L}+\frac{I^2}{2k\sigma A^2}L\right] = -\left[\left(\frac{I^2\left(x-\frac{L}{2}\right)}{k\sigma A^2}\right)+\frac{T_h-T_c}{L}\right] \tag{14}$$

$$\mathring{q}_{h,cond+J} = \mathring{q}_{x=0} = \mathring{q}_{x=0,p}+\mathring{q}_{x=0,n} \tag{15}$$

Specified equations are

$$\mathring{q}_{x=0,n} = +\frac{k_nA_n}{L_n}(T_h-T_c)-\frac{L_n}{2\,\sigma_nA_n}I^2 \tag{16}$$

$$\mathring{q}_{x=0,p} = +\frac{k_pA_p}{L_p}(T_h-T_c)-\frac{L_p}{2\,\sigma_pA_p}I^2 \tag{17}$$

Thus,

$$\mathring{q}_{h,cond+J} = (K_p+K_n)(T_h-T_c)-\frac{R_p+R_n}{2}I^2 \tag{18}$$

Now, to attain the total heat which is absorbed from the heat source, the Peltier cooling effect must be added to the above. Note that although the Seebeck and Peltier effects occur in the junctions and may seem interfacial phenomena, they depend on the bulk properties of the material involved. Back to the problem, the heat absorbed as Peltier cooling is:

$$\mathring{q}_{h,Pel} = (\alpha_p-\alpha_n)IT_h \tag{19}$$

Then, the total rate of heat flow from the source becomes:

$$\mathring{q}_h = (\alpha_p-\alpha_n)IT_h+(K_p+K_n)(T_h-T_c)-\frac{R_p+R_n}{2}I^2 \tag{20}$$

Likewise, the heat rejected to the sink can be obtained as:

$$\mathring{q}_c = (\alpha_p-\alpha_n)IT_c+(K_p+K_n)(T_h-T_c)+\frac{R_p+R_n}{2}I^2 \tag{21}$$

The current flowing through the thermocouple is another interesting parameter which can be obtained from the Seebeck coefficient as follows.

The Seebeck coefficient of the thermocouple is $(\alpha_p - \alpha_n) = V/(T_h - T_c)$. Therefore, by substituting the voltage from the Seebeck coefficient into the Ohm's law, and relying on the fact that the total resistance of the TEG is the summation of the load resistance and that of the two branches (because they are connected in series), one can obtain:

$$I = \frac{(\alpha_p-\alpha_n)(T_h-T_c)}{R_p+R_n+R_L} \tag{22}$$

The second objective is to determine the power generated by the thermocouple, which is given by:

$$P_L = R_L I^2 = \left(\frac{(\alpha_p - \alpha_n)(T_h - T_c)}{R_p + R_n + R_L}\right)^2 R_L = \mathring{q}_h - \mathring{q}_c \tag{23}$$

The third parameter of interest is the conversion efficiency of the thermocouple, which can be expressed as:

$$\eta = \frac{P_L}{\mathring{q}_h} = \frac{R_L I^2}{(\alpha_p - \alpha_n) I T_h + (K_p + K_n)(T_h - T_c) - \frac{R_p + R_n}{2} I^2} \tag{24}$$

According to the circuit theory, maximum power is produced when the external and internal resistances are equal. However, according to the above, the efficiency could never exceed 50% even without any heat losses through the thermal conduction and Joule heating.

It is useful to express the efficiency in terms of the figure of merit, Z, it can be shown that:

$$\eta = \frac{(T_h - T_c)\left(\sqrt{1 + ZT_m} - 1\right)}{T_h\left(\sqrt{1 + ZT_m} + \frac{T_c}{T_h}\right)} \tag{25}$$

where T_m is mean temperature and Z is equal to $(\alpha_p - \alpha_n)^2 / \left[(K_p + K_n)(R_p + R_n)\right]$. It is clear that with ZT_m approaching numbers much larger than one, the efficiency would approach $(T_h - T_c)/T_h$, which is equal to the Carnot efficiency. Thus, when selecting thermoelectric materials, the main concern should be getting the largest value for the thermoelectric parameter, Z.

Another interesting fact is that the figure of merit itself can be optimized for a pair of materials. While the bulk properties of materials are fixed, the product $(K_p + K_n)(R_p + R_n)$ can become smaller by altering the ratio of length to cross-sectional area (the form factor). It can be substantiated that the product becomes minimum when the form factors of the two branches satisfy the below relation.

$$\frac{L_n A_p}{L_p A_n} = \sqrt{\frac{\sigma_n k_p}{\sigma_p k_n}} \tag{26}$$

This is used after selecting the materials to find the best form factor, optimizing the figure of merit. It is worth noting that the figure of merit is expressed in two common forms. One form of the figure of merit is expressed for a thermocouple consisting of two TE materials and based on the extensive properties of $K_{p,n}$ and $R_{p,n}$and it can be maximized using the aforementioned relation; this form is mainly used in the design process of TE modules. The other form is expressed for a single TE material and based on intensive properties of $\sigma_{p,n}$ and $k_{p,n}$, mainly used to measure and compare merits of different TE materials. In general, the former expressed using the capital letter, Z, and the latter using the smaller letter, z.

Note that the mathematical model presented here is a simplified one, and can misjudge the exact behavior of the TEG, especially under broad temperature ranges. For advanced analytical/computational models, check out the following references [19,25,26].

As a final remark, for a thermoelectric module consisting of a certain number of thermo-elements, N_{TE}, it can be shown that:

$$P_{L,module} = N_{TE} P_L$$

$$\mathring{q}_{h,module} = N_{TE} \mathring{q}_h, \mathring{q}_{c,module} = N_{TE} \mathring{q}_c$$

Thus, it is evident that:

$$\eta_{module} = \eta$$

3. Thermoelectric materials

As previously mentioned, according to the efficiency relation (Eq. (25)), efficiency of a TEG solely depends on the figure of merit and temperatures of hot and cold junctions. This means that one solution to improve the efficiency of TEGs is to find materials with properties leading to a higher z value or manipulate the existing materials to enhance the z value (like increasing the thermal resistivity and/or electrical conductivity of the materials). C. Vining [27] compared the efficiency of best in-practice mechanical heat engines with an optimistic thermoelectric estimate (Eq. (25)), and showed that at least a zT of around 4 is necessary for thermoelectric materials to be capable of competing with the large-scale energy conversion systems. Nevertheless, the high scalability of thermoelectric generators can become an important feature for their development. The study indicates the necessity of search for better thermoelectric materials and new techniques to improve the existing ones. Although it is not the primary concern of the present review, it may be beneficial to provide some information on the current state of material science in the field of thermoelectricity. For this purpose, it is enough to represent some substantial advancements in the field.

3.1. Recent advancements in bulk thermoelectric materials

A tangible progress has been made in the field of thermoelectric material, including chalcogenides, silicides, skutterudites, Zintls, clathrates, Heusler, oxides, organics, and composites through various approaches such as electronic band engineering, phonon-glass electron-crystal (PGEC) strategy, nano-engineering, magnetic effects strategy, etcetera [5,28]. Recently, C. Zhou et al. [29] reported a remarkable zT of 3.1 at 783 K for polycrystalline SnSe through removing the Oxide impurities. This report not only breaks the ceiling zT of 3 for thermoelectric materials, but also shows great average zT of around 2 in temperature range of 400–700 K, which is an incredible achievement for a polycrystalline SnSe thermoelectric material. Such encouraging achievement have not been rare during the past two decades, and there is a huge literature around different thermoelectric materials and techniques to improve their properties. X. Shi et al. [30] reviewed the advancements in thermoelectric materials, structures, and device design with great detail and comprehension. D. Beretta et al. [5] took a historical viewpoint and reviewed the progress made in the field of thermoelectricity from the beginning of it till the present time. Moreover, some other great reviews have been published on thermoelectric materials, including carbon allotrope hybrids [31], fiber based thermoelectric materials [32], and flexible and wearable thermoelectric materials and devices [33-35]. Basically, the research field of thermoelectric materials is so vast that covering all of its different branches would be impossible, out of context for the present review, and also purely repetitive. Nevertheless, as previously mentioned, some background information on the state-of-the-art thermoelectric materials and the advancements in the field is necessary for the awareness of the possible directions for thermoelectric applications. Accordingly, Fig. 4 shows selected up-to-date n/p-type bulk TE materials' figure of merit against temperature, reported over the past two decades. It is evident from this figure that even the best performing thermoelectric materials are only applicable and well-performing for certain ranges of temperatures. Combining these materials for achieving the best possible performances is among the main concerns of device-level design. Furthermore, increasing the value of zT and improving the thermoelectric properties of TE materials are just the starting point. There are other challenges to put these materials in the practical application levels like the availability of raw material, machinability, mechanical stability, thermal stability, chemical stability, the toxicity of the materials involved, and so forth. G. Li et al. [36] recently summarized a work on fracture toughness of TE materials, and investigated strategies to improve the mechanical strength of thermoelectric materials; similar investigations can be helpful for the development of high-performance TE devices with excellent mechanical reliability. Nevertheless, the improvements in thermoelectric materials are really promising and proceeding, both being essential to widen the practicality of thermoelectric devices.

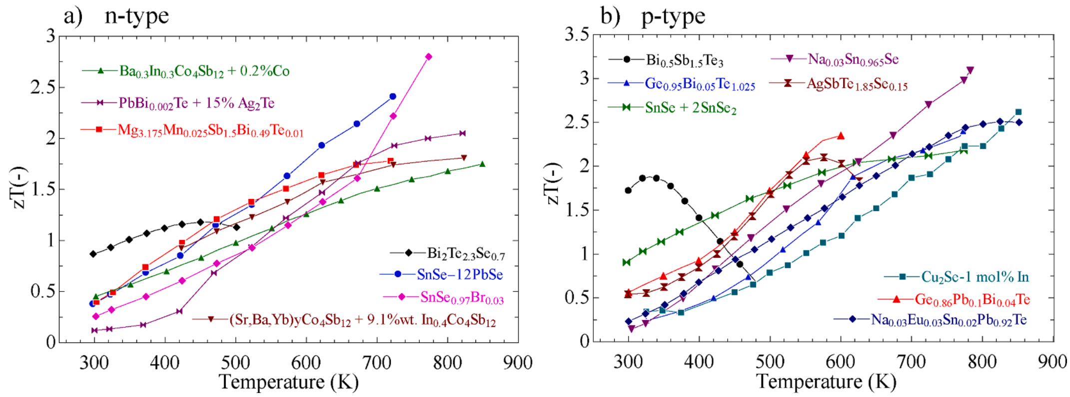

Fig. 4. Summary of some of the best zT for bulk thermoelectric materials to date as a function of temperature; (a) n-type thermoelectric materials: $Bi_2Te_{2.3}Se_{0.7}$ [37], SnSe–12PbSe [38], $SnSe_{0.97}Br_{0.03}$ [39], (Sr,Ba,Yb)yCo_4Sb_{12} + 9.1 wt% $In_{0.4}$ Co_4Sb_{12} [40], $Ba_{0.3}In_{0.3}Co_4Sb_{12}$ + 0.2 %Co [41], $PbBi_{0.002}Te$ + 15 %Ag_2Te [42], $Mg_{3.175}Mn_{0.025}Sb_{1.5}Bi_{0.49}Te_{0.01}$ [43], and (b) p-type thermoelectric materials: $Bi_{0.5}Sb_{1.5}Te_3$ [44], $Ge_{0.95}Bi_{0.05}Te1_{.025}$ [45] SnSe + 2$SnSe_2$ [46], $Na_{0.03}Sn_{0.965}Se$ [29], $AgSbTe_{1.85}Se_{0.15}$ [47], Cu_2Se–1 mol% In [48], $Ge_{0.86}Pb_{0.1}Bi_{0.04}Te$ [49], $Na_{0.03}Eu_{0.03}Sn_{0.02}Pb_{0.92}Te$ [50].

4. Device level (Module) design

The first concern when designing thermoelectric devices for any applications is finding a TE material with a high zT; however, this is only the starting point, designing these thermoelectric materials into devices is the next challenge. Shape of a module, geometry of thermoelectric legs, form factor (Eq (26)), fill factor (area of thermoelectric legs to ceramic cover), number of legs in a module, and insulation materials are some of the important engineering parameters to optimize a TEM's performance.

Scalability is one of the main advantages of thermoelectric generators, that is, they can be manufactured with various modular sizes and then used at larger scales through combining the modules. On the one hand, some properties of thermoelectric generators are highly dependent upon the operating conditions like temperature or intensity of heat source, suggesting a customized and different design for different applications. On the other hand, customized design would affect the commercialization of thermoelectric generators. Nevertheless, it must be possible to introduce standard designs for specific temperature ranges and applications to address this problem. This section elucidates the potential solutions to improve a thermoelectric module used under certain conditions.

4.1. Optimum geometrical parameters for a thermoelectric module

A typical thermoelectric module comprises of several thermocouples with n- and p-type legs, electrically connecting in series by high electrical conductors while thermally operating in parallel. These thermocouples are covered by high thermal conductors and electrical insulators made of ceramic. However, this is not the only way to configure a thermoelectric module. That is, to improve the performance and/or to optimally adapt the shapes for the relevant applications, other design structures can be employed. Take annular [51], segmented annular [52], cascaded annular [53], and cylindrical [54] structures as salient examples, all positively affecting the performance of a generator in its corresponding application (See Fig. 5). Moreover, according to the basic mathematical model provided in section 2.1, it is obvious that electrical resistance (Eq. (7)) and thermal conductance (Eq. (7)) of a

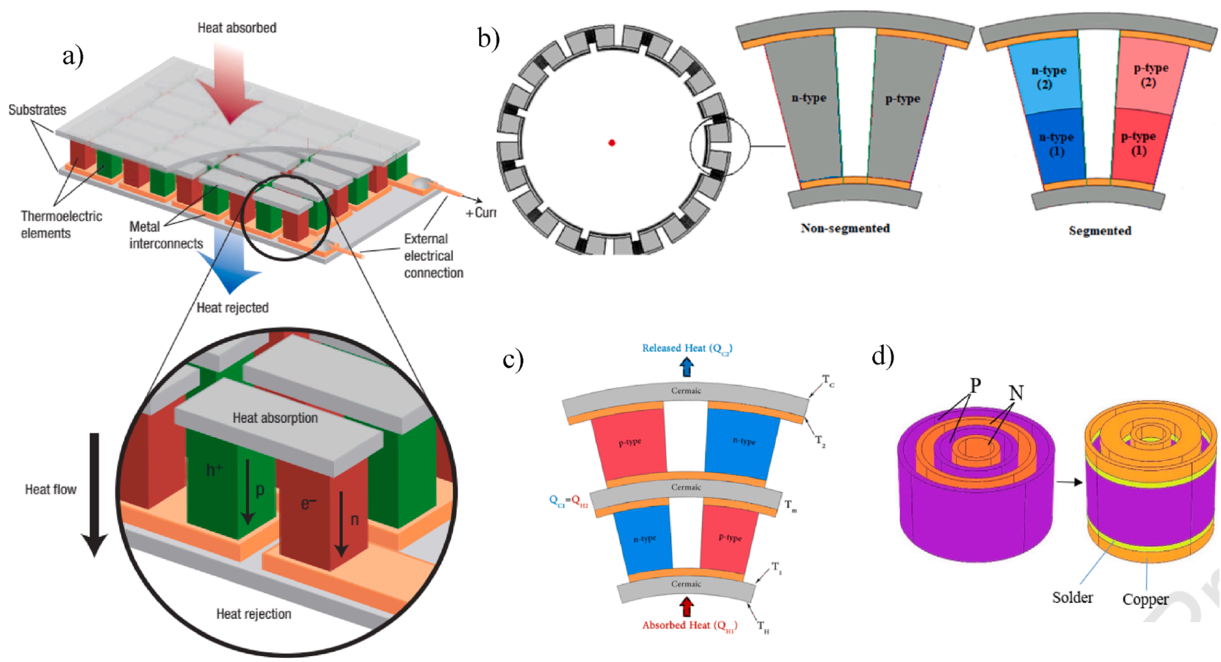

Fig. 5. Different thermoelectric structure designs: a)conventional TEM [60], b) segmented annular [52], c) cascaded annular[53], and d) cylindrical (ring shaped) [54].

thermoelectric module, and in general, heat transfer (Eqs. (20) and (21)), and overall performance (Eqs. (23) and (24)) of a TEG are highly dependent on the geometrical parameters, including leg length, leg's cross-sectional area, and number of unicouples in a module. Therefore, performance optimization of a thermoelectric device must be considered based on these parameters. G. Schierning et al. [55] provided fundamental and insightful information on the substantial geometrical parameters of TEGs. They found that the performance and costs of thermoelectric modules are remarkably altered by the device design. It was also concluded that the geometrical configuration should be optimized regarding the modules' applications. In another fundamental study, D. M. Rowe and G. Min [56] discussed the design theory and optimization of TEMs for power generation. According to the results, the optimum leg length for the highest power generation differs from that of the highest efficiency. Specifically speaking, longer legs were recommended for the maximum efficiency, while for the maximum power, the optimum leg length was found to be much shorter. Therefore, considering the economic factor, an optimization procedure was introduced by the authors. However, there are limits for changing the thermoelectric elements geometry. To reduce a TEM's costs, one way is to use less raw material, but in that case, one envisages with heat transfer problems. In essence, by decreasing the cross-sectional area, the size of a desired module becomes smaller, making it difficult to transfer heat at a reasonable rate through it. A solution is to use larger end-plates and increase the space between the thermo-elements; but it would cause higher thermal losses (convection and radiation) through the increased space. This problem was analyzed by H.J. Goldsmid [3] assuming a thermal insulation filling a fraction (g) of the area occupied by the thermo-elements. The results revealed that for expanded polyurethane ($k = 0.02(\frac{W}{mK})$) as the insulator and with a fill factor (g) of around 2, the module's performance becomes 93% of that of the theoretical one which has no thermal losses. S. Lv et al. [57] experimentally investigated the effect of different insulating materials on the performance of a thermoelectric module and found that use of aerogel as the insulator improves the efficiency of the TEM by 8.2% compared to that of the unfilled TEM. Moreover, the electrical contact resistance is another challenge limiting the thermo-elements length, which becomes considerable when the length trespasses a minimum value [58]. To keep the paper concise while having a better understanding, the authors recommend the study conducted by S. Shittu et al.[59]. This study has comprehensively reviewed the literature to expound the effect of various geometrical parameters and shapes for thermoelectric modules and potential advantages and challenges of the mentioned configurations. All in all, these studies are unanimous with the careful and customized optimization of geometry with respect to the applications and the desired outcomes, including costs, efficiency, and output power.

4.2. Thermal arrangement of thermo-elements and modules

In some applications, the temperature difference is so broad that employing only one material is inefficient (any thermoelectric material has a peak zT value in a limited range of temperature). For such cases, suitable solutions are to manufacture segmented thermo-elements employing different materials or utilize modules made for different ranges of temperature in a cascade arrangement. The employment of cascaded modules causes challenges like thermal contact resistance and increased heat losses in the whole system, unless they are manufactured in cascaded configuration [53]. Although segmented legs give better results, they can be problematic; not all the TE materials are compatible with one another. As Snyder and Ursell [61] revealed, if the difference between the compatibility factors of two materials is more than 2 units, the electrical and thermal fluxes arduously match with each other, causing a remarkable reduction in the efficiency. However, segmenting different materials in a right manner can bring about good results. W. Chena and Y. Chiou [62] numerically investigated the segmentation of two thermoelectric materials for power generation (Fig. 6-a). By optimizing geometrical parameters and the materials' ratio in p- and n-type legs, they achieved an efficiency of ~14% for a 400 K temperature difference. In a similar manner, but employing four sets of different materials as shown in Fig. 6-b, Z. Ouyang and D. Li [63] attained an efficiency of 17.8% and a power density of 3 W/cm^2 for a 700 K temperature difference. S. Shittu et al. [64] assessed the performance of a segmented asymmetrical thermoelectric generator (SASTEG) under pulsed heat conditions and compared it with a traditional TEG device. Optimizing each material's length in both legs, it was concluded that the rectangular pulsed heat significantly increases the performance of both SASTEG and TEG and decreases the thermal stress compared to the steady heat. The output power of SASTEG was 117.1% greater than that of the conventional TEG. X. Ma et al. [65] studied segmented TEGs for engine exhaust recovery shown in Fig. 6-c. They developed a numerical model and optimized the length ratio of two materials used, namely Bi_2Te_3 for the cold side and $CoSb_3$ for the hot side of the leg. The study showed that for a fixed temperature difference, the optimal percentage of $CoSb_3$ is slightly lower for the p-type leg, and for broader temperature differences, the output power increases as $CoSb_3$ percentage becomes larger. Also, it was deduced that compared to a segmented model with half $CoSb_3$ and half Bi_2Te_3, the maximum output power increases with optimizing the $CoSb_3$ percentage by 13.8% and for a system-level application, the enhancement becomes 6.8%. Note that the optimum percentages would be different for maximum efficiency.

This section highlights the importance of optimizing a thermoelectric device before being applied in a power generation system. Regarding the low efficiency and high costs of thermoelectric generators, it is necessary to utilize them at their full potential by optimizing the device for a set of given conditions. Nevertheless, optimum devices can be designed for different general applications, and as it will be discussed in the next sections, it is not impossible to regulate the heat source and heat sink so that the conditions become ideal for commercial thermoelectric devices.

5. System-Level design and engineering

The design of TEG-based power generation systems is always accompanied by different challenges. Due to the low efficiency of thermoelectric generators, the TEG-based systems should be designed to operate around their nominal performance; otherwise, the application of such systems is less likely to be justifiable in many cases. Current section briefly introduces the existing challenges and the proposed solutions; more examples are expounded in the application section.

5.1. Contact thermal resistance

Thermal resistance between the two sides of a module and heat source and sink surfaces has a significant impact on the performance of a thermoelectric module. Numerous studies have examined this topic and offered several solutions like clamping the module between the heat source and sink, designing novel configurations to dominate the contact thermal resistance, and utilizing thermal interfaces such as thermal greases, conductor plates, metallic separators, etc. The research conducted by W. He et al. [66] revealed that contact thermal resistance has a strong impact on TEG performance; it was discovered that a contact thermal resistance, which is in the vicinity of 10^{-3} m^2 K W^{-1} affects the peak power of a TEG by 11.5%. K. Karthick et al. [67] investigated the influence of three different thermal interfaces and also the clamping pressure on the contact thermal resistance and overall performance of a TEG both theoretically and experimentally. The findings demonstrated that an interface material with a thermal conductivity of 0.6 W/mK can be of practicality with respect to the high cost of better materials. Moreover, they showed that by applying an interface, the influence of clamping pressure and surface roughness becomes insignificant, while without an interface, the module's performance enhances as clamping pressure rises and diminishes as the surface roughness increases. S.

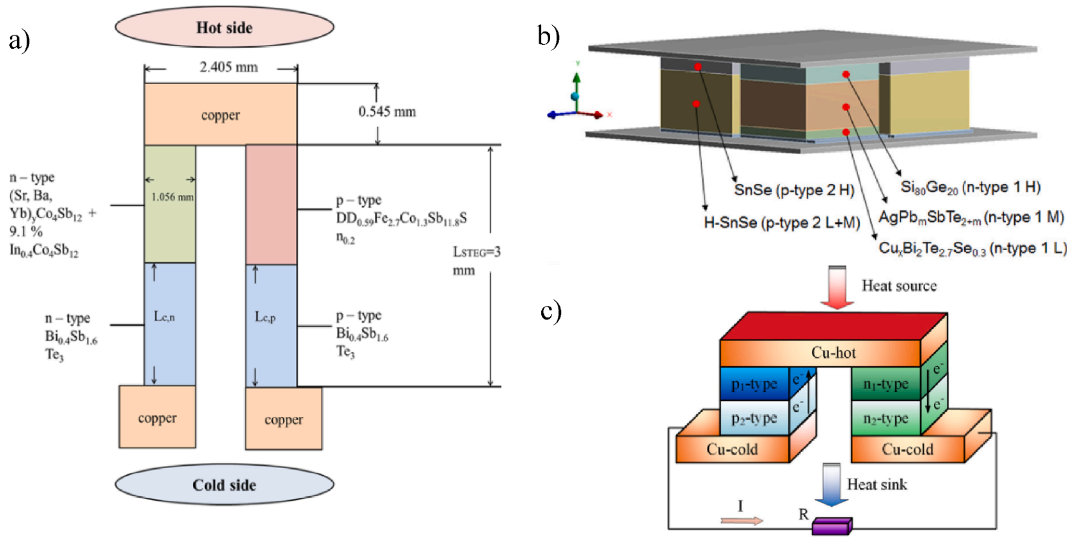

Fig. 6. Segmented thermoelectric designs by a) W. Chena and Y. Chiou [62], b) Z. Ouyang and D. Li [63], and c) X. Ma et al. [65].

Wang et al. [68] conducted an experimental study on the effect of contact thermal resistance on a TEG module's performance and evaluated the possible solutions. The results showed that the application of thermal grease results in improvements by 61% and 13% in the maximum output power and conversion efficiency, respectively (loading pressure was not reported). In the meantime, applying both thermal grease and clamping pressure contributed to further improvements so that with an increase in the clamping pressure from 109 to 765 kPa, maximum output power and efficiency enhanced further by 33% and 20%, correspondingly. Note that over-clamping a module, especially when the load is not evenly distributed, can lead to modules' failure. Considering the possible damages under high clamping pressures, thermal interfaces seem to be a better option; however, as A. Rodriguez et al. [69] revealed, operating temperature and time can significantly affect the performance of interface materials. The authors experimentally studied the effect of temperature and aging on three different interface materials under two operating temperatures. The results indicated that the thermal impedance could increase up to 300% after 70 days of operation under the interface temperature of 180°C, while for lower operating temperatures, the interface performance is independent of the investigated parameters. D. Kim et al. [70] developed and experimentally evaluated a new thermal interface for relatively high temperatures (up to 500 °C). According to the experiments, compared to the cases without any interface material, the new-made interface material provides 101∼132% and 40∼73% improvements in power output and conversion efficiency, respectively. They also performed a set of thermal cycling experiments demonstrating the long-lasting performance of the interface. Another solution to bypass the contact resistance is employing fluid heat exchangers in direct contact with the endplates [71], eliminating the contact thermal resistance. A noteworthy point is that although these papers report improvements in the performance of TEGs, they actually investigate the prevention of performance degradation due to contact thermal resistances in TEGs. Altogether, these studies show one of the differences between a theoretical assessment and practical applications, indicating the necessity of careful system design in TEG applications.

5.2. Heat exchangers

Being of vital importance, a major part of the research conducted in the thermoelectric field has been dedicated to designing heat exchangers. Reconsidering the efficiency relation for a TEG (Eq. (25)), it is obvious that there are two effective parameters for the improvement of TEG's efficiency, namely the temperature difference and zT of the employed thermoelectric materials. Thus, in the design process and after choosing the appropriate materials based on the certain heat source and sink, design of heat exchangers constitutes the second most important part of a TEG system design [72]. Specifically speaking, ill designed heat exchangers can reduce the effective temperature difference and heat transfer rate through the TEG; this, in turn, leads to a decrease in efficiency (Eq (25)) and output power (Eq. (23)) of the TEG. D. Astrain et al. [73] investigated the influence of heat exchangers in both sides of a TEG on its performance. Using a computational model, they were able to show the fundamental influence of thermal design on the TEG's performance; specifically speaking, they found that a 10% improvement in the thermal resistance of both heat exchangers results in an 8% improvement of power generation. They also concluded that it is essential to achieve a similar improvement on both sides heat exchangers for improvement in the output power of the system. However, the performance of a heat exchanger is not the only design parameter and other parameters like cost and auxiliary consumption must be considered in design and optimization process of the system [74]. With respect to the performance and cost, different types of heat exchangers can be used at either side of a TEG system. In general, because of the low efficiency of TEGs, auxiliary consumption in a TEG system can be of critical importance; based on this, heat exchangers are classified into two categories of passive and active. Generally speaking, an active heat exchanger involves forced convection like fin-fan dissipater or a fluid circulating system. Active heat exchangers offer a low thermal resistance and therefore, a good performance; however, the auxiliary consumption and maintenance needs are some of the challenges of utilizing active heat exchangers. On the other hand, passive heat transfer does not require any external force for operation and even when the heat transfer is occurring through circulation of a fluid medium, the heat exchanger utilizes capillary action or gravity for that matter; examples of this type of heat exchangers include extruded heat sinks, heat pipes, and thermosyphon. Passive heat exchangers, which include a phase change process (heat pipes and thermosiphon), offer special advantages like high heat transfer rate, no auxiliary consumption, high reliability, and uniform temperature distribution even when the heat source has a fluctuating behavior. The crucial role of auxiliary consumption was perfectly pointed out by P. Aranguren et al. [75]. Investigating the effect of auxiliary consumption of a water circulating heat exchanger on a TE power generation system they found that about 40% of the produced power is consumed by the heat exchanger system. Moreover, the authors showed that employing a thermosiphon not only eliminates the auxiliary consumption but also improves the TEGs performance; also, downfall of these systems was concluded to be a bigger heat transfer surface. Overall, if there is no space limitation and the system is stationary thermosiphon offer great characteristics. The next step after choosing a heat exchanger is optimization of it based on the performance of the whole system. P. Aranguren et al. [76] showed that a 29% improvement in net output power of a thermoelectric generator is achievable through optimization of heat exchangers. More importantly, they found that there exists an optimum number of thermoelectric modules for a certain heat exchanger after which, increasing the number of modules does not contribute to the thermoelectric power generation.

Furthermore, in design and optimization of the heat exchangers for a TEG system, requirements of the application and/or economic considerations can affect the choice of heat exchangers; thus, one might choose a fluid circulating heat exchanger, phase change materials (PCM), metal extruded heat sinks with or without a fan, and so on. Among different types of heat exchangers, Heat Pipes (HPs) offer countless good characteristics in cooperation with TEGs, since they can dissipate a large amount of heat in a passive manner with no need for maintenance and high reliability. Such features make HPs the most appropriate choice for TEGs especially in sensing and monitoring applications where reliability is the most important character of the system. An HP-assisted TEG system was modeled, optimized, and experimentally validated for on-pipe wireless sensors by J. Chen et al.[77]. As exhibited in Fig. 7-a, the HP was used to absorb heat from inside of the pipe and deliver it to the hot side of two TEG modules, while extruded Al heat sinks were connected to the cold side of TEG to help the heat dissipation. The results indicated that employment of heat pipes boosts the output power by six times over a design using a simple aluminum rod. S. Lv et al. [78] performed an analytical-experimental study on the impact of different heat exchanger technologies on TEGs' performance. Having investigated four types of heat exchangers and conducted economic analysis, they discovered that although finned heat sinks are the most commonly applied and cheapest exchangers, they are of a relatively poor performance and have the lowest cost performance among the examined heat exchangers. On the other hand, the water heat exchanger showed a better performance than the air heat exchanger simply because of the higher convective heat transfer coefficient of water. However, the challenge is that the consumed auxiliary power is higher for the water heat exchanger, leading to a lower net efficiency. Finally, the heat pipe cooling method exhibited the best output performance and net efficiency, meanwhile representing a better cost performance. Moreover, the power density of the system and space limitations can play a role in heat exchanger design. W. Lee and J. Lee [79] employed printed circuit heat exchangers (PCHEs) for low-temperature TE power generation (Fig. 7-b). In agreement with their experiments, the numerical analysis substantiated that PCHEs are good choices in terms of compactness, power density, and pressure drop. In addition, for the same output power, PCHEs require lower hot fluid flow compared to other heat exchangers. Recently, the use of radiative cooling as a passive mechanism of heat transfer for the cold side of TEGs is introduced. Z. Zhang et al. [80] investigated the performance of nano-porous anodic aluminum oxide (AAO) grown on an aluminum heat sink to enhance a TEG's output power with radiative cooling. They found that the optimization of the AAO samples' parameters improves radiative, convective, and conductive cooling processes, significantly increasing the TEG's output power (by 55~70%) compared to the case with commercial Al heat sink. On the other hand, active cooling has shown a superior performance in most thermoelectric applications simply because of higher heat dissipation rates. B. Aravind et al. [81] experimentally examined the influence of heat exchanger type on the performance of a micro-combustion TEG. In the proposed system, two TEG modules were mounted to the sides of a combustor made of aluminum, and different kinds of heat sinks, encompassing simple aluminum fin, fin fan, and water-cooling block were used. Both active heat exchangers showed the best performance among similar systems in the literature; however, the water-cooling heat sink had better performance than the air-cooling heat sink and was more favorable from an economic perspective. Another interesting idea for heat dissipation from the cold side of TEGs is utilizing the latent heat of evaporation. L. Zheng et al. [82] theoretically analyzed the effect of natural evaporative cooling through a thin water film with a thickness of 1 mm, covering the cold side of a TEG (see Fig. 7-c), on efficiency of the TEG module. Their numerical analysis revealed that the output power and efficiency of the case with natural evaporative cooling are respectively 100.53 and 10.53 times greater than those of the case with natural convection cooling. The authors concluded that the new method is an applicable, environmentally friendly, low-cost, and effective cooling technique. Furthermore, a constant temperature is sought after when TEGs are utilized to generate a steady electrical power, voltage, and current. Yet, it is challenging since the heat dissipation is not steady in most applications like using

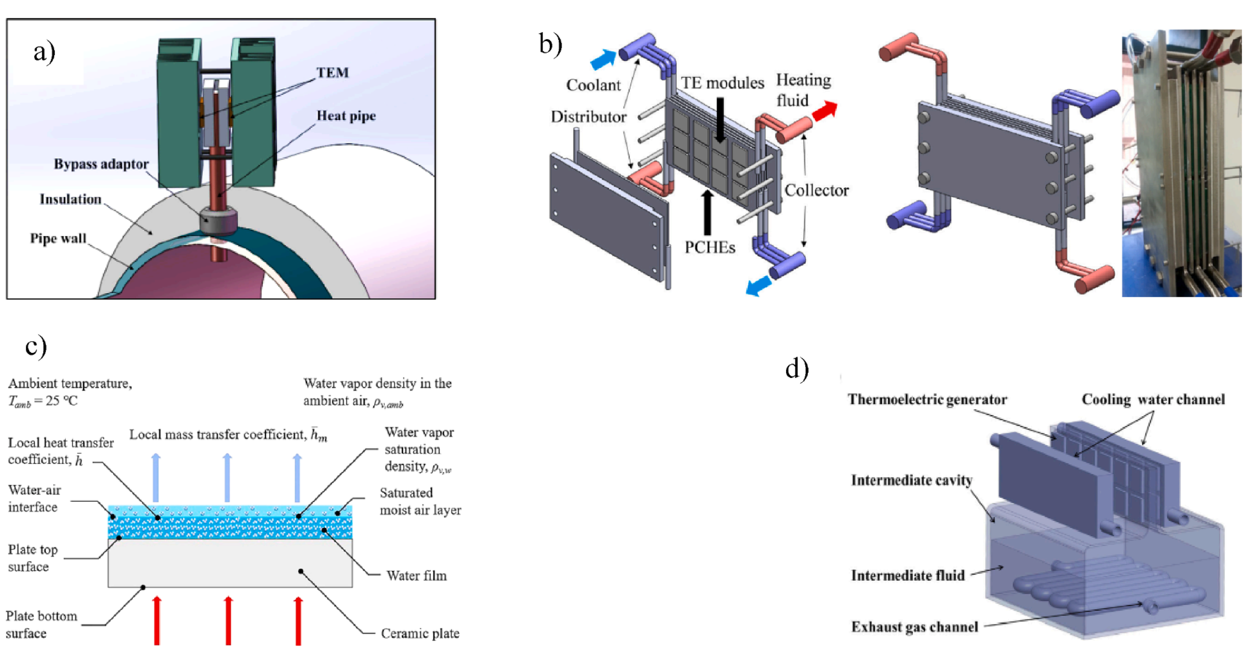

Fig. 7. Examples of heat exchangers used for thermoelectric generation: a) Chen et al. [77] b) W. Lee and J. Lee [79] c) Zheng et al. [82] d) Zhao et al. [83].

vehicle waste heat, solar energy, industrial waste heat, and so on. One way to tackle this problem is to use latent heat as the heat transfer method, which needs phase changing medium. The challenges one would face are the temperature range the system is used for and also the heat exchanger design. Y. Zhao et al. [83] investigated the performance of an intermediate fluid for vehicle exhaust waste heat recovery. As demonstrated in Fig. 7-d, the intermediate fluid absorbs heat from the exhaust channel passing through the bottom of the intermediate cavity, producing vaporized fluid which is condensed at the top of the cavity, where the TEG modules are placed. The cold side of the modules is cooled by a water channel. Together with a uniform temperature distribution, the results showed that compared to traditional systems, the peak output power and efficiency respectively increase by 32.6 and 14%, while the optimal TEG module area decreases by 73.8%.

Overall, it is evident that although using metal heat sinks may reduce the initial cost compared to other types, it is not the best choice one could have. Moreover, the application type has a vital role in the determination of heat exchangers' type; if the main objective is to keep a system reliable, compact, and with the least maintenance, heat pipes and phase change heat exchangers can be the better recommendation. However, if there is a need for heat dissipation with a high rate and/or there is an opportunity to use the dissipated heat in bottoming applications, active cooling systems with water or nanofluids as the working fluid may offer more benefits. It is worth noting that TEGs reject a great portion of the absorbed heat to the heat sink due to their low efficiency, and the utilization of such an amount of energy by bottoming subsystems can boost the overall performance of the system. G. Min and D. M. Rowe [84] proposed the concept of "symbiotic" generation as a solution for the low conversion efficiency of TEGs. In the proposed system, TEGs were used as an efficient heat exchanger to preheat combustion air with combustion exhaust gases. The considered system's main purpose was to produce hot fluid, and the electricity was a by-product of the system. In such a case, the low conversion efficiency problem of the TEGs does not matter. Obviously, the heat exchanger size and heat transfer rate should be considered in such a system, and as the authors indicated, the thermoelectric materials suitable for this application should have a high power factor ($\alpha^2\sigma$) and operate in a wide range of temperatures. Overall, choice and optimization of heat exchangers is a crucial part of design process for thermoelectric power generators and will be further discussed in the application section where the requirements of every application would be evident and evaluation of heat exchanger in the context of corresponding applications will be more relevant.

5.3. Electrical management

To take full advantage of the power generated by modules, it is essential to manage the output power, current, and voltage difference. According to the circuit theory and Eqs. (22) & (23) the maximum output power of a TEG is achieved when the load resistance equals the internal resistance of the module. However, that is not always the case as M. Liao et al. [85] showed; their results indicated that increasing the load resistance improves the performance of the TEG because when the electrical resistance of the system increases the heat transfer through the modules decalins, this in turn leads to an increment in temperature difference and efficiency of the TEG. However, this effect only improves the output power of the system to the point where the increment of voltage occurs at a higher rate compared to the decrement of current. Nevertheless, this effect would not have existed if constant temperatures were considered as the boundary conditions. In other words, if the heat transfer coefficient at both sides of the TEG are infinite, increasing the load resistance will not affect the effective temperature difference and maximum output power will exactly occur at the point where load resistance is equal to the internal resistance of the TEG. This study shows the importance of managing the electrical outputs of a TEG system. Also, it is sometimes necessary to apply DC-DC converters along with some techniques of maximum power point tracking (MPPT) to operate the system under maximum output power conditions. As stated before, the load resistance can be an effective parameter in the performance of a TE power generator; also, since the operating conditions for many applications of TEGs are not fully steady, applying an MPPT algorithm can ensure the operation of the system at maximum output power regardless of the thermal conditions of the system. Countless research has studied maximum power point tracking techniques. R. Rodriguez et al. [86] presented a new MPPT scheme for TEGs, named high-frequency injection. The experiments revealed that the new MPPT scheme has a response time of 2.4 ms, which is the fastest among existing techniques in the literature. Additionally, they found that the tracking efficiency of the proposed scheme reaches 99.73% and 98.7% under steady-state and transient conditions, respectively.

The modules' electrical array is another factor influencing both the solitary and overall outputs of TEGs. Although the above-mentioned techniques help TEG systems work at their best conditions, they cannot tell if there is a better electrical array of modules. That is, the techniques are applied once the modules and the whole system are arranged; therefore, designers must understand and employ the best electrical and thermal arrangements of TEMs, especially in large-scale generators. I. Cozar et al. [87] numerically analyzed the electrical and thermal configurations of thermoelectric modules (TEM) in a large-scale TEG system. The simulations indicated that pure series produces the maximum output power up to a certain number of TEMs. For a higher number, TEMs start to produce negative voltage due to temperature drop along the flow and notable amounts of joule heat, which overcame the Seebeck voltage produced in the downstream TEM. The authors suggested a mixed configuration that produces more power compared to the pure series for the same number of TEMs. In addition, it was found that there exists an optimum number of TEMs after which, the output power can be kept around that produced by the optimum number of TEMs at best. Therefore, it is important to consider the effect of electrical array of modules, especially when the thermodynamic conditions differ for a set of connected TEMs.

6. Applications

A careful survey of the thermoelectric generators' applications constitutes the main objective of present review. The fundamental and basic information provided up to this point will be essential in understanding and evaluating the feasibility of TEGs' applications. Moreover, in each of the following sections we have provided basic information about the requirements of each application and then assessed the effectiveness of designs in improving the performance of those applications, providing an in depth analysis and realistic prospective on applications of thermoelectric generators.

6.1. Waste heat recovery

Waste heat is defined as the unconsumed heat rejected from a thermal process. Waste heat mainly arises from two sources; (a) equipment inefficiencies and (b) thermodynamic limitations governing the process. Heat losses due to the inefficiencies must be prevented as much as possible; but, heat losses due to the thermodynamic limitations are inevitable and should be recovered and reused in another process. Being free and clean, waste heat is an attractive source of energy. Nowadays, waste heat from many processes is utilized to improve the efficiency of the processes; take preheating the combustion air by use of the exhaust gases as the most patently obvious example. The reutilization of waste heat in a system can considerably decline fuel consumption and consequently, CO_2 emissions, in turn, leading to improvements in the performance of the system. However, even for an optimized system, there would still be certain amounts of heat that cannot be consumed in the process. The challenge is to convert this waste heat into a useful type of energy [88,89]. Depending on its quantity and quality, waste heat can be utilized in different ways. To find the best option for waste heat recovery, E. Woolley et al. [90] introduced a systematic approach. They proposed a four-stage framework. First, the system of which the waste heat is discharged must be identified and then, the characteristics of both system and wasted heat. After that, technically suitable technologies for recovering the waste heat are determined, and at the end, considering economic and environmental aspects, the best technologies are selected. The framework is useful to adopt the best option for the system considering energy/CO_2 savings. There are different types of technologies to harvest and utilize the waste heat, which are employed for space heating, cooling, electricity generation, etc. In general, if there is an end-use for the waste heat in short distances, the low-grade heat is preferred to be used for heating and cooling purposes; otherwise, the best option is to convert the waste heat into electricity as it is a high-quality type of energy that can be conveniently stored, transported, and consumed[91].

Transportation and industries are the world's two significant energy-consuming sectors; both use fossil fuels as the primary energy source and discharge vast amounts of untapped heat into the environment [2]. The reutilization of such energy can alleviate fossil fuel resources depletion, CO_2 emissions, and global warming problems. Moreover, because waste heat is a free source of energy, the relatively low efficiency of TEGs will not be a problem while other features of them like compactness, scalability, and reliability can be of great value for these applications.

6.1.1. Industrial waste heat

Utilizing approximately 40% of the world's total delivered energy, the industrial sector is the second-largest global source of energy sector CO_2 emissions [1,2]. It is not easy to quantify the exact amount of industrial waste heat worldwide. However, according to a study by I. Johnson et al. [88], 20–50% of the energy consumed by the U.S. industry is released to the environment in the form of waste heat, and based on a 25 °C reference temperature, about 60% of waste heat losses are at temperatures below 230 °C. In another study, M. Papapetrou et al. [92] estimated that the total waste heat potential in EU is about 300 TWh/year of which 30% is at temperature level of 100–200 °C, 25% at 200–500 °C, and the remaining fraction mostly at temperature levels of 500–1000 °C. Accordingly, most of the waste heat is released at low to medium temperature levels and recovering this heat is challenging and economically less-attractive; on the other hand, most of the high-temperature waste heat sources, encounter other technical difficulties such as the presence of chemical constituents in carrying mediums or heat transfer mechanisms and environments challenging for recovery [88].

Different technologies can be applied to recover waste heat. S. Viklund and M. Johansson [91] investigated different options for recovering and reusing excess industrial heat from different sources in Gävleborg County. Evaluating the effect of each waste heat recovery option on global CO_2 emissions, they found that depending upon the technology, the recovery and reutilization of waste heat can impose positive or negative impacts on the environment. Consider a high-grade heat source applied for space heating; significant exergy destruction would occur in such cases. Therefore, it is important to consider the type of technology and utilize them in the most beneficial manner.

As it is the primary objective of the current section, the applicability of TEGs for industrial waste heat recovery will be explored. Thermoelectric devices are solid-state, compact, and need no maintenance. Such features make these devices a promising technology for waste heat recovery in limited spaces and toxic environments. Furthermore, compared to other technologies, TEGs are more compatible with different heat exchangers and heat transfer mechanisms and are capable of recovering wider temperature ranges. The only drawback of using TEGs is their low conversion efficiency; however, using a free source as waste heat overcasts this downside of thermoelectric devices.

Over the recent years, TEGs have been used in different waste heat recovery (WHR) systems and they can be classified into different categories; however, as there are different waste heat sources in the industrial sector and the most apparent advantage of thermoelectricity is its integration with different heat sources; here, the thermoelectric applications are categorized by the heat source types.

6.1.1.1. Flue gas waste heat recovery. Flue gases are the most available type of waste heat source for different technologies; despite the low heat transfer coefficient of the gaseous products, they are more likely to be recovered compared to other types. However, flue gas heat recovery has its own challenges; one is that the temperature of flue gases cannot be dropped below the dew point, and usually, these gases are discharged at high temperatures to be secured from condensation. Meanwhile, condensation is a process with high and dens energy release, which increases the quality and quantity of the recovered heat. Y. Zhao et al. [93] analyzed the characteristics of flue gas waste heat recovery from a natural gas boiler by TEGs. Applying an anticorrosion heat exchanger, they recovered the sensible and latent heat of the flue gas. Moreover, they evaluated the effect of humidification of the gas before entering the recovery system. The results showed that humidification of the flue gas at 120℃ improves the maximum output power by 15% and reduces the thermoelectric module area required for maximum power by 17.4%. They also showed that there is a humidification temperature maximizing the power density of the system. The interesting point is that although the humidification of flue gas decreases the TEG's hot side temperature the system performance improves thanks to the enhancements in the heat transfer rate. Furthermore, flue gas condensation causes the dissolution of NO_X and SO_X, making the discharged gas cleaner. Another challenge is the low conversion efficiency of thermoelectric generators, making other technologies with higher conversion efficiencies more favorable. As previously discussed, the solution could be a combination of heat recovery and power generation. M.F. Remely et al. [94] experimentally investigated this concept with HP-assisted TEGs. Two sets of heat pipes were installed on each side of a TEG unit, one set connects the cold side of the TEG to the cold duct, while the other set connects the hot side of the TEG to the hot duct, as shown in Fig. 8-a. The system is supposed to receive heat from the hot duct and transfer it to the cold one (like an air preheater), and simultaneously generate power from this heat transfer with the aid of thermoelectric generators. According to the experiments, a conversion efficiency of approximately 1–2.2% was achieved from an average temperature difference of 20-30℃ and hot side temperatures of 60-110℃. Moreover, the system's combined heat and power efficiency was 42–54%. Not only were the results far better than a stand-alone TEG system, but also the system design was practically remarkable. The fact that the system is entirely passive (using TEG and HP) makes it more reliable than other technologies. Furthermore, the authors concluded that the overall system can still be considered economically viable as the system's energy input is free (waste heat). However, to have a better understanding of the system, detailed economic analysis and consideration of parasitic losses like pressure drops are desired.

Often, TEGs are deemed as low-power systems, but they can be utilized to generate several tens of kilowatts, especially in industrial waste heat recovery. Apparently, the higher the power generation capacity of a system is, the more critical the heat exchanger and thermal and electrical configurations of that system are. R. Elankovan et al. [95] evaluated different thermal configurations and two types of heat exchangers for thermoelectric generators recovering waste heat from 2- and 50-meter-long ducts. They optimized the hot side fins and studied the effect of three configurations for these ducts while comparing them with a reference case in which the hot side temperature is assumed constant. The findings showed that the configuration with cold heat sink exposed to the ambient is of better performance in terms of output power and conversion efficiency. The maximum output power for a practical 25 W/m^2K heat transfer coefficient was 11.3 and 172.3 kW for 2 and 50 m ducts, which are approximately 1.7% and 40.2% lower than the

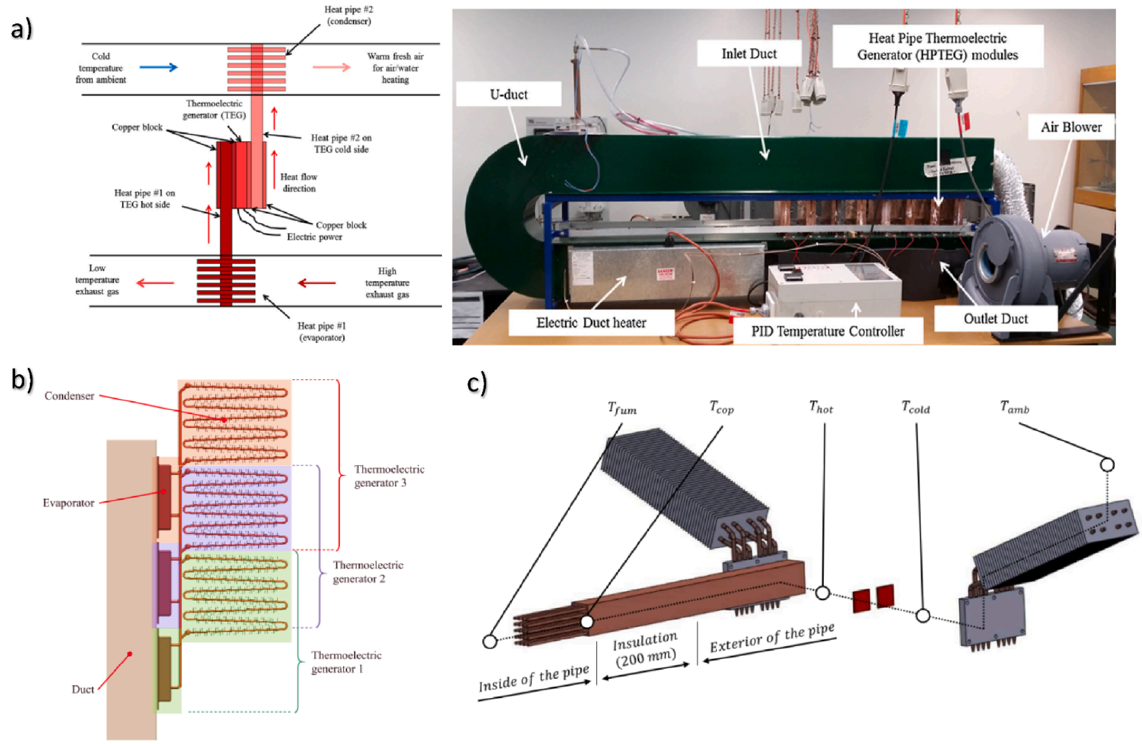

Fig. 8. Systems of waste heat recovery from flue gas: a) M.F. Remely et al. [94], b) M. Araiz et al. [96], and c) A. Casi et al. [97].

reference case, respectively. The deviation from the reference case was seen to grow with increasing length due to higher temperature drops along the hot duct. Moreover, because of the increase in the cold side duct temperature, the deviation increases if another configuration (counter- or parallel-flow) is considered. The authors concluded that for a 50 m duct length, the cold sink exposed to the ambient configuration is economical, while the counter-flow configuration is recommended for regeneration purposes. The study is a salient example for the application of TEGs in high power waste heat recovery and exhibition of the advantages of different heat exchangers under different conditions. However, for an even more accurate evaluation, heat losses to the surroundings, pressure losses in ducts, and auxiliary power consumptions should be considered. Moreover, thermoelectric generators have a reputation that they are not commercially feasible and should be used for most applications; thus, the economic analysis for thermoelectric generators is usually passed up. In an arguably perfect study, M. Araiz et al. [96] analyzed a commercial TEG's economic aspect and output power for waste heat recovery. The heat source was a 30 m long duct with a temperature of 230°C. The proposed system was composed of a fin dissipater, as the hot side heat exchanger, and a two-phase thermosiphon as the cold side heat exchanger, assembling an entirely passive system, as illustrated in Fig. 8-b. Considering different parameters, the proposed system was optimized from output power and economic viewpoints. The maximum net output power was obtained to be 45838 W, with an installation cost of 11.60 €/W (10.63 €/W for the case with minimum installation cost). Furthermore, to draw comparisons, they used the Levelized Cost of Electricity (LCOE), substantiating that the proposed system is economically competitive with other renewable systems. Although these theoretical studies indicate the great potential of TEGs for recovering the waste heat from hot gas ducts, there is a need for more practical studies to prove the real feasibility of such systems. Recently, A. Casi et al. [97] conducted a comprehensive study demonstrating the practicality of TEG for waste heat recovery from hot fumes in rockwool manufacturing plant. As shown in Fig. 8-c, the optimized configuration was a fully passive system using four TEMs with a zT value of 0.73. After performing a 30-day test, the authors concluded that using the full capacity of the system with 1152 TEMs, the proposed configuration would be able to produce 30.8 MWh/year with 3.52 kW of average total output power and an efficiency of 2.89%. This study shows the high potential of thermoelectric generation for flue gas waste heat recovery even with a zT value below 1. Overall, going forward with more advances in the thermoelectric materials and practical utilization of the mentioned studies and ideas, TEGs are highly likely to be the first-choice technology for these applications.

6.1.1.2. Waste heat recovery from products of an industrial process. A waste heat source that is mostly untapped is the heat inside the products of a process. The technical difficulties of recovering such type of waste heat are space limitation, the transient behavior of the source, radiative heat transfer, and so on. Scalability and compactness are the characteristics of TEGs that make them suitable for heat recovery from these types of sources. The metal casting process is one of the processes that have become more convenient for waste heat recovery after the improvement of thermoelectric generators. T. Kuroki et al. [98] described the performance and durability of an implemented 10-kW-class grid-connected TEG system for a continuous steel casting line. As shown in Fig. 9-a, the TEG system consisted of 896 TEMs (56 TEG units), a blackened copper block as the heat collector at the hot side, and a water circulating copper block as heat dissipater at the cold side. During the experiments, for slab temperatures of approximately 1100–1200 K (hot side temperature of ∼ 475 K), an output power of 9.1 kW was obtained. It was estimated that if it were not for the broken or deteriorated units, the system would have shown an output power of 10.1 kW. Some of the units deteriorated after a 400-hour working time, and the reason was expressed to be the junction quality between the electrode material and the thermoelectric element. The area occupied by the TEG was only 8 m^2 (4*2); this is one of the reasons why TEGs are suitable for these applications; that is, implementing this type of systems does not demand significant design changes. In a detailed theoretical study, S. Ghosh et al. [99] assessed the radiative heat recovery from hot steel casting slabs (1200 K) by TEGs. After optimizing the geometries of the generator, they estimated a power density of ∼1.5 kW/m^2 and a system

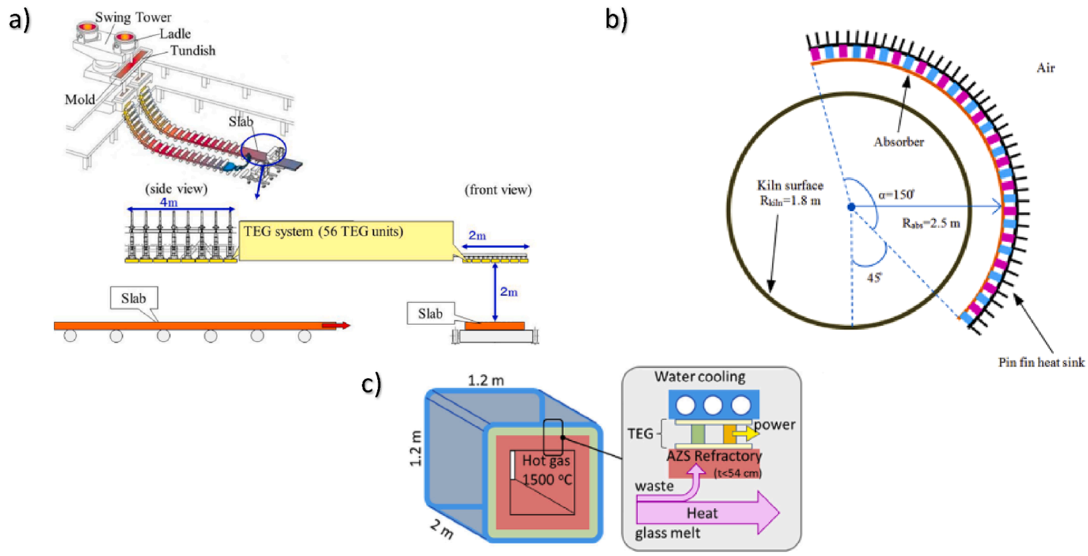

Fig. 9. Schematic views of a TEG system for waste heat recovery from: a) steel casting line, T. Kuroki et al. [98], b) rotary cement kilns, M. Mirhosseini et al. [101], and c) fire port of a furnace in glass melting process, K. Yazawa et al. [102].

efficiency of ~4.6% at a 2 m distance from the slabs. Moreover, based on the optimized system, they estimated a material cost at ~0.2 $/W or lower. The proposed model is realistic in terms of considering the parasitic losses and temperature-dependent properties, and shows the potential of TEGs for radiative heat recovery. However, an array of TEMs would behave differently compared to a single TEM. Also, the cost estimation considers merely the TE material costs, while other costs are also substantial, like the micro-channel heat exchanger, which is considered as the cold side heat exchanger. Silicon casting is another potential radiative source for thermoelectric waste heat recovery. I. Savani et al. [100] investigated a TEG's performance in the transient environment of a silicon production plant via a mathematical model and on-site experiments. The proposed system composed of 36 TEMs installed in a 0.7 m horizontal distance from casting ladles, an aluminum block as the heat collector, and another aluminum block with circulating water as the cold side heat exchanger. The heat source had a transient behavior repeating in two-hour periods. After optimization, they obtained a peak power density of 1971 W/m^2, while the average power density during one casting period was as low as 146 W/m^2. Furthermore, they showed that there is an optimum fractional area (fill factor) corresponding to the cooling capacity of the system, concluding that increasing the cooling capacity may be economical up to a point after which enhancing the cooling capacity does not contribute to the power enhancement insofar as to justify the fractional area increment. Considering the above reviewed studies, it is fair to express that TEGs have a prominent potential to be applied for this type of energy source even without the anticipated improvement of TE materials. However, such systems' economic feasibility has not been adequately assessed yet, and there is plenty of room for studies and experiments with high-temperature materials and combined systems.

Cement kilns are another source of radiative waste heat with relatively high surface temperatures. Thermoelectric generators can be considered as a potential technology to recover this waste heat. Because of the shell's rotation, non-uniform added weight by the system, and some other reasons affecting the performance of the process, it is not efficient to make direct contact between the source and the recovery heat exchanger although having a high surface temperature makes it an attractive source for WHR systems. On the other hand, TEGs are light in weight and scalable, and there is an opportunity to implement an entirely passive system with minor effects on the performance of the process. M. Mirhosseini et al. [103] evaluated and optimized a TEG system for waste heat recovery from rotary cement kilns. They used an arc-shaped absorber concentric with the rotary shell (to minimize the system's effect on the process) and with a distance of 0.7 m from the shell's surface as represented in Fig. 9-b. The absorber temperature was estimated to be within a range of approximately 550 ~ 570 K, and the TE material was chosen considering the temperatures. They studied the effect of three different pin–fin heat exchangers and different fill factors on the output power and system cost. According to the results, a minimum cost per power of 17.40 $/W with a power density of 99.19 W/m^2 was obtainable with staggered pin–fin heat exchangers and a 0.1 thermoelectric fill factor. Also, the economic analysis revealed that the heat sink plays the role of the dominant component in the system costs. This indicates the role of different components in economic analysis and that the thermoelectric material price could become plausible with lower fill factors, knowing that the heat exchanger they have used is relatively inexpensive.

6.1.1.3. Other unconventional heat sources for TEGs in industry. Moreover, in an exemplary study, K. Yazawa et al. [102] investigated the performance of TEGs in waste heat recovery from the glass melting process. By evaluating different possible waste heat sources and sinks in the glass melting process and suitable TE materials, they used segmented thermoelectric materials to recover waste heat from fire ports of the furnace with a water-cooling heat sink as demonstrated in Fig. 9-c. The thermoelectric system was set to replace a part of the fire port wall thickness such that the overall thermal resistance of the wall would not change. Also, fill factor and leg length of TEMs were optimized to produce maximum output power with minimum system costs. In accordance with the results, the designed TEG can generate 55.6 kW of electricity from a 500 ton/day (5.8 kg/s) glass production system at an additional cost of $ 1–2/W. Furthermore, a comparison between the proposed system and other technologies was drawn, indicating the competitiveness of the system with a much better form factor. According to the authors' conclusion, the low cost of the system was because of the high temperature and exergy of the heat source. Although they have used simplifying assumptions for the evaluations, such as the constant material properties, the study represents the potential of thermoelectric waste heat recovery from unconventional sources without any impacts on the process and major changes in the system design. Moreover, TEGs are flexible towards using different types of sources. M. Ge et al. [104] proposed the interesting idea of waste cold recovery during the gasification process of liquefied natural gas. Designing a novel air-heated vaporizer with tubular thermoelectric generator, they were able to recover the wasted energy by an efficiency of 1.57–2.12%. Later in another study M. Ge et al. [105] experimentally assessed the applicability of this idea for waste cold recovery from vaporization of nitrogen with commercial TEMs and flat plate heat sinks. The results showed that the effective temperature difference was limited, which led to a very low conversion efficiency and limited output power. Nevertheless, the idea of recovering such a wasted energy has a great potential and as the authors concluded, excellent performance of cryogenic liquid cold energy power generation can be obtained by improving the hot side heat exchanger and thermoelectric materials.

6.1.2. Vehicle exhaust waste heat

Transportation accounts for 37% of CO_2 emissions from end-use sectors and on road transportation is responsible for more than 15% of total energy-related CO_2 emissions today [1,2]. According to IEA[1], a huge shift toward electric mobility is necessary in the near future and therefore the vehicle exhaust recovery might be of less importance. Nevertheless, even in the best-case scenario, still, 75% of transportation would be reliant on fossil fuels by 2030. Additionally, there is a rich literature and useful information in vehicle exhaust recovery in terms of system design and heat transfer optimization, which can also be applied to other fields of thermoelectric power generation. Accordingly, it is not absurd to review TEG vehicle exhaust recovery applications. Generally, about a third of fuel energy in internal combustion engines (ICEs) is lost to the atmosphere through exhaust gases. The wasted heat with a temperature within the range of approximately 400–1000 k could be used to generate electricity and increase the engine's thermal efficiency while decreasing the fuel consumption and CO_2 emissions. However, the conversion of such waste heat into electricity faces several technical challenges like space limitation, transient nature of exhaust flow, added weight, added back pressure to the exhaust system, complexity, maintenance need, and etc. Having said that, it is difficult to produce an overall positive amount of energy at an acceptable cost. Furthermore, even with an efficient heat exchanger, the conversion efficiency of WHR systems used for vehicle exhaust would be low due to the characteristics of vehicle exhaust flow. Nevertheless, considering the vastness of the transport industry and its energy consumption, even a 2–5% conversion efficiency would be significant for these systems. There are different techniques on waste heat recovery of exhaust gases, encompassing thermoelectric generators (also called automobile thermoelectric generators (ATEG)), organic Rankine cycle (ORC), turbocharger technology, and so on [106]. E. Hervas-Blasco et al. [107] investigated the fuel-saving potentials in a CNG-powertrain obtainable from kinetic and exhaust gases waste heat recoveries. The recovery system for waste heat in the exhaust system was realized through cascading a TEG and a turbogenerator. The authors deduced that even though the main source of lost energy in a vehicle is the exhaust system, any of the existing technologies do not offer the potential to recover the wasted energy in a way that affects the overall performance of a vehicle. Therefore, a combination of these technologies is needed to achieve an impactful improvement. Accordingly, by using a combination, they obtained a 7.5% fuel saving during an ACEA driving cycle (representing heavy-duty vehicles driving cycle in Europe).

Despite the low conversion efficiency, TEGs have advantages such as lightweight, solid-state operation, almost no maintenance requirement, relatively high reliability, making them one of the promising technologies in vehicle exhaust recovery. Over the last decade, numerous research has been carried out on the same subject, all aiming to get a better performance out of a TEG system by optimizing heat exchangers (more heat transfer and less pressure drop), assessing different thermal and electrical configurations, evaluating the transient flow characteristics effect, and so on. To have a clear and overall understanding of TEGs applicability in vehicle exhaust waste heat recovery, Table. 1 represents a summary of the state-of-art in the past few years with the essential characteristics of systems as well as the obtained results. Some of the systems mentioned in Table. 1 will be discussed further.

Surveying through the literature, one can see that there is no general way to determine the impact of a TEG system on a vehicle although one can rate TEG's solo performance by output power and conversion efficiency. However, to assess the performance of a vehicle exhaust TEG system, its overall effect on vehicle performance should be considered. An important purpose of introducing the TEG to vehicles is lowering their fuel consumption; thus, the fuel consumption improvement can be a logical performance determining parameter. As well as that, another effective way to assess the TEG system performance is to evaluate the net power and the efficiency of the whole system. There are three main power-losing potentials when integrating the TEG system into a vehicle. (a) The pumping power needed to overcome the pressure loss made by the TEG hot side heat exchanger, which if becomes more than several tens of millibars, can lead to incomplete combustion and declined engine efficiency. (b) The added weight by the system, which is insignificant in most cases. And (c) the added load of pumping and cooling power to the engine cooling system (the engine cooling system usually provides the cooling of the TEG system). Therefore, these parameters should be considered in any realistic evaluations.

6.1.2.1. Challenges of vehicle exhaust recovery. First and foremost, engine working condition is vital as it influences the intensity of the transient nature of the flow, range of operating temperature, and mass flow rate of the exhausts. In other words, the engine working condition designates the amount of recoverable heat and its stability. Although most researchers assumed steady-state conditions for the exhaust flow, it is not a realistic point of view unless the whole driving process takes place in the extra-urban areas in which one can take the steady conditions somehow realistic. By considering the steady-state conditions, the performance of TEGs may be overestimated. A. Massaguer et al. [120] analyzed the behavior of a TEG system (Fig. 10-a) under four steady-state operating conditions plus the transient New European Driving Cycle (NEDC). Using the same system for transient and steady conditions, they found a significant reduction in the output power under transient conditions. Also, they found a 24 times better energy generation using a low-temperature TE material and a better heat exchanger for the transient operation with a by-pass flow option to prevent the temperature from rising above the module restrictions. Moreover, this study showed that the engine efficiency and output power are decreased by adding the TEG system to the vehicle, and this deterioration grows with the exhaust flow rate. It was concluded that the reason is the back pressure caused by the TEG heat exchanger; thus, it is necessary to consider this effect when integrating TEGs into an exhaust recovery system. Furthermore, R. Wang et al. [124] proposed a numerical model analyzing the performance of a TEG system (Fig. 10-c) for a mild-hybrid vehicle under two driving cycles (Urban Dynamometer Driving Schedule, UDDS, and Highway Fuel Economy Test Cycle, HFETC). The results indicated an improvement of the fuel economy by 3.64% and 2.17% under the UDDS and HWFET cycles, respectively. In another mentionable study, A. Nour Eddine et al. [125] experimentally investigated the effect of engine exhaust gas pulsations on a TEG performance. They found that the pulsation of gas flow due to the engine piston's movement and the inlet and exhaust valves of the cylinder head are responsible for a 7–20% improvement compared to a fully steady (no pulsating) flow. Moreover, they found that the engine exhaust gas composition contributes to an improvement of up to 12% compared to air with the same flow characteristics; therefore, it is essential to consider these exhaust flow traits in test rigs simulating engine exhaust with hot air flow. More examples could be found in Table. 1. Overall, the vehicle type and the driving cycle are determinant factors, and it seems that heavy-duty vehicles with extra-urban driving cycles are more likely to effectively host TEG systems, not that other types are not suitable for the thermoelectric generation. However, with in the advent of new TE materials with higher zT values, TEGs will become more beneficial to be used in every type of vehicles.

Table 1
Characterization of selected recent ATEG systems.

Method	Max Output Power, Max Efficiency	Cold Side (temperature)	Hot Side (temperature)	Evaluated Conditions	Important Outcomes	Ref
Experimental assessment of a compact TEG (12 TEMs) system for a hybrid electric engine (a 2-L four-stroke four-cylinder gasoline engine)	P: 118 W η : 2.1 %	Four flat plate channels with low-aspect-ratio plate fins cooled by engine cooling system (353 K)	Rectangular flat plate channel with plate-fin structures and two perforated plates embedded for flow straightening (NA (924 K gas temperature)	Nine steady-state engine conditions, pressure drop and the factors causing it, temperature distribution, conversion efficiency, heat transfer, voltage-current and power-load relations	68.0%–77.3% of the total pressure drop across the current TEG was due to the two perforated plates, maximum pressure drop was ~ 1250 pa	[108]
Numerical simulation and optimization of a TEG system for a light-duty 4-cylinder gasoline engine with 72 high-temperature TEMs	P : 267 W η : 2.84 %	Flat plate heat exchanger cooled by engine cooling system running in counter to exhaust flow (91℃)	Rectangular channel with parallel plate fins (two different materials and corresponding optimum geometries) (573℃)	Output power and efficiency, pressure drop, parasitic power losses, optimum HE geometry and material, optimum TEM distribution, fuel efficiency increase, highway driving	Silicon carbide HE material results in a 25% better TEG performance than steel HE, optimized TEG yields 2.5% (max) fuel efficiency increase during the highway driving conditions	[109]
Experimental and a numerical optimization of direct contact TEG with 40 TEMs for a six-cylinder diesel engine	P : 43 W η : 2.0 %	Four aluminum channels fabricated with ten openings for placement of TEMs with 50–50% water–ethylene glycol mixture(298 K)	A rectangular aluminum exhaust gas channel fabricated with ten openings with flanges on each side for the placement of 40 TEMs (~370 K)	Output power and efficiency, pressure drop, effect of clearance, 12 steady engine conditions, voltage-power-current curves	If the clearance between the TEMs and hot and cold side channels be removed, the output power further improves by 132%(up to 100 W), and pressure drop decreases by 23%	[71]
Experimental performance study of a hexagonal shape TEG system with 18 TEMs for a passenger vehicle (gasoline 4-cylinder engine)	P : 98.8 W η : 2.6 %	Six rectangular channels through which the engine coolant flowed in counter with gas flow direction, clamped and coated with graphite layers (353 K)	hexagonal exhaust gas channel with finned structures fabricated on the inner surface and a cone structure that induced the gas flow into the internal finned structures (401–659 K)	Output power, efficiency, pressure drop, eight steady engine conditions, temperature distribution, heat recovery efficiency, reasons causing pressure drop	Pressure drop across the TEG was maintained below ~ 2.1 kPa with 15.6–36.7% of it being caused by the finned structures and the remaining by change in flow direction, 18–32.9% heat recovery efficiency	[110]
Parametric study and optimization of TEG system on two types of freight vehicles(3.5 & 40 tons) with different TE materials and different heat exchanger geometries	P_{net} : 153 & 739 W η : 4.45 & 8.15 %	cooling water flowing through a duct of rectangular channel in the same direction with gas flows (~385 & ~410 K)	Rectangular channel with two different fin structures: plain fins, offset strip fins and two different external geometries (480–515 & 615–660 K)	Net output power, efficiency, two different vehicles and one steady driving condition for each, optimum geometry of heat exchangers and TE legs height, pressure drop, temperature distribution	In terms of net power, plain fins provide better performance than offset strip fins due to less pressure drop; the best recovery efficiency found is approximately 2%, which is low but still considerable	[111]
Numerical evaluation of heat exchanger inner topology influence on TEG system	P : ~210 W η : NA	Independent cooling system containing a pump, a radiator, and a fan with water as coolant and in counter direction of gas flow (~330–350 K)	Rectangular channel with three different inner topologies: smooth flat, with cylindrical grooves and with random distribution of inserted fins (~380–460 K)	Output power, pressure drop, heat exchanger inner topology and height (6 types of HEs), temperature distribution, TEMs distribution, overall performance of TEG system	Properly decreasing the height of HE with cylindrical grooves and inserting few fins to keep flow uniform yields a high power generation with an acceptable pressure loss, there is an optimal module area	[112]
Experimental investigation of 40 customized TEMs performance on a six-cylinder diesel engine	P : 119.1 W η : 2.8 %	Rectangular channels with plain finned structures, clamping, and thermal pads are used (~293 K)	Rectangular stainless steel channel with plain fins and a perforated plate placed upstream of channel to straighten the flow, a thermal grease applied (~473 K)	Output power, efficiency, pressure drop, 12 steady engine conditions, V-I (voltage-current) and P-R (power-load resistance) curves	Pressure drop due to TEG system installation is below 1.46 kPa under all experimental conditions	[113]
Experimental investigation of porous medium effect on 30 customized TEMs performance for a six-cylinder diesel engine	P : 92.3 W η : 2.83 %	Rectangular channels with plain finned structures, clamping and graphite films used as thermal interface materials (~300 K)	Rectangular channel with plain fins and a plate-type porous medium placed upstream of the channel to straighten the flow, graphite films used (NA)	Output power, efficiency, five different porosity ranges, pressure drop, heat recovery efficiency, three engine operating conditions, V-I and P-R curves	Installation of a perforated plate improved the power output and energy conversion efficiency by 44.5 & 10.1%, respectively; there is minimum porosity beyond which pressure losses exceed 3 kPa	[114]
Numerical study with experimental validation of a TEG system (80 TEMs) on passenger vehicles (& comparison with an electric turbo-generator)	P : 270 W η : NA	Circulating engine water in exchanger blocks (~50℃)	NA	Two engine types(CI & SI), power generation, fuel economy, under full load and typical driving cycles, backpressure, by-passing strategy,	Up to 0.56 & 1.09% of fuel savings for CI & SI engines, SI engine showed a better potential in typical driving cycles, TEG shows a better overall performance than eTG	[115]
Experimental study simulating the automobile exhaust with 8 TEMs	P : ~19 W η : ~1.2 %	Rectangular channels with water as coolant (25 ~ 35℃)	Rectangular channels filled with porous copper foam (modules clamped) (~90℃)	Output power, heat transfer, pressure drop, HE filling ratio, flow rate, foam metal pore density	Foam metal filling increases heat transfer and output power by four and two times and there exists a	[116]

(continued on next page)

Table 1 (*continued*)

Method	Max Output Power, Max Efficiency	Cold Side (temperature)	Hot Side (temperature)	Evaluated Conditions	Important Outcomes	Ref
					limit of filling due to pressure drops (a min of ~ 6kpa)	
Mathematical modeling of TEG system for optimization study	P : ~160 W η : ~4 %	Rectangular channel with circulating coolant in co– & counter-flow configurations (water (~350 K) & air(300–450 K))	Rectangular channel with hot air flow simulating the hot exhaust gases (~500–670 K)	Output power, temperature distribution along the channel, flow configuration, coolant type, optimum module area, mass flow rate	Temperature gradient along the flow direction results in an optimum module area, overall co-flow leads to a better TEG performance with less module area	[117]
Numerical performance assessment (both component & system level) and optimization of 108 TEMs with segmented legs($CoSb_3$ & Bi_2Te_3)	P : 84.3 W η : ~9.6%	A constant heat transfer coefficient representing the cooling effect is defined (~335 K)	Hexagonal heat exchanger with an air deflector in the center to constrain the exhaust gas to flow along the inner wall of the exhaust channel (425–525 K)	Output power, length ratio and cross-sectional area, temperature distribution, heat transfer, each material percentage in p- & n-type TE legs, conversion efficiency, component and system levels, current–voltage-power	Optimum percentage of $CoSb_3$ is slightly different in p- & n-type(23 &26%) legs, maximum output power is improved by 13.8% & 6.8 % in device and system levels respectively	[65]
Numerical performance evaluation of an off-road car (diesel engine) TEG system with 240 TEMs	P: 618 W P_{net}:133.46 W η : 0.68%	Strip-shaped coolant channels mounted in tandem on the TEG and connected in parallel to the engine cooling system (~365 K)	Four flat plate heat exchangers: once with scattered fins inserted inside and once with symmetrical and staggered dimpled surfaces(485–505 K)	Output power, power losses: pressure drop, TEG weight & pumping power, efficiency, temperature distribution, two heat exchangers types	Pressure drop in the ATEG with dimpled surface to that with inserted fins was reduced by 20.57%, net power output was increased by 173.60% main reason being pressure drop decrease	[118]
Mathematical modeling of an intermediate fluid heat exchanger compared to traditional TEG systems for automobile exhaust system	P : 183.0 W η : 5.38%	Flat plate water circulating channels (90 ℃)	An intermediate fluid absorbs heat from exhaust pipe, evaporates and then loses heat to the TEMs by condensing on the upper side of intermediate cavity (230 ℃)	Output power, heat exchanger area, optimum TE module area, heat transfer, efficiency, temperature distribution, power density	For the same heat exchange area on the exhaust side, the peak output power increased by 32.6% compared to the traditional TEG system, optimal thermoelectric module area is reduced by 73.8%	[83]
Numerical simulation with experimental validation, module area and hot side heat exchanger internal shape optimization for a light-duty diesel engine	P: 106.2 W P_{net}:24.2 W η : NA	Water circulating channels (NA)	Rectangular channel with different internal shapes (300℃)	Output power, optimal number of TEMs in columns and rows, internal shape of hot side HE, pressure drop and power losses, temperature distribution, nine engine operating points	Power loss due to backpressure leads to a negative net power in low-speed engine points, TEG system works better in higher engine speeds with a simpler internal heat exchanger geometry	[119]
Experimental and numerical investigation of transient and steady behavior of 12 TEMs for a mid-sized gasoline engine	P: 111.22 W η : NA	Aluminum rectangular channels with circulating water as coolant (different from engine cooling system) (40–95 ℃)	Two types: a copper HE containing six round holes & two aluminum finned HEs joined together (with a bypass channel for Bi_2Te_3 system) (50–350 ℃)	Output power, backpressure and engine efficiency, fuel consumption, four steady-state regimes and a transient driving cycle, two TE materials, two heat exchangers, temperature distribution	Backpressure has a significant effect on engine efficiency and fuel consumption, TEG system performance decreases in transient conditions but can be enhanced by using lower temperature TEMs and a temperature control	[120]
Steady-state engine experiment and a 1D transient cycle	Estimated P: ~1100 W NA	Attached to the engine coolant pipes (a mixture of ethylene glycol and water) (~298 K)	Attached to the engine exhaust channel (700 ~ 870 K)	Four regulatory test drive cycles with 40 and 60 TEMs	The energy gain by TEG system:1.71% ~1.92%	[121]
Experimental study on a six-cylinder diesel engine with 40 TEMs	P: 125.7 W η : 3.0 %	Rectangular coolers finned inside(circulating water as coolant) with thermal pads(283, 293 K)	Rectangular exhaust channel pipe with thermal grease(TEMs clamped between HEs)(473 K max)	Three engine rotation speeds and coolant flow rates, two coolant temperatures, degradation in TEM performance at high temperatures	A 10 K decrease in coolant temperature improves P_{out} by 1.5 ~ 33.7% and η by 34.8 ~ 57.1%, coolant flow rate change improves P_{out} by 6.8 ~ 8.5%	[122]
MATLAB/Simulink-based approach on a hybrid electric bus under a realistic urban drive-cycle with 96 TEMs (Skutterudites & SiGe)	Average: P: 1.97& 1.66 kW η : 6.99 & 5%	Each TEM is provided with a simple aluminum heatsink (Assuming a cold side temperature of 308 K)	Simple rectangular channel (445 K min, 805 K max, with the average temperature being 585 K)	TEG system optimum placement, two kind of TE materials, back pressure, power conditioning effect, fuel economy, CO_2 emission	Skutterudites show a better performance than SiGe TEMs(in all the terms that evaluated), a resultant fuel saving of 7.2 & 6.5%, 7.58 & 6.82% reduction in CO_2 emissions	[123]
Simulation study on a mild hybrid vehicle with 20 TEMs(8 PbTe & 12 quinary alloys)	P_{net}: 225 W η: NA	Circulating engine coolant in rectangular aluminum channels (TEMs are clamped)	Rectangular duct with fins inside (TEMs are arranged with respect to temperature decries along the duct)	Two driving cycles, parasitic losses of TEG system (back pressure, weight, coolant pumping), fuel economy, CO_2 emission	Fuel economy improved by 3.64 & 2.17%, power losses due to TEG system integration is 30% of TEG output power (main source being TEG weight)	[124]

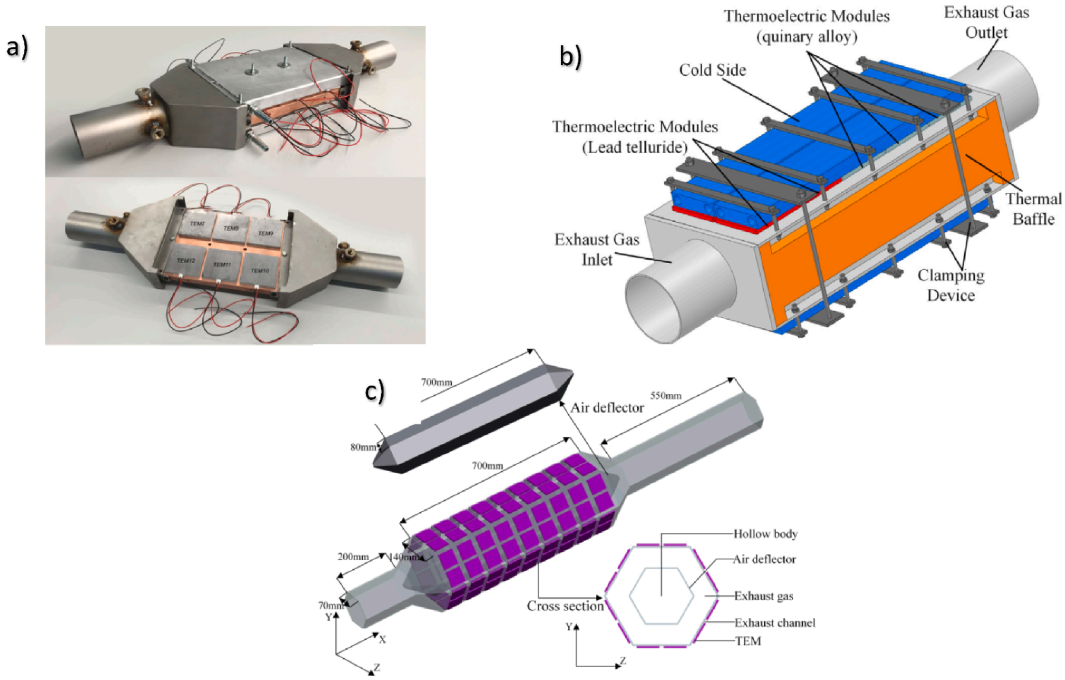

Fig. 10. Vehicle exhaust TEG recovery systems used by a) A. Massaguer et al. [120], b) R. Wang et al. [124], and c) G. Shu et al. [126].

The next important step after understanding the flow's characteristics is to select the best TE material to operate under such conditions. As discussed earlier, TE materials have a range of optimum temperature, and sometimes, not just one TE fits into the range of exhaust gas temperature; therefore, some techniques have been applied to improve the system's performance. G. Shu et al. [126] studied different configurations of single and segmented TEGs. Using two layers for each p- and n-type legs, a mid-temperature skutterudite and low-temperature Bi_2Te_3, the segmented TEG could perform better within a broader range of temperature. The authors showed that using a TEG system (Fig. 10-d) with only segmented legs produces 13.4% more output power compared to a TEG system with only Bi_2Te_3 legs. They also discovered that the employment of a configuration with both types (segmented TEMs upstream and single material TEMs downstream) and consideration of the temperature drop along the heat exchanger increases the output power by 30.8%. X. Ma et al. [65], with a similar system, investigated different ratios of $CoSb_3$ and Bi_2Te_3 in both p- and n-type legs. The study showed that by optimizing the ratios, the output power improves further by a factor of 6.8% compared to the best configuration from the above-mentioned study. Sometimes in lighter vehicles, the temperature rises above a particular TE material's limits (take Bi_2Te_3 as an example) just at the highest engine speeds and loads, occurring infrequently. In such cases, a bypass flow during the high engine speeds can assure that the temperature of hot side remains within the limited range. Moreover, having a by-pass option reduces the back-pressure effect at high flow rates. P. Fernández-Yáñez et al. [115] conducted a study on a TEG's performance in the exhaust systems of spark-ignition and compression-ignition engines and compared it with an electric turbo-generator (eTG). According to the results of both engines without by-passing, the net power is negative at most of the engines operating conditions due to backpressure effect. Also, the results indicated that by-passing could significantly reduce the power losses due to the backpressure effect while ensuring a safe operation in broader engine operating points. Furthermore, the authors deduced that TEGs are more suitable for lower engine operating points (common driving conditions), while eTGs would be a better option for higher operating points (extra-urban engine conditions). However, other solutions have been proposed for this challenge; a good example is heat exchangers with a phase-changing approach, which can introduce a constant temperature even under transient heat sources like exhaust gases.

Next challenge is the optimization of heat exchanger under the operating conditions to obtain the best heat transfer while generating the least pressure drop; in addition to this, there is an optimum TE module area to be found. Researchers' primary focus on the exhaust TEG field has been to find the optimum heat exchanger and module area. There is a consensus that a water-cooling heat exchanger may be the best option for the cold side of ATEG; however, other types of heat exchangers have been examined in the literature. On the other hand, for the hot side of a TEG, there are plenty of different concepts, mostly concentrating on the geometry of the heat exchanger and heat transfer mechanism. There are different examples of heat exchanger optimization articles in Table. 1, and in general, it is not easy to choose the best heat exchanger for the systems are different from one another. However, there are clear advantages for applying some of the proposed ideas. Regardless of the inner shape, rectangular flat-plate channels are the most common heat exchangers because of simple geometry and easy integration with TEGs and cooling channels on the vehicle. Y. Wang et al. [112] evaluated the influence of the inner geometry of rectangular heat exchangers on the performance of ATEGs. Using four thermally parallel heat exchangers with different inner shapes, as shown in Fig. 11-a, they found that employing heat exchangers with dimpled surfaces slightly improves the system's temperature difference and output power while significantly decreasing the pressure drop in the system. These improvements led to a 173.60% increase in the system's net power compared to the system with inserted fins. In another study, T. Kim et al. [127] considered the concept of direct contact TEG to surmount the contact thermal resistance. They proposed a heat exchanger that exposes the modules directly to the exhaust and coolant flows (see Fig. 11-b). They observed a maximum output power of 43 W and a maximum conversion efficiency of 2.0% in their experiments. Moreover, in a numerical assessment, they introduced a flush-mounting configuration that successfully decreased the pressure drop by 23%, leading to a 132 % improvement in the output power compared to experiments. Although the idea is exciting, to fully understand the effect of the contact thermal resistance removal, there is a need for comparison with conventional models and further investigations regarding the modules' health and the

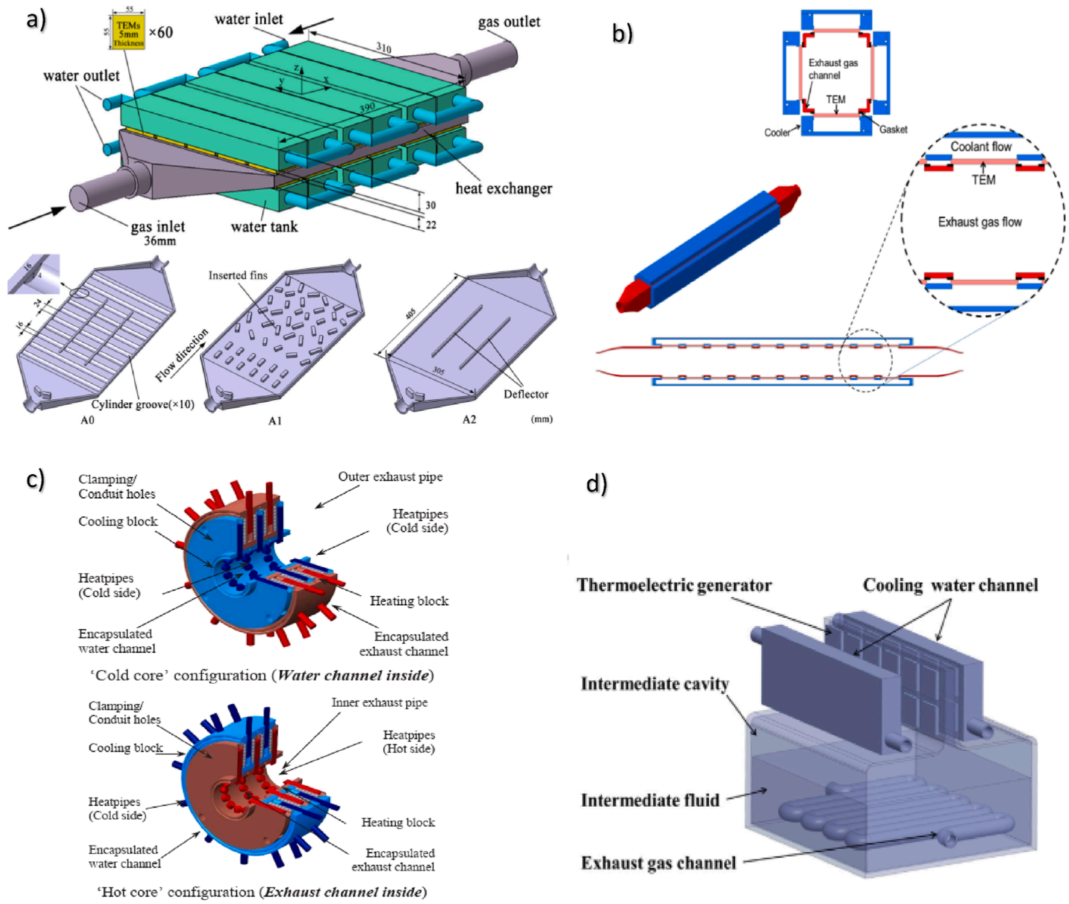

Fig. 11. Schematic of different heat exchangers utilized for vehicle exhaust TEGs: a) Y. Wang et al. [112], b) T.Y. Kim et al. [127], c) B. Li et al. [128], and d) Y. Zhao et al. [83].

safety of such configurations. As previously mentioned, heat pipes possess characteristics making them an attractive candidate to cooperate with TEGs. Considering the nature of exhaust flow, they can add other advantages to these recovery systems like controlling the hot side temperature, which is an issue for these systems. However, there are challenges for introducing heat pipes to vehicle exhaust system. B. Li et al. [128] presented a new configuration, where concentric thermoelectric generators employ heat pipes for heat transfer at hot and cold sides, forming a modular system (see Fig. 11-c). They evaluated two different arrangements and the impact of heat transfer on the system. Moreover, using Bi_2Te_3 based TEs, they achieved a maximum output power of 29.8 W per 0.45 L. The idea of the system and its performance showed promising signs; however, as the authors concluded, further investigations are necessary in terms of practicality. Furthermore, even if it does not take place through a heat pipe, the phase changing process has desirable features like a relatively higher heat transfer rate and uniform temperature distribution. Y. Zhao et al. [83] investigated an intermediate fluid's performance as the heat exchanger of a TEG system. As illustrated in Fig. 11-d, the proposed system comprised of a cavity with a phase changing fluid to absorb heat from the exhaust pipe in the bottom of the cavity, evaporate and release the heat at the top of the cavity to the TEMs. According to the results, applying the proposed heat exchanger leads to a 32.6% enhancement in the maximum output power and a 73.8% reduction in the module area compared to the traditional TEG with the same exhaust heat exchanger area. Moreover, using intermediate fluid for heat transfer, the power density became 5.12 times greater than that of the traditional TEG. Although the effects of added weight and other power losses have not been evaluated, the study shows the potential of such configurations. Note that although we have introduced some challenges of integrating TEGs into vehicle exhaust systems in a level-by-level manner, most of these challenges must be resolved simultaneously, and this type of expression is merely used to give a broad view of the challenges and advancements.

Although vehicles' exhaust gas is the most convenient source of waste heat recovery, it is not the only one. The highest power density of an ATEG was reported for an oil pan thermoelectric generator in a numerical study conducted by M. Aljaghtham and E. Celik [129]. The proposed system, schematically shown in Fig. 12, utilizes the oil pan at

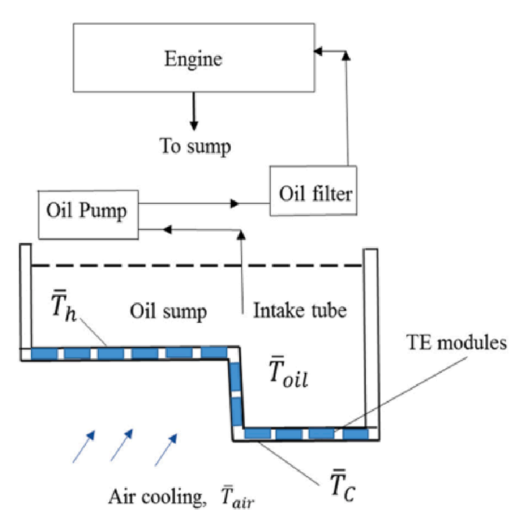

Fig. 12. schematic illustration of M. Aljaghtham and E. Celik [129] TEG system for waste heat recovery from an IC engine's oil pan.

the bottom of an IC engine (temperatures up to 110°C) as the heat source and the cold side is cooled by air convection with and without fins. According to the reports, the case with an ambient temperature of 25 °C, which is generally more realistic, produced 40% lower power than the original case, where the ambient temperature was assumed to be 0°C. The findings showed that for the optimized geometry, maximum output powers of 751 and 2713 W for a standard passenger IC engine and a heavy-duty engine are achievable, respectively. The authors indicated that the proposed TEG is low-cost and easy to implement and that the only challenge would be the fabrication of these systems in the proposed shapes. Hopefully, this research is a starting point for TEGs with some new advantages over the exhaust TEGs, and there is no limitation for both systems to be used in the same vehicle. However, the idea, in general, should be assessed from other perspectives too. Moreover, the potentials of the radiator of vehicles have been studied for thermoelectric waste heat recovery; however, because of rationales like lower temperatures and more complexity, the application of TEGs for vehicles' radiators has been relatively unsuccessful.

In the aggregate, TEGs show a great potential for waste heat recovery from exhaust gases in some cases, while in some others they have negative effects much more than positives ones. Moreover, with the push for electric vehicles, application of TEGs in vehicles is even more under doubt. Nevertheless, the rich literature on vehicle exhaust TEGs is more about thermoelectric generators rather than vehicles and offers some useful information on TEG system designs specially under transient conditions.

6.2. Photovoltaic thermoelectric hybrid systems

Electricity generation is responsible for 36% of energy related CO_2 emissions in 2020, and in order to reach net zero by 2050, energy conversion systems must go through fundamental changes [2]. Specifically speaking, by 2050, electricity production must experience a 2.5-time growth, of which 90% must be supplied from renewables including solar and wind [1]. Photovoltaic plays a major role in this transition, and its capacity triples over the next decade [2].

Photovoltaics (PVs) are devices with the ability to convert the sun irradiance directly to electricity, and similar to other heat engines, there is a thermodynamic limit for their conversion efficiency. Considering the sun as the hot source, the Carnot efficiency for PV cells is much higher than that of other conversion systems; however, with the presence of irreversible losses due to different reasons, the conversion efficiency of available PV cells is much lower than the thermodynamic limit [130]. As exhibited in Fig. 13-a, considering an ideal single-junction PV cell, only around 33% of the solar radiation energy would be available for power generation, while about 33% will be lost through thermalization effect. The remaining third would be lost through phenomena like photons not absorbed (note that although this fraction is not absorbed by the solar cell, in practical applications, it is absorbed by other parts of a PV panel) and unavoidable thermodynamic losses [131]. Forbearing the details of these energy losses and their mechanisms, a large portion of the solar irradiance transforms into thermal energy, causing a temperature increase inside the cell. Moreover, the temperature rise has negative effects on photovoltaic cells' performance. Fig. 13-b shows the output power and energy losses of a c-Si PV cell along with their temperature sensitivity at the operating cell temperatures [132]. It is evident that the power produced by the PV declines with an approximately linear behavior as the temperature increases. Furthermore, there are reports indicating the failure and lifetime shortening of PV cells due to operation at high temperatures [133]. Thereby, over the past decades, researchers have come up with different solutions, including the improvement of PV cell itself and hybridizing it with thermal systems to drag the thermal energy out of PV cells and utilize it in a bottoming system.

A noteworthy point is that the first purpose of hybridization is to extract the excess heat from solar panels while operating under the best possible conditions. Nonetheless, due to its low quality (low temperature), the utilization of the extracted heat gives rise to several challenges and causes optimization requirements. Consider a flat black body under the standard solar irradiance of 1000 W/m^2; according to the Stefan-Boltzmann law, its temperature can only rise to approximately 365 K. However, in a PV cell, a portion of this energy is converted into electricity, and another portion of it is not absorbed. Regarding the nature of the excess heat from solar panels, it is challenging to find an option that can justify the hybridization from energy and economic viewpoints.

One of the systems that have gained lots of interest in recent years is the thermoelectric generator. The number of research papers and reviews dedicated to the PV-TEG hybrid system in the literature is enormous; however, the station of the hybrid system is yet in need of more clarity in terms of economics, energy productivity improvements, and the advantages that this hybrid system is offering in comparison to other hybrid photovoltaic systems. TEGs have some similarities with PV cells; they both are solid-state and direct conversion devices with considerably long lifetime and maintenance-free operation. However, adding a TEG to a hybrid configuration with PV is challenging due to the high thermal resistance and low efficiency of thermoelectric generators. The present section reviews conducted studies on PV-TEG hybrid systems, their potentials, configurations, determinant parameters, merits and demerits, and possible future improvements.

6.2.1. Important parameters for a hybrid PV-TEG system

The quantity and quality of the available heat from a PV panel are the most determinant parameters for hybridization as they affect the performance of both PV cells and TEGs. Furthermore, this available heat itself is affected by other parameters like irradiance, concentration ratio,

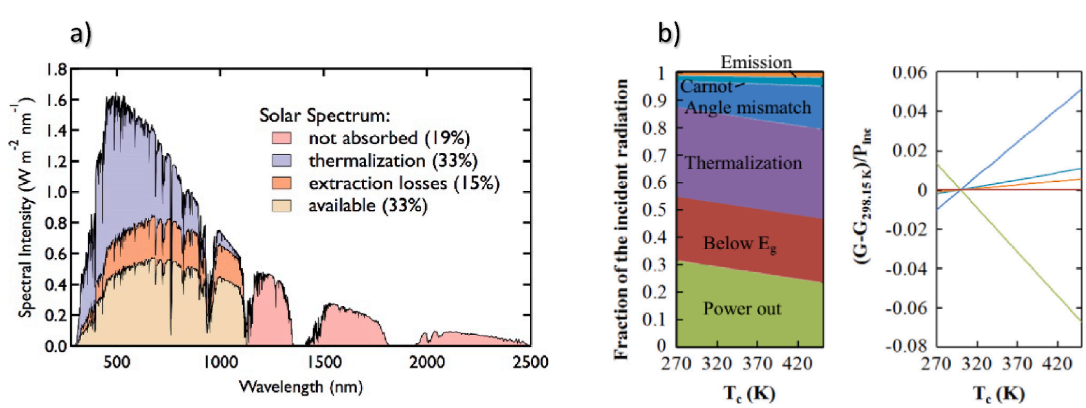

Fig. 13. a) Spectral analysis of the minimum losses for a silicon solar cell (bandgap = 1.1 eV). These are the losses accounted for in the Shockley-Queisser limit and represent an upper limit for solar cells made from single-junction bulk semiconductors [131]. b) Temperature dependences of the fundamental losses for a bandgap of 1.12 eV (Eg of c-Si at 298.15 K) [132].

and ambient conditions. O. Rejeb et al. [134] analyzed the impact of four different input factors on the efficiency of a concentrated hybrid PV-TEG system. Adopting a statistical approach, they classified the effectiveness of parameters on the system's efficiency as follows: 1) The production of solar radiation and optical concentration, 2) thermoelectric leg length, 3) external electrical resistance load, and 4) ambient temperature (see Fig. 14). Although finding the most critical factors in a precise manner is not easy, the study offers a helpful model to statistically understand the importance of different parameters and recognize the decisive factors for the optimization of a hybrid system. Moreover, S. Shittu et al. [135] studied and optimized a concentrated PV-TEG performance considering four contact resistances, namely thermoelectric thermal and electrical contact resistances, and interface thermal contact resistance between PV-TEG and TEG-heat sink in 12 different cases. The research's outcomes showed that the thermal contact resistance between the TEG and heat sink and that between the PV-TEG interfaces are the most influential ones on the performance of the system. Furthermore, they found that by ignoring all the contact resistances, one may overestimate the output power and efficiency of hybrid system by a factor of around 7.5%. The authors highlighted the significance of the interface thermal contact resistances, which are simply ignored in most studies. The study provides useful information on the effect of different contact resistances and, in the meantime, shows the urgent areas to improve the hybrid system. Additionally, R. Lamba and S.C. Kaushik [136] showed that considering the Thomson effect in the thermodynamic model of the concentrated hybrid PV-TEG reduces the hybrid system's output power by 0.7% and 4.78% at C = 1 and 5, respectively. The Thomson effect is neglected in almost every theoretical study; however, as the results suggest, it may not be necessary for the systems without an optical concentrator, but it would cause a considerable overestimation in the high concentration systems. Knowing the importance of a parameter in the performance of a hybrid system will be sufficient for improving that system in the best way possible; however, the mentioned factors are not the only ones to affect the performance of a hybrid PV-TEG system; that is, other factors are pointed out in the upcoming sections.

6.2.2. Un-Concentrated PV-TEG systems

For hybridization, a simple configuration is to mount the thermoelectric modules to the PV module's rear side without any types of concentrators. In this configuration, it is difficult to maintain a considerable temperature gradient or heat transfer rate across the TEG without a good heat exchanger on the TEG's cold side. R. Bjørk, and K. Nielsen [137] investigated the maximum theoretical potentials of an un-concentrated PV-TEG system. Considering two different configurations, they showed that even if the TEG has a Carnot engine's efficiency and the PV performance is not dependent on temperature, the maximum efficiency improvement by adding the TEG would be 4.5 percent-point. This indicates the low-temperature difference across the TEG for an un-concentrated system. Moreover, they discovered that for a more realistic case, the improvement by the hybridization would be significantly lower. In addition, it was found that corresponding to the cell's temperature coefficient (β, the temperature sensitivity constant for a PV cell), a minimum zT value is needed for the hybrid system to be more efficient than a stand-alone PV. Furthermore, it was concluded that the temperature coefficient and solar irradiance density are among the key parameters for the hybrid system performance as they determine the performance reduction of the PV cell with temperature rise and the quantity and quality of the heat, respectively. D. Kossyvakis et al. [138] experimentally analyzed the performance of a hybrid PV-TEG system with two different PV cells and two different thermo-element lengths. A water circulating block was applied as the cold side heat exchanger, and an operating temperature range of 25-86℃ was examined for the PV cells, resulting in an 8-43℃ temperature gradient across the TEG. The results showed that for the examined maximum temperature, adding the TEG to PV improves the output power of the system by 22.5% for the Poly-Si and by 30.2% for the dye-sensitized based PV cells (pumping power was not considered), while the system efficiency maintains the level approximately equal to that of the sole PV under the standard conditions. Moreover, the PV cell's operating temperature in the hybrid configuration is reported lower than the sole PV. In addition, for the shorter thermo-elements, PV's operating temperature was observed to be even lower, mainly because the thermal resistance would be lower using a shorter element. This study revealed that adding the TEG to the PV enhances the power output far better when the input is larger. In other words, the TEG contributes to the system by compensating the power loss of the PV cell due to the temperature rise while preventing the PV cell from reaching the unsafe temperatures. F. Rajaee et al. [139] performed an experimental analysis on the performance of a PV-TEG system using a water block heat exchanger with different solutions of cobalt oxide and the addition of phase change materials. According to the results, with 1% nanofluid, the hybrid system generates 10.91% more power compared to sheer water at noon. Furthermore, the employment of the PCM and 1% nanofluid yields to a 4.52% increment in the overall electrical efficiency. The PV operating temperature reported lower than approximately 40℃, and the maximum temperature difference across the TEG reaches approximately 10℃, explaining the low power production of TEGs. Looking through the numbers, the system could be deemed a successful hybridization, while from an economic standpoint, the system should be compared to a similar system without thermoelectric modules and PCMs. However, the authors expect that the system would appear as a practical and reliable device in future energy supply. In another theoretical study, the performance of a PV-TEG system was investigated by C. Babu & P. Ponnambalam [140]. Using a mathematical model, they simulated a simple configuration, where the TEG is mounted to the rear side of a multi-crystalline solar cell, and the cold side of the TEG has a constant 20℃ temperature. Referring to the results, an additional energy production of 5% with a 6% increase in the overall efficiency were attained compared to a stand-alone PV module. Also, it was pointed out that the TEG contribution is 1–3% of the PV energy rate. As the study shows, the improvement of the system performance is not merely because of the TEG's additional power; nearly half of this improvement is due to the cooling effect provided through the TEG and employing an appropriate heat exchanger. One must keep in mind that in practice, it would not be effortless to keep the cold side of a TEG at 20℃, especially under the conditions assumed by the study. In a more realistic theoretical study, P.

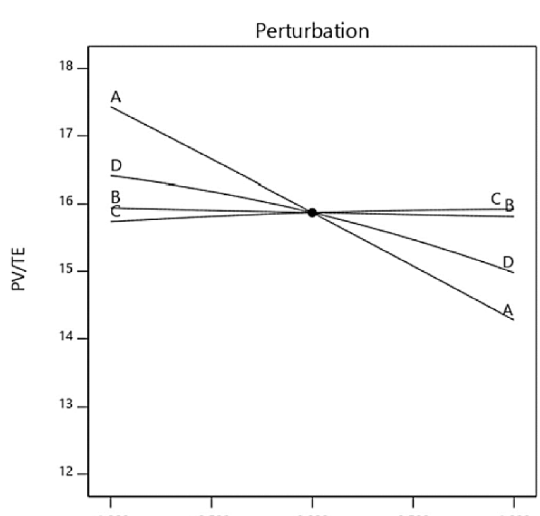

Fig. 14. Perturbation plot for the electrical efficiency of CPV-TE (how the hybrid system efficiency varies as each variable changes from the determined reference point, with all other variables kept fixed at the reference value), (A: product of solar radiation and optical concentration, B: ambient temperature, C: external electrical resistance load, D: the leg height of TE) [134].

Motiei et al. [141] analyzed a hybrid PV-TEG system's performance via a 2D unsteady numerical model. The proposed system consisted of TEGs directly connected to the backside of a PV module, and the TEGs' cold side was directly exposed to the ambient. The results indicated that integrating a TEM into the rear side of PV yields to a reduction in PV temperature by about 8.49 °C along with 0.59% and 5.06% enhancements in PV efficiency and output power, respectively. A part of this improvement is because of the temperature decrement in the PV cell. Moreover, the authors reported a maximum temperature difference of 2.48℃ across the TEG, which explains the low power production of the TEG subsystem. Probably, this is not the best possible hybridization, but it shows the challenges and potentials of this type of hybridization. J. Darkwa et al. [142] investigated a hybrid PV-TEG-PCM system and compared it with sole PV and PV-TEG systems adopting experimental and numerical approaches. The proposed system employed phase change materials as the cold side heat exchanger for the TEGs. The results showed that the integrated PV-TEG-PCM system achieved a 9.5% power enhancement compared to the other two systems during the initial 1.5 h period. However, for longer periods, the PCM layer had an insulating effect on the system and thus, a significantly lower average improvement in the longer period was observed. Furthermore, the effect of three types of heat sinks have been compared for each considered system, and the results are presented in Table. 2. It is obvious that the new system has better performance when the cooling source at the bottom of the system is natural convection. More evident is that adding a heat sink to a sole PV has a much better effect on power generation while being less complex and economically much more beneficial compared to other systems. Overall, this study has shown the effectiveness of different configurations with a perspicuity that has been missing in other studies. Furthermore, in the abovementioned studies, the TEGs were added to PV cells without utilizing any concentration method, causing minor heat transfer rates and temperature differences across the TEGs that eventually yielded inefficient use of materials. To have a clear view, the TEG contribution should be distinguished from the hybrid system improvement due to the cooling effect provided by a heat exchanger, and the economic features of such systems need to be assessed more frequently. All in all, it seems that adding a TEG to PV in this configuration is not the best idea, and probably the case would not change even with the expected improvement for thermoelectric materials. Nevertheless, this is the general induction we could derive from unconcentrated PV-TEG systems.

6.2.3. PV-TEG systems with thermal concentration

As discussed earlier, the excess heat from a PV cell is not sufficient to be effectively used in a TEG. One way to boost this energy is to apply a thermal concentration that can be realized using a conducting plate or any other heat exchanger between the TEG and PV modules. Applying a heat exchanger or a conducting plate would add to the thermal resistances between the PV and TEG, leading to a reduction in the quality of the heat on the hot side of TEGs and also the cooling load on the PV cells. Therefore, in such configurations, a significant cooling load on the cold side of TEGs is vital to recuperate the mentioned effects. G. Li et al. [143] developed the concept of a novel PV-TEG system, analyzed the system's preliminary economics, and compared the new system with a conventional PV-TEG and a stand-alone PV. The proposed system

Table 2
Cumulative PV power output in kW/m^2 for the three cases from J. Darkwa et al. [142].

Cooling sources	Convective heat transfer coefficient	PV	PV/TEG	PV/TEG/PCM	Differential %
Natural air	5 W/m^2 K	0.393	0.394	0.400	1.9%
Forced air	100 W/m^2 K	0.573	0.567	0.522	−8.9%
Forced water	500 W/m^2 K	0.595	0.588	0.535	−10.0%

utilized a flat plate micro-channel heat pipe (MCHP), as a thermal concentrator for TEG as shown in Fig. 15-a. The results showed that the new system produces 6.44 kWh more annual electricity output than the sole PV, and about 5.40 kWh lower annual electricity output than the conventional PV-TEG. Hybridization adds an extra cost to the system compared to the stand-alone configuration; the authors found that the new system's extra cost is 41 times lower than the conventional PV-TEG. This is because by introducing the MCHP to the system, the thermoelectric module area decreases significantly, while the performance decrease is much lesser. Although PV cell temperature, as an important parameter, was not reported, the study showed the importance of an appropriate design for the system's feasibility. In a similar study, G. Li et al. [144] conducted preliminary experiments on a hybrid PV-MCHP-TEG system along with a comparison to a sole PV the same conditions. The system is similar to the previously mentioned one by the author (Fig. 15-b). The outcomes of the study showed that the new system is of better performance in terms of the output power and efficiency compared to the sole PV; however, the PV cell temperature in the new system (∼50℃) is higher than that of the sole PV (∼40℃), and a temperature difference of more than 10℃ is observed across the TEG. Although the cell temperature was higher in the new system, it was still within an acceptable range. S. Shittu et al. [145] performed an experimental study and exergy analysis on a hybrid PV-MCHP-TEG system with addition of a water-cooling block to the cold side of the TEG (Fig. 15-c). The effect of different parameters was assessed, and the results were compared with those of a sole PV without any heat exchanger. The PV cell temperature of the new system was slightly lower than that of the sole PV, but still as high as approximately 62℃. Also, a steady temperature difference of 30-35℃ was achieved across the TEG. Moreover, the authors found a higher system efficiency (12.19%) compared to that of the sole PV (11.94%), while the new system produced hot water (∼30℃) in the tank with a thermal efficiency of around 60%. The study clearly showed the advantages of the new system compared to a stand-alone PV; however, the comparison of this new hybrid system with a sole PV would exaggerate the effect of the TEG on the system. To have a clear perspective, better comparisons should be made. A. Makki et al. [146] numerically investigated a similar system of PV-HP-TEG as revealed in Fig. 15-d. Achieving a temperature difference of about 30℃ across the TEG, the authors showed that the new system has a better performance than conventional PV systems (over a 1% increase in the system efficiency). However, the PV cell temperature was not mentioned in the results, and the cold side temperature of the TEG was assumed to be 25℃ at any given conditions. W. Zhu et al. [147] carried out an experimental study on a hybrid PV-TEG system's performance with thermal concentration. The system contained a PV panel stuck on a copper plate (as the thermal concentrator) to the center of which, four TEG modules were mounted and water-cooling block was used as the heat sink for the TEGs (Fig. 15-e). According to results, adding the TEG in this new configuration enhances the hybrid system's efficiency by 25% compared to the stand-alone PV; this is without considering the auxiliary consumption. Moreover, the maximum PV cell temperature and the highest temperature difference across the TEG were reported around 80℃ and 52℃, respectively. Furthermore, an optimum thermal concentration ratio was found for the system, and also through the economic analysis, a feasible region was defined for the hybrid system considering different parameters. Another interesting part of this study is that the authors have examined the system in the absence of the sun, finding that the TEG unit is capable of producing an extra energy of 648 J from the moment that the sun is off. Having a minor power when the main power source (sun) is out of reach can be another positive aspect of using such a hybrid system. To sum it up, the study is an example of a good hybridization, but one should note that for such systems, problems are the high cell temperature and the temperature gradient and possible thermal tensions caused by the thermal concentration. Such problems can cause a degradation in the PV cell performance in the long-time operation. To draw a conclusion for the current

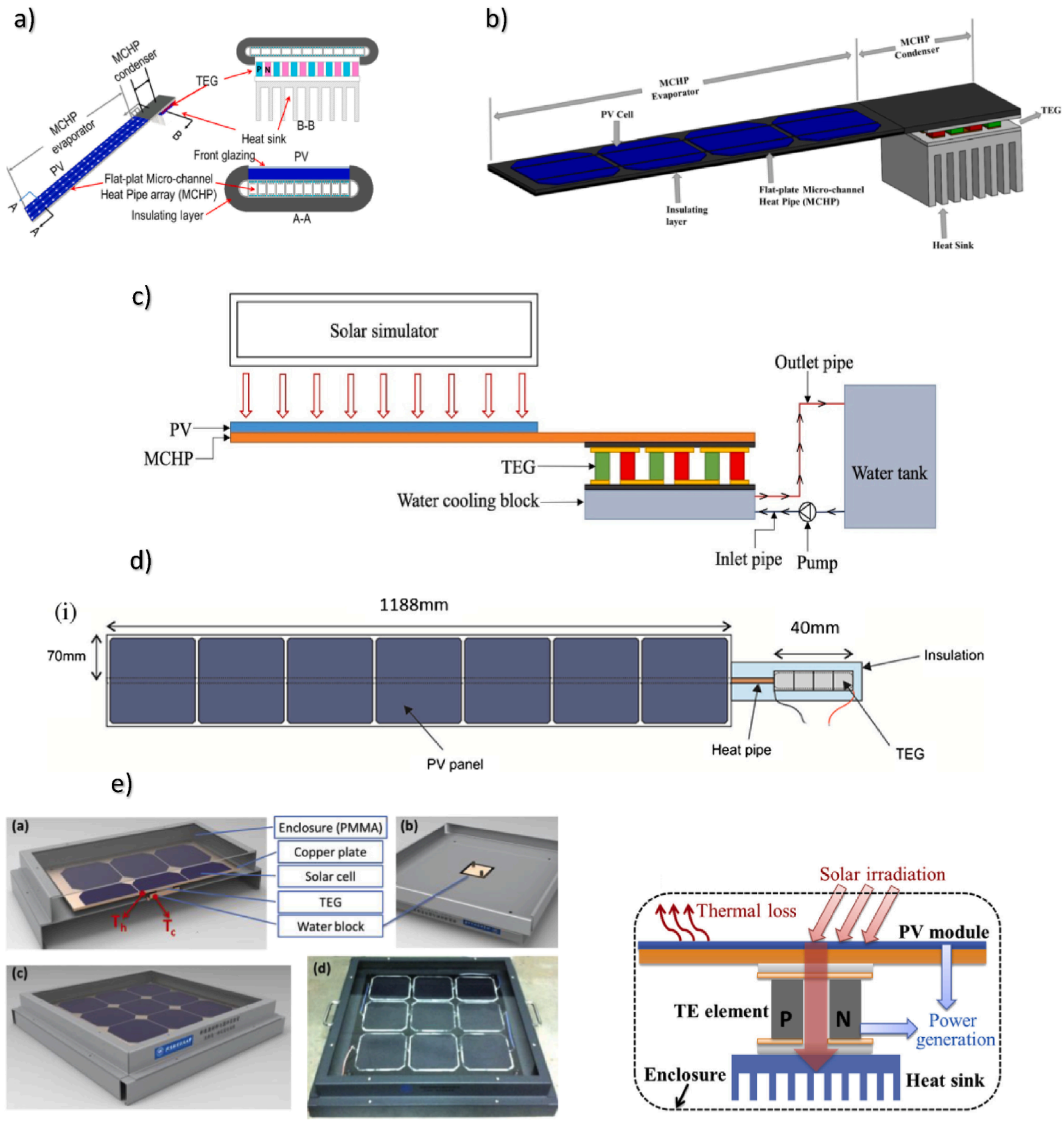

Fig. 15. Schematic view of different hybrid PV-TEG systems adopting thermal concentration technique: a) G. Li et al. [143], b) G. Li et al. [144], c) S. Shittu et al. [145], d) A. Makki et al. [146], and e) W. Zhu et al. [147].

section, thermal concentration concept benefits the system; although it may result in higher PV cell temperature or temperature gradient and thermal tensions, these effects can be diminished by employing suitable heat exchangers. On the other hand, the whole system would cost less, and the materials would be used more efficiently.

6.2.4. CPV-TEG hybrid systems

Solar concentration is a solution to utilize photovoltaic materials more effectively. A solar concentrator is a device that collects the sunlight from a larger field and concentrates it to a smaller area. Using solar concentrators increases the power production of a PV cell by increasing the input irradiance. On the other hand, it causes a higher cell temperature due to the same reason; accordingly, the excess heat from a concentrated-photovoltaic (CPV) is of better quality and quantity compared to a non-concentrated photovoltaic. Moreover, in CPVs, it is vital to use an appropriate heat exchanger in order to extract the excess heat from the cells and maintain them under safe thermal conditions. Among the different types of hybrid photovoltaic-thermoelectric systems, those with concentrated photovoltaics are more advantageous; however, the challenges are still there because of low efficiency and high thermal resistance of the TEGs. Recently, S. Indira et al. [148] summarized the different configurations of hybrid CPV-TEG systems. To their recognition, there are seven general configurations of CPV-TEG systems in the literature. Moreover, they highlighted the advantages of each configuration compared to the others. Here, we intend to briefly cover different types of CPV-TEG systems and review their advantages and challenges compared to other photovoltaic-thermoelectric systems. As previously discussed, adding a concentrator is a way to use photovoltaic materials more effectively, but other challenges arise with this configuration. First, with the higher input and the same thermalization rate, the temperature will increase immediately in the PV cell; thus, an appropriate cooling mechanism is necessary for CPV systems. Second, a concentrator illuminates the light in a non-uniform way on the PV cell, which might damage the cells in long operation periods. Moreover, concentrating will amplify the oscillation of the input radiation, and the output power would become more unsteady. The easiest configuration is to mount the TEG modules to the rear side of a CPV cell and use a heat exchanger on the TEG's cold side. A. Rezania and L.A. Rosendahl [149] investigated the feasibility of a CPV-TEG system and compared it with a stand-alone CPV. Evaluating the effect of critical parameters on the performance of the hybrid system, they showed that applying a zT of around unity for TE materials, hybridization will improve the efficiency of the system, and that the TEG's contribution to power generation is more significant at higher concentrations. Moreover, they showed that up to a point increasing the heat transfer coefficient has a great impact on the system performance after which, the heat transfer coefficient becomes ineffective. Furthermore, the economic analysis showed that for both systems, the energy cost decreases by increasing the concentration, meanwhile at any evaluated concentration ratio, the energy cost for the CPV-TEG system is lower than that of the stand-alone CPV. The authors concluded that, in general, a higher zT value for TE materials and a lower temperature coefficient (β) for CPV cells improve the hybridization. The study theoretically showed the advantages of the hybrid systems; however, in a more realistic case, the results might be different because of the multiple simplifying assumptions used by the authors. S. Mahmoudinezhad et al. [150] numerically investigated a hybrid CPV-TEG system's behavior under variable solar radiation. In the proposed system, a TEG was directly connected to a CPV cell, and the cold side of TEG was cooled by a water circulating block. Considering an unsteady radiation cycle, they calculated the temperature at different positions and also studied the output power and efficiency of TEG and CPV systems. According to the results, TEG and CPV react inversely to the concentration ratio, i.e., increasing the input radiation enhances the cell temperature and the excess heat, eventually yielding to an improvement in the TEG performance and a decline in the CPV performance (Fig. 16-a, b). Therefore, adding the TEG was seen to stabilize the overall power generation. In a similar study, S. Mahmoudinezhad et al. [151] investigated the transient behavior of a CPV-TEG applying experimental and numerical methods. This time, they also assessed the impact of TE leg length on the overall system performance and showed that increasing the leg length enhances the TEG power production and CPV cell temperature. A hybrid system like this offers various advantages like more stable power and more overall power production; however, the TEG is not covering the whole power loss imposed on CPV due to the temperature rise. Meanwhile, the operating temperature could become as high as 120°C, showing the importance of leg length and heat transfer optimization on the performance of the hybrid system. A. Lekbir et al. [152] proposed a hybrid CPV-TEG system with nanofluid cooling at the TEG's cold side. The proposed system was composed of a concentrated PV, a TEG, and a nanofluid cooling block. Considering the absorbed thermal energy by the coolant as an output of the system, the authors compared the new configuration with three others, namely a sole CPV, a CPV-TEG with a metal heat sink as the cold side heat exchanger (CPV-TEG-HS), and a CPV with a nanofluid heat exchanger (NCPV-T). According to the results, for the main case, PV cell temperature for a C = 5 concentration ratio was kept under ~ 100°C, while the nanofluid temperature reached ~ 90°C with a temperature gradient of 6.6°C across the TEG. Furthermore, the electrical performance of the proposed system was improved by approximately 10, 47.7, and 49.5% compared to NCPV-T, CPV, and CPV-TEG-HS systems, respectively. In essence, the results indicated that adding a TEG to a CPV system without an appropriate heat exchanger has a negative effect on the CPV and overall system. Moreover, although the temperature difference across the TEG was insignificant, the exergy analysis showed that the new system produces ~ 6% more daily exergy compared to the NCPV-T system, probably due to high heat transfer rates. However, the question, whether the system is financially feasible

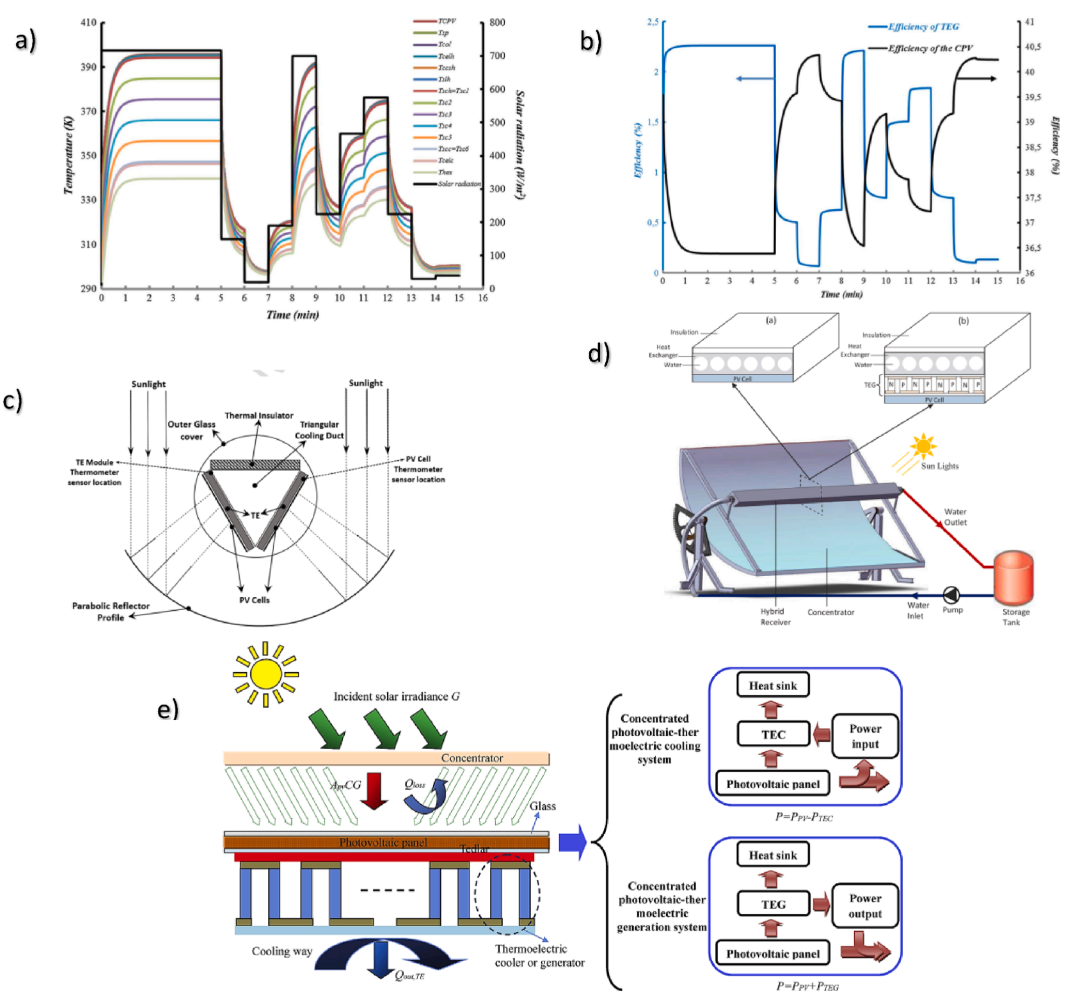

Fig. 16. a) Variation of solar radiation and the temperatures of hybrid module components versus time, S. Mahmoudinezhad et al. [150] and b) Variation of the efficiency of the CPV cell and the TEG versus time in response to the variations illustrated in (a), S. Mahmoudinezhad et al. [150]. And schematic illustration of the proposed models by: c) M. Mohsenzadeh et al. [154], d) S. Mahmoudinezhad et al. [158], e) Y. Cai et al. [159].

or not remained unanswered. Other studies have also highlighted the importance of the heat sink in CPV-TEG hybrid systems. W. Gu et al. [153] investigated the performance of a hybrid CPV-TEG via a thermal resistance model. According to the results, the thermal resistance of heat sink is the dominant parameter when determining the hybrid system performance. It was also showed that the output power of CPV-TEG is 1.24–2.85% higher than that of the CPV alone; however, the operating temperature of CPV-TEG was higher. Moreover, the authors concluded that the ideal conditions for the hybrid system are higher concentration ratios and lower PV temperature coefficients. Different configurations have different characteristics of their own. M. Mohsenzadeh et al. [154] proposed a new configuration and experimentally investigated its electrical and thermal performances. As shown in Fig. 16-c, the proposed system consisted of a parabolic trough reflector with a sun tracking system and a receiver placed on its concentration axis. The results showed that the new system produces 303% higher daily electricity than a stand-alone PV of the same area; however, the new system's average daily efficiency was 57.52% lower than the stand-alone PV. The authors explained the reason to be the system's low optical efficiency and the higher temperature of the PV cell (94℃) compared to the stand-alone PV cell (52℃). The average thermal efficiency of ∼ 51% was obtained during the experiments. Moreover, the contribution of the TEG to the output power of the PV cells was around 2.8%, which may not justify their application of it in the system. The proposed system offers a good idea to produce electrical and thermal energy from a fairly simple approach, and more importantly, it can be used on large scales. However, it does not have the best performance from the thermoelectric viewpoint. In a numerical study, M. Shadmehri et al. [155] used the same idea and configuration to evaluate the effect of the aperture width of the reflector and the apex angle of the triangular absorber on the performance of the hybrid system and found an optimum range for both of them. In other words, they optimized the concentration system, resulting in better electrical and thermal outputs for the system. A. Riahi et al. [156] proposed a similar system by adding a TEG to a CPV thermal (CPVT) system. As shown in Fig. 16-d, the proposed system mainly consisted of a parabolic trough concentrator, a hybrid receiver (PV-TEG), and other equipment. The results showed that the efficiency is enhanced by 7.46% compared to the CPVT without a TEG; the output power is also improved. However, the PV cell's operating temperature was increased from 56℃ in the CPVT system to 63℃ in the new system, while the stored water temperature (∼48℃) and thermal efficiency (∼46%) were both slightly lower for the CPVT-TE system. Moreover, through an annual analysis, the authors showed that adding TEG to the CPVT system generates 359 kWh more electricity. The study is a good example of such systems' potential to produce electrical and thermal energy on different scales. Y.J. Cui et al. [157] studied the performance of a high concentration PV integrated with segmented TEGs. While the operating temperature of the common CPVs are in a range that just one thermoelectric material would normally have the best performance, in this study, the operating temperature of the CPV was considered to be more than 600 K. Therefore, segmented legs were used to have the best performance within the operating range. In certain conditions assumed by the study, the efficiency of the hybrid system was estimated around 14%, which is high knowing that the efficiency for the PV cell under the standard conditions was 15%. Moreover, the authors studied the effect of different factors on the lifetime of the segmented legs, indicating the potential of TEGs in high concentration systems. Although there is a question on the feasibility of PV cells in practice with such high operating temperatures, this type of system would be more favorable for TEGs to fit in and significantly impact their performance. S. Mahmoudinezhad et al. [158], investigated the performance of a low concentration PV-TEG hybrid system via experimental and numerical approaches. The suggested system was comprised of a sun simulator, a triple-junction solar cell, a TEG, and a water-cooling block. The experimental results unveiled that increasing the solar concentration has a negative effect on the efficiency of the PV cell, decreasing it from 35.33 % to 23.02 %. But, such an increase in the solar concentration was seen to have a positive effect on the efficiency of the TEG, increasing it from 0.63 % to 1.20 %, which is because of the temperature rise in the PV cell with its highest temperature exceeding 120℃. The numbers simply do not justify the TEG application in the new system since the TEG cannot recover the considerable power loss of the PV cell during the temperature rise. Y. Cai et al. [159] investigated the solar energy harvesting potential of a CPV-TE by the thermoelectric in cooling and power generation modes. The two operating modes of the TE have been comprehensively compared. The proposed system was composed of a CPV, a TEC/TEG unit, and an active cooling system, as demonstrated in Fig. 16-e. The TE devices worked as a TEG when its current was below a certain value after which, the TE devices would change to TEC mode. The results showed that the CPV-TEG produces the highest power before the CPV-TEC and stand-alone CPV, respectively, while the PV cell's operating temperature was observed to be the lowest for the CPV-TEC before the CPV-TEG and sole CPV, respectively. Moreover, according to the exergoeconomic analysis, the unit energy cost for the CPV-TEG system was slightly lower than that of the CPV-TEC system. The study showed that the effect of efficient cooling provided by the TEC could be as important as the extra power generation of the TEG in the general conditions. Nevertheless, the authors concluded that understanding the environmental and seasonal effects on the performance of the system would be helpful in order to use the transitional characteristics of the thermoelectric devices to overcome the seasonal challenges. Considering the mentioned studies, it can be concluded that the combination of TEGs with CPV systems has far more potential compared to the other hybrid photovoltaic-thermoelectric systems. However, knowing the reaction of both systems to certain conditions makes it difficult and complex to unquestionably determine whether the hybridization is generally beneficial or not. Nevertheless, there are signs of potentials and advantages in integrating TEGs into CPVs, but at the end, there should be better comparisons with other potential hybrid systems to perfectly understand what advantages of these systems are the most significant ones.

6.2.5. Techniques to bypass the negative effects of TEG on PV

It is evident that TEGs show better performance when they are directly connected to the rear side of a CPV cell compared to those with un-concentrated PV cells. However, TEGs also have a more negative effect on CPVs than the un-concentrated PV cells when they are simply connected to the rear side of the PV cell no matter how efficient the cold side heat exchanger is. There are investigations for some advanced systems to bypass the negative effect of a TEG on a solar cell. A. Abdo et al. [160] proposed a new configuration combining a CPV and a solar thermoelectric generator (STEG). The system was composed of a microchannel heat sink sandwiched between the PV and STEG modules to promote efficient cooling. As shown in Fig. 17-a, the PV and the STEG modules are individually under concentrated radiation, and the system is hybrid because of sharing a heat exchanger. The newly designed system is compared with a conventional CPV-TEG with the same components connected to each other in a tandem configuration. The outcomes revealed interesting information on the new configuration; with a concentration ratio of 20, the average cell temperature was maintained at 77 °C, achieving an electrical output power of 3.2 kW/m^2. Meanwhile, for the conventional configuration with a concentration ratio of 10, the cell temperature and output power reached 90℃ and 1.28 kW/m^2, respectively. The main advantages of the new configuration compared to the conventional systems are; (a) a better cooling effect on PV cells, (b) a higher hot side temperature for the TEG, and (c) a better thermal energy production. Although the authors had selected a proper system for the comparison, the question is why they have not used PV cells on both sides of the heat exchanger while PVs offer a higher efficiency compared to TEGs. Apart from that, it is obvious that such a system offers much better results compared to the conventional system. Moreover, experimental investigations could always show different

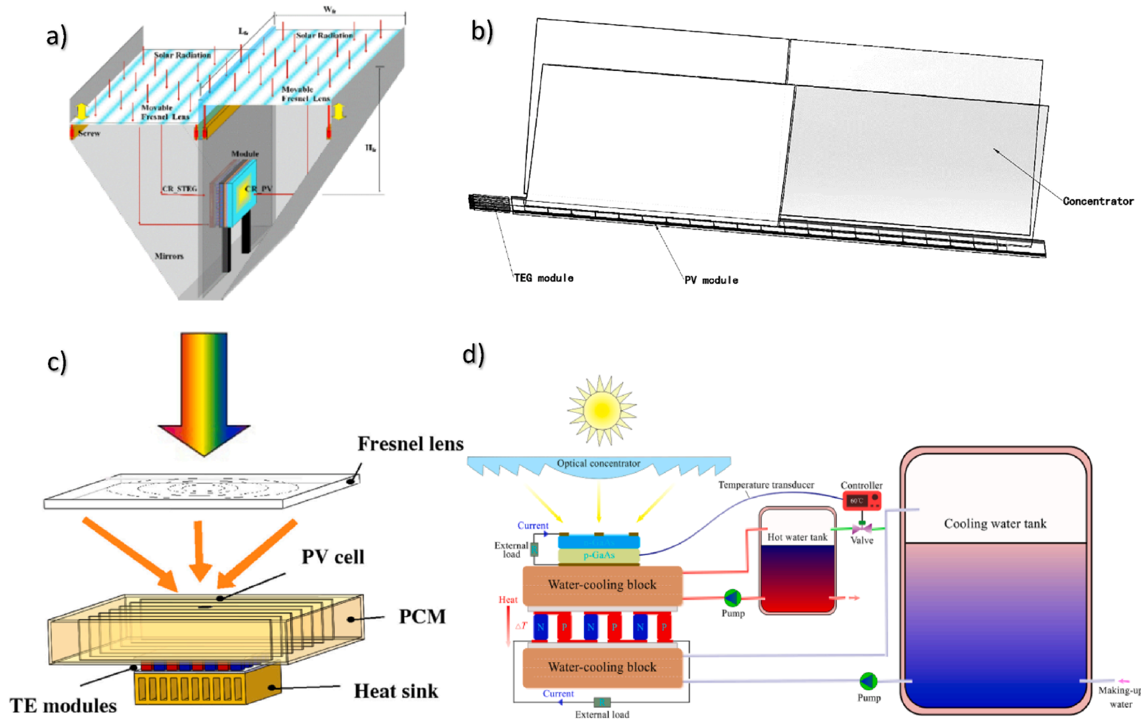

Fig. 17. a) Schematic view of the novel configuration proposed by A. Abdo et al. [160]. And schematic view of different hybrid PV-TEG systems using both thermal and optical concentration techniques: b) C. Haiping et al. [161], c) T. Cui et al. [162], d) E. Yin et al. [163].

results; C. Haiping et al. [161] experimentally investigated a novel low-concentration PV-HP-TEG system. As shown in Fig. 17-b, the proposed system was composed of a concentrated PV cell, an array of MCHPs, 20 TEMs, and water-cooling blocks to generate low-grade heat as well as electrical power. The new proposed system takes advantage of both solar and thermal concentrations. However, the results showed that the TEG unit's maximum output power only reaches 3.52 W at the best conditions; the reason behind this could be the small temperature difference across the TEGs. Nevertheless, the performance of the system is much lower than what one may expect. In conclusion, the study shows the complexity of putting a good idea into practice. T. Cui et al. [162] designed and optimized a novel hybrid CPV-PCM-TEG system; the proposed system consisted of an optical concentrator, a PV cell, a phase change material container, a TEG, and a water cooling block as depicted in Fig. 17-c. The authors optimized the system proportionally to the optical concentration ratio. The results showed that the new system's performance is superior to that of the CPV-TEG and stand-alone CPV, while PCM helped retaining a constant temperature for PV cells and TEGs under fluctuations. The new system introduces a way to simultaneously use the optical and thermal concentration while improving the system's overall performance, and if it was not for the high cost of PCMs, the new system could have been a great approach to reduce the overall cost significantly. E. Yin et al. [163] designed a new CPV-T-TEG system to overcome the disadvantages of the conventional hybrid systems. The new system consisted of an optical concentrator, PV cell, TEG, and two water cooling cycles (Fig. 17-d). Basically, the new system's working principle is similar to the CPV-PCM-TEG system, while utilizing different equipment. Employing a hot water cycle rather than the PCM provided a better control on the whole system and generated useable high-temperature water. A controller connected two thermal cycles to keep the hot water at the desired temperature. Moreover, the overall output power of the new system was higher than that of the CPV system and slightly lower than that of the CPV-TEG system, while having a significantly lower cell temperature. Moreover, the TEG contribution to the overall output was more than 8%. Furthermore, although the new system's cost per output power was around 10% higher compared to the conventional system, it had significantly lower energy and exergy production costs. Altogether, the mentioned studies have introduced advanced configurations for hybridization, and many of the aforementioned challenges have been addressed. However, there is a need for more advancements and also some experimental investigations in this area. Nevertheless, these studies have shown that TEGs could be influential on the improvement of solar energy utilization.

As mentioned before, solar concentration is a way of using photovoltaic materials more effectively. However, this method has a downside; the high rate of thermal energy produced in the cell leading to high operating temperatures causes further reductions in the performance and lifetime of a PV cell. An effective way to partially prevent the temperature rise in PV cells is to use spectrum splitting devices. A spectrum splitter is a device to split the incident irradiance into two parts, reflecting the radiation with a wavelength higher than a particular wavelength and transmitting the part with a lower wavelength. This particular wavelength, called cut-off wavelength, can be optimized so that the part of the solar spectrum, which is not absorbed by the cell's bandgap, would be reflected onto another surface, the TEG in this case. Using this method would have several advantages at the expense of a more complex system and some design challenges. Z. Yang et al. [164] studied the maximum efficiency and parametric optimum selection of a solar spectrum splitting CPV-TEG system. The new system's energy flow diagram is shown in Fig. 18-a. Through the optimization of the bandgap energy and the area ratio of the TEG collector to the solar cell and two other parameters, the authors found that the new system's maximum efficiency would reach 40.2%, which is 2.19% higher than that of the stand-alone CPV. A. Mohammadnia et al. [165] proposed a novel hybrid energy harvesting system based on the separation of the solar irradiation; the new system, shown in Fig. 18-b, was composed of a solar concentrator, a beam splitter, PV cells, STEG, and Stirling engine. The CPV produced electrical energy directly from the reflected photons, while the transmitted photons got trapped in the cavity and produced a high-quality thermal energy, used by the TEG and Stirling engine to generate additional electricity. Moreover, the rejected heat from the Stirling engine and the CPV was transferred to a reservoir. According to

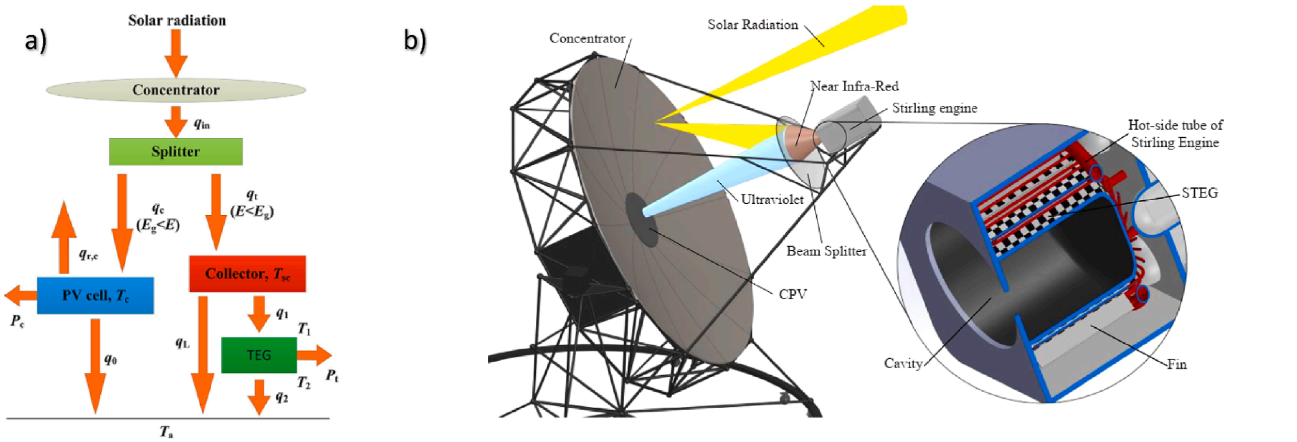

Fig. 18. a) The energy flow diagram of a concentrated solar spectrum splitting PV-TEG system by Z. Yang et al. [164]. b) Schematic diagram of the hybrid CPV-STEG-Stirling engine system, A. Mohammadnia et al. [165].

the results, a system efficiency of 21.8% and a total electric power of 45.4 kW at 455 suns during the peak solar irradiance hours were achieved. The TEG unit was capable of generating 1.2 kW electricity from a temperature difference under 230 K. Furthermore, the reported cost performance for the system was approximately 3.7 $/W, with the Stirling engine showing the lowest cost performance of 7.2 $/W and the TEG and CPV are next with 3.146 and 2.33 $/W, respectively. The study shows the grate potential of TEGs in such hybridizations to produce relatively high performance and low-cost electrical energy on large scales. Overall, these new configurations add a lot to the hybrid photovoltaic-thermoelectric systems, giving them an independency to work at their best mode simultaneously. Although these systems would be costlier and more complex, they introduce the best potential for the hybridization of thermoelectric generators with photovoltaics.

6.3. *Solar-Thermoelectric generators*

A solar thermoelectric generator (STEG) is a thermoelectric device driven by solar radiations to produce electricity. Unlike PV cells, TEGs cannot directly convert solar radiations into an electromotive force. Accordingly, TEGs would need a medium to convert solar radiation into thermal energy; this could be realized using solar absorbers, solar ponds, and so on. Moreover, solar-driven TEGs offer some advantages over PVs and could be an alternative to solar energy utilization. A. Allouhi [166] reviewed the recent advancements in solar systems using TEGs and demonstrated the advantages and challenges of such systems. The main challenge for the TE conversion is the low efficiency of the system, and the main focus is to increase it through finding advanced material and improving system designs[16]. In general, the low conversion efficiency is not favorable for any conversion device; however, low efficiency means that a significant fraction of the heat source energy is rejected to the heat sink. This, in turn, makes TEGs a good option for solar-thermal applications, where there is a good use for thermal energy along with acceptable electricity. Although the heat rejected to heat sink would be of lower quality, it could be optimized based on the demands of the applications.

6.3.1. *Challenges in design process of solar TEGs*

A challenge for solar-thermal systems is that the energy density of solar radiations is relatively low. Thus, it is necessary to consider energy concentration methods for such systems. Optical concentration would improve the quality and quantity of the absorbed heat and the system's efficiency. However, the challenge is that with increasing the concentration, the radiation losses would become more extensive. On the other hand, with high optical concentrations and high temperatures, there will be a need for segmented TE legs to cover the broad temperature difference along with the absorbers limits to work with high efficiency at higher concentration, and other limitations. Therefore, the optical concentration ratio should be optimized according to the characteristics of the system. Another method is to use thermal concentration. Q. Li et al. [167] investigated solar thermal heating applications' energy concentration limits. They classified the thermal concentrations into passive and active methods for heating applications. The active methods would not suit the electricity generation applications because they demand external power to operate as a heat pump; however, the passive techniques (like conductive plates and heat pipes) are used widely in STEG systems. With a passive concentration method, one can only increase the heat flux density, and obviously, with this method, the temperature of the applied heat on TEG would be lower than the absorber temperature. According to the results, a concentration ratio of 52–176 was available for heat pipes with carbon nanotube absorbers, offering an efficiency of 26–81% depending on the concentration ratio and application temperature. As one would expect, lower concentration ratio and application temperature lead to a higher concentration efficiency. In STEGs, usually, both thermal and optical concentrations are used simultaneously, and often, there is an optimum value for each concentration ratio depending on the system properties. This section will briefly introduce the applications, challenges, and future prospect of solar thermoelectric generators.

The first step to be taken when applying a TEG system in solar applications is to find an efficient absorbing system that has a simple design, prevents energy losses, is capable of providing sufficiently high temperatures, and has a low cost. Regarding the absorbing system's overall properties, one should select the most effective thermoelectric material(s) to operate within the available temperature range, which would also be affected by the cooling system. The cooling system usually depends on the application and could have different temperatures. Realizing all these items, then one should optimize the system with respect to the application and system outputs. Furthermore, identifying the effect of different parameters and possible improvements for a system is an important step to understand the restrictions and advantages of that system. D. Kraemer et al. [168] introduced a STEG model and a methodology to optimize STEGs for terrestrial applications. Through a careful investigation of parameter's effect on the system, they achieved a peak predicted efficiency of 5% under the standard spectrum with a TE material cost below 0.05$/W. The greatness of this study comes from evaluating different parameters and introducing a simplified model for further investigations. Moreover, they considered two application scenarios for STEGs on rooftops: (a) generating only electricity and (b) producing hot water together with electricity. The authors concluded that integrating STEGs into solar hot water vacuum tube systems for cogeneration can introduce a cost-competitive system for domestic applications. L. Li et al. [169] experimentally studied a high-performance STEG system to optimize the absorbing system and find the effect of its parameters on the performance of the system (see Fig. 19-a). According to the results, optical efficiency of around 82% was achieved at the optical concentration ratios lower than 80 and was decreased rapidly as the concentration ratio increased due to radiative heat losses. Moreover, the authors showed that adding a glass cap to the absorber and TEG increases the temperature difference by 12–67% due to the decrement of convective heat losses. Through optimization of the absorbing system, a pick efficiency of 4.3% was attained for the system. In summary, the study shows the importance of an appropriate absorbing system on the performance of a STEG. In an experimental study, D. Kraemer et al. [170] were able to achieve an exceptional system efficiency of 7.4% (STEG efficiency of 9.6%) for a concentrated STEG with segmented legs (see Fig. 19-b) under a solar radiation flux of 211 kW.m^{-2} and absorber temperature of 600°C. The segmented TE legs were made of doped bismuth telluride and Skutterudite materials for low- and high-temperature sections, respectively. The effect of two types of absorbers, thermal and optical concentrations, the figure of merit for TEGs, and other parameters were investigated. The results showed that for an approximately equal combined concentration ratio (product of thermal and optical concentration ratios), the system with higher optical concentration has a better performance compared to the one with higher thermal concentration, mainly because of the higher temperature. Furthermore, the authors revealed that using segmented legs for such a broad temperature offers much better performance compared to other configurations for TE legs (Fig. 19-c). Although the study was experimental, it is worth mentioning that it was conducted under special circumstances, which would not be easy to achieve at practical levels. Nevertheless, the study indicates the potentials of STEGs for electricity generation from solar radiation. In a comprehensive study, E. Bellos and C. Tzivanidis [171] investigated the energy and financial performances of a STEG system. The investigated system's schematic view is depicted in Fig. 19-d. The system employs a thermal concentration ratio of 299 without any optical concentrations. With assumptions rather realistic, the results showed that a maximum system efficiency of around 4.5% and yearly mean system efficiency of 3.2% are achievable. Moreover, the financial analysis indicated that the proposed system has a payback period of 4.55 years with a Levelized cost of electricity (LCOE) of 0.0441 €/kWh, both being lower than PV and CPV systems. The above-mentioned studies show the ultimate potential of STEG systems with available thermoelectric materials. The challenge, then, would be to bring these estimations to the real applications with larger scales. Moreover, with the expected improvement of TE materials, STEGs

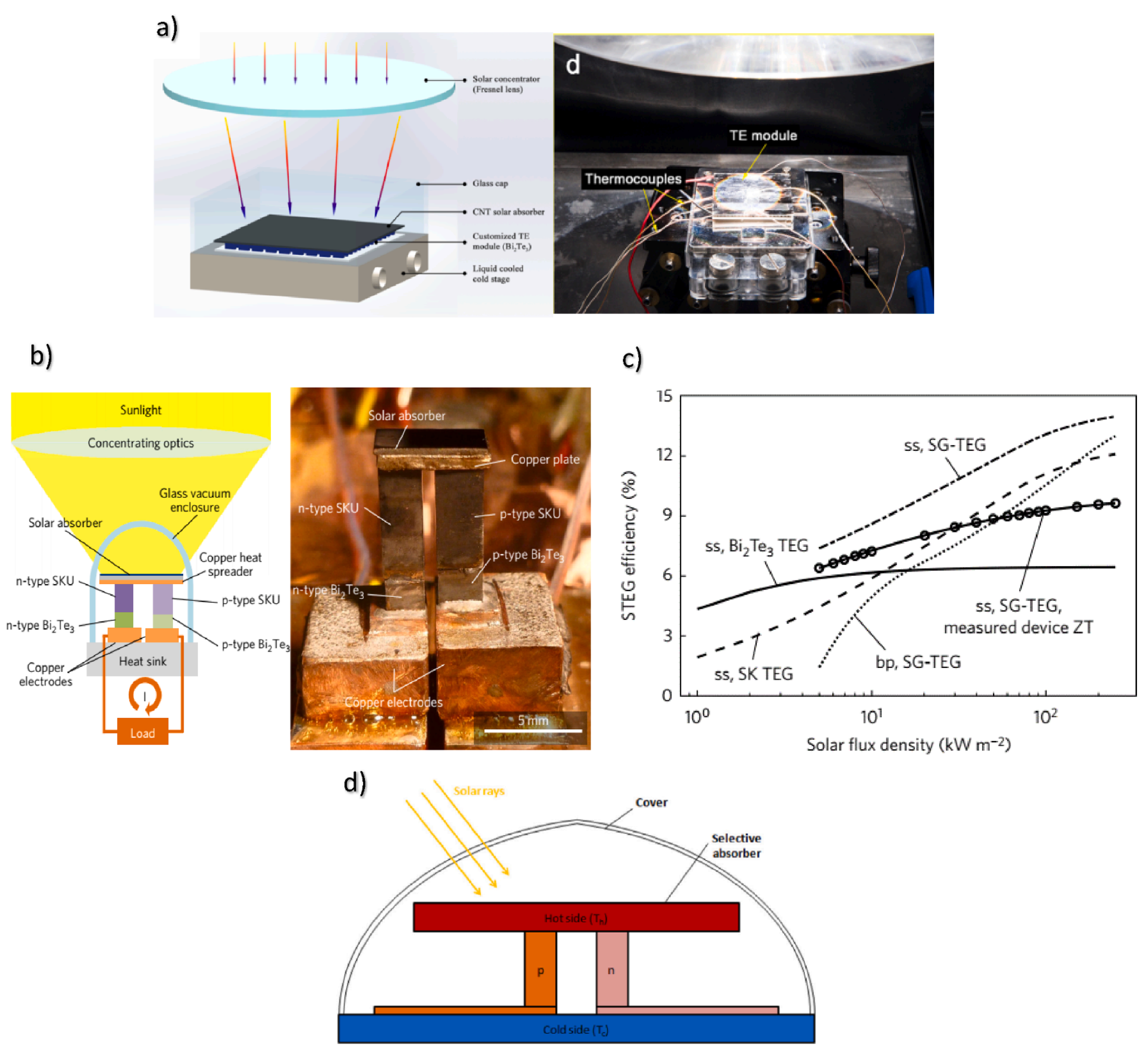

Fig. 19. a) Schematic illustration and test setup view of the STEG system proposed by L. Li et al. [169], b) Diagram of the STEG system and prototype view of a STEG cell, D. Kraemer et al. [170], c) Simulated maximum efficiencies of STEGs with various design configurations optimized over a range of solar flux densities: STEG with spectrally selective (ss) solar absorber and a TEG based on bismuth telluride (Bi_2Te_3) (solid line), skutterudite (SK, dashed line), segmented (SG, Bi_2Te_3 + skutterudite) legs (dash-dotted line) and a TEG based on measured effective device *zT* (solid line with open circles); STEG with black paint (bp) absorber and segmented TEG (dotted line), printed from D. Kraemer et al. [170], d) Schematic view of the examined solar thermoelectric generator by E. Bellos and C. Tzivanidis [171].

would definitely be one of the attractive alternatives in solar systems.

6.3.2. Absorber designs for solar TEGs

Different designs have been proposed for absorbing systems in the literature to improve STEG systems performance. One way to efficiently reduce the losses from the absorbing system is the utilization of light trapping cavities. M.A. Al-Nimr et al. [172] proposed a novel solar thermal collector with a cavity receiver and TEG, manifested in Fig. 20-a. The system was designed to simultaneously generate electrical power and hot water. Although the temperatures of the hot and cold sides of the TEG and the produced hot water were not mentioned in this study, the design idea was excellent and could be improved and further investigated. According to the results, TEM and system efficiencies of ~ 2.5 and 86% under a solar flux density of 2.5 kW.m^{-2} were achieved for the proposed system, respectively. Moreover, the authors analyzed the effect of different parameters on the system's performance, showing that solar radiation and water mass flow rate have the most profound effects on the output power and overall system efficiency. H. Hazama et al. [173] introduced a new design of a STEG for cogeneration purposes. As exhibited in Fig. 20-b, the proposed model consisted of a solar concentrator, an absorbing layer, a conducting layer, a ring-disk thermoelectric, and a cooling pipe passing through the thermoelectric rings. The authors found that using cylindrical TEGs offers better performance compared to the pillar TEGs with the same absorber area; however, using a design like this would cause a non-uniform temperature, thermal tensions, and other challenges mentioned in the study. The results showed a maximum TEG efficiency of 1.8% along with water heating efficiency of 58% for a Skutterudite TEG with a temperature difference of 428 ℃. Hot water was also produced with temperatures around 40-48℃. The system design was compact, and with further improvements, could be applied to eco-houses and factories. This is a solution towards increasing the system's absorption efficiency. Considering the promising characteristics of these systems, they have not been exclusively investigated; it is evident that there is still room for lots of improvements for these systems.

Another challenge in solar thermal applications is the solar radiation fluctuations, which affect the performance of STEGs and also the production of hot water. X. Luo et al. [174] investigated the effect of modified PCMs for thermal management of a STEG system. As represented in Fig. 21-a, in the proposed system, the solar radiations are absorbed directly by the PCM inside an evacuated tubular solar collector, then the heat is concentrated to the hot side of two TEMs employing MCHPs. Thereafter, the extra heat is rejected to the metal heat sinks on the cold sides of TEGs. PCMs in this study are used to make the input heat steady while using a metal heat sink on the cold side will make the temperature difference across the TEG unstable with a change in the ambient temperature. Experimental results showed that the system could not create temperature differences over around 20℃. However, the system could generate electricity up to three hours after the absence of the sun. Although adding the PCM and heat pipes resulted in a reduction in the quality of the thermal energy on the hot side, the advantages of such a configuration are evident. Probably, with a better design for the absorbing system and using solar concentration, the system would improve dramatically because the TEGs are not working at their full potential in this system. Another way to avoid solar fluctuations is to use solar ponds as the absorbing system. Solar pond has been a reliable supply of heat source for industrial processes that require heat at temperatures under 100 ℃ [175]. This heat could be used for power generation with different systems; however, the conversion efficiency would be low because of the low temperatures. TEGs could easily fit into such power generating systems, introducing a reliable and simple system. L. Ding et al. [175] comprehensively predicted the performance of TEGs coupled with solar pond using a transient model. With the proposed system shown in Fig. 21-b the authors discovered a TEG efficiency of 1–1.5%, with the highest potential of energy production being about 4.834 kWh/year-m^2. B. Ziapour et al. [176] investigated the effect of adding TEGs to a solar pond ORC system considering two configurations of direct (Fig. 21-c) and indirect integration of TEGs into the condenser of ORC. According to the results, adding TEG enhanced the system's power production up to 1700 W, and the overall efficiency increased

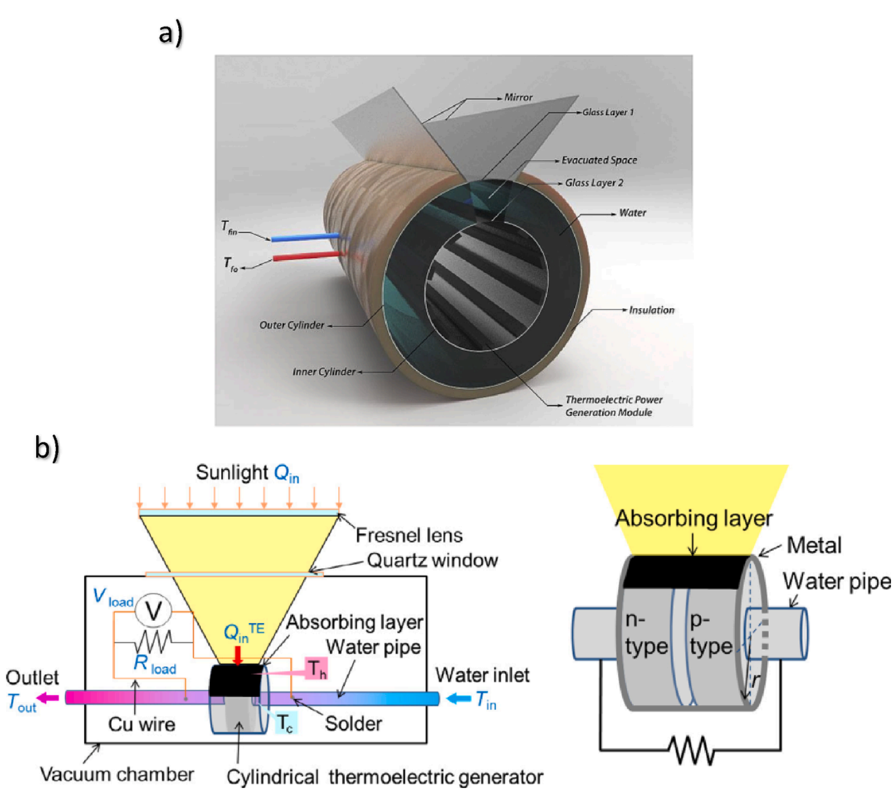

Fig. 20. Illustrations of the proposed systems by: a) M.A. Al-Nimr et al. [172], b) H. Hazama et al. [173].

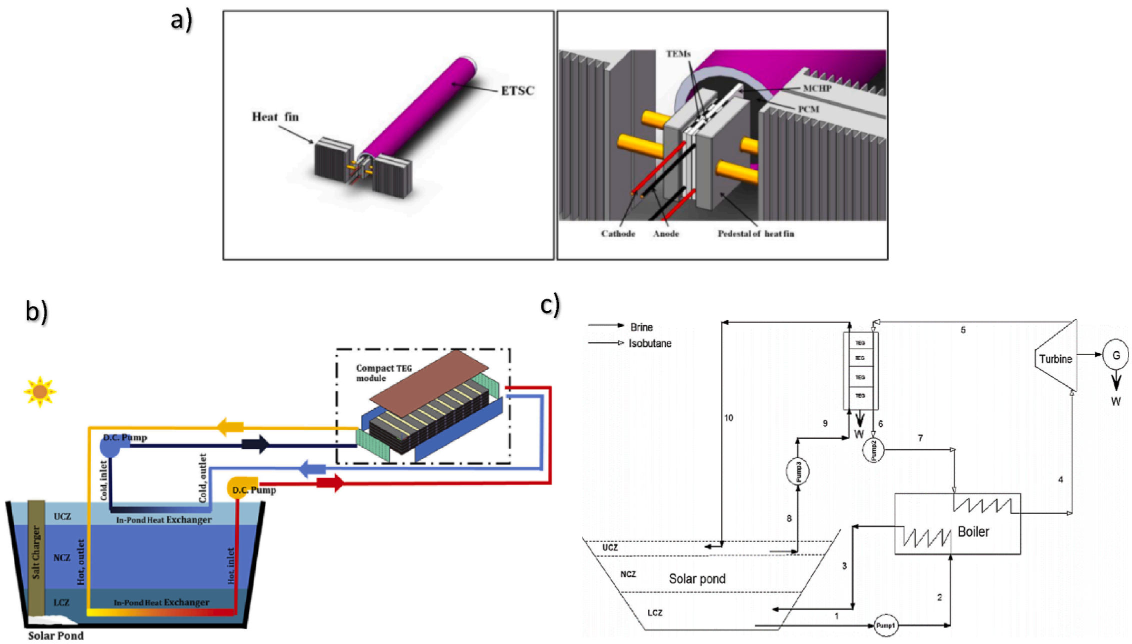

Fig. 21. Schematic views of a) STEG with modified PCM on the hot side, X. Luo et al. [174], b) Solar pond TEG, L.C. Ding et al. [175], and c) Solar power plant with TEG used directly in the condenser of ORC, B. M. Ziapour et al. [176].

around 0.2%, with the TEG efficiency being around 1% for a zT value of unity. Moreover, the authors showed that using TEGs directly in the condenser would result in higher average output power and efficiency than the other model. The study shows, the flexibility of TEGs to cooperate with different systems. Although these designs might not utilize the TEGs in the best way possible, at the moment, they seem to be the best option for TEGs in relatively high-power solar systems. Moreover, it is likely that these systems could be practically used because of the simplicity and reliability they offer compared to ORCs and other options.

6.3.3. Solar TEGs for small and reliable power generation

Another application of STEGs is for low power systems with reasonably simple designs thanks to the TEGs high scalability. G. Li et al.

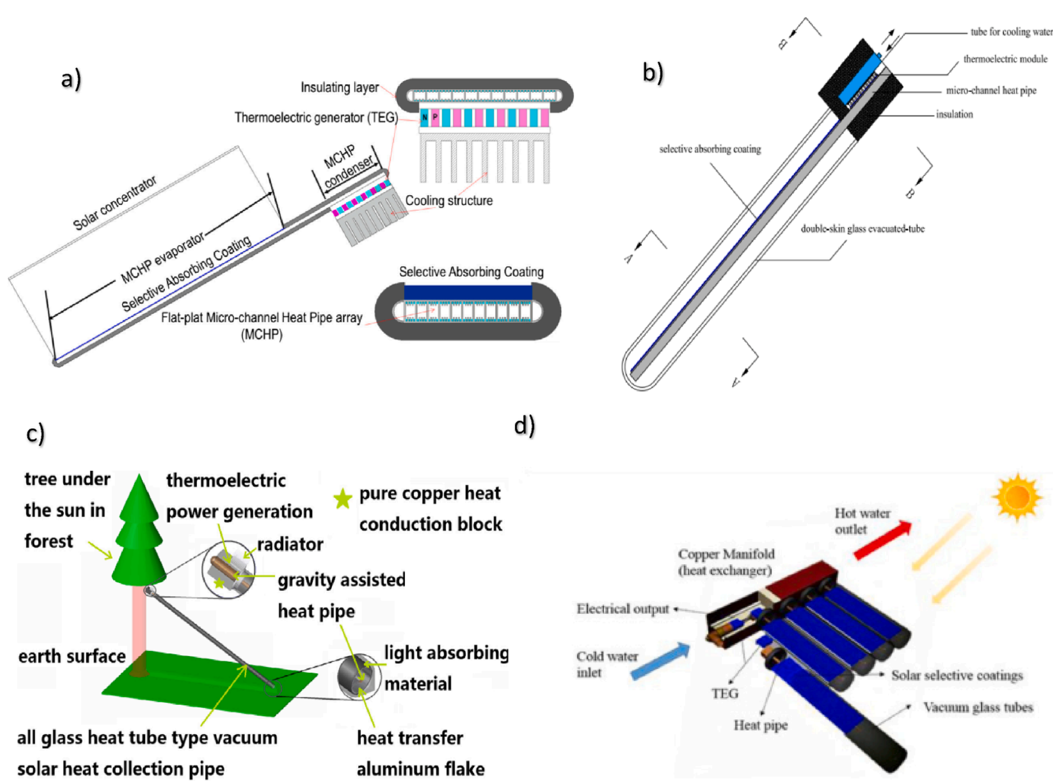

Fig. 22. Schematic diagrams of HP-assisted systems for low power applications: a) G. Li et al. [177], b) S. Lv et al. [137], c) Z. Zhe et al. [179], and d) S. Lv et al. [180].

[177] proposed an MCHP as the absorbing system for STEG in low optical concentrations in order to reduce the thermoelectric material cost. The proposed system is shown in Fig. 22-a. According to the results, a temperature difference of 59.6℃ was achieved at a solar concentration of 8 suns, resulting in an efficiency of 0.82% for the TEG. The proposed system was relatively simple in design and could operate with available TE modules and, as authors showed, has a better performance compared to a STEG system without MCHP while reducing the cost sufficiently. However, the statement about cost is not valid for STEG systems because in a STEG system, as opposed to a PV-TEG system, there is no limit for temperature and optical concentration. In fact, a series of TEGs can be employed in a similar system with a higher concentration and probably better performance, that is, a denser system can operate better on larger scales. Moreover, this proposed system's energy losses would be higher because of the absorbing system's large area. However, the system has a specialty; it is entirely passive with the least maintenance needs and can be used for low power applications. In a similar study, S. Lv et al. [178] proposed a STEG system for combined heat and power production. The new system was similar to the latter, but has no optical concentrator, utilizes an evacuated tube to reduce the heat losses from the absorbing system, and has a water-cooling system which is also used for hot water production as demonstrated in Fig. 22-b. The findings showed that applying this relatively simple design, a TEG efficiency of 1.956% is achievable. Moreover, without mentioning the output water temperature, a thermal efficiency of 50–60% was reported. The improvement in the system's performance compared to the above-mentioned study is evident; this shows the importance of certain parameters and their effects on the system. In another study conducted for applications in low-power wireless sensors, Z. Zhe et al. [179] investigated a STEG's performance based on gravity-assisted heat pipes both experimentally and theoretically. The authors concluded that the proposed system (Fig. 22-c) is able to generate the electricity demand of wireless sensors with the help of a DC-DC converter. A temperature difference of 30–40 K was reported across the TEG with hot side temperatures up to 335 K. Moreover, the economic analysis indicated the competitiveness of the new system for a low-voltage wireless sensor network. A practical design to realize the potential of STEGs has been conducted by S. Lv et al. [180]. They proposed a high-performance STEG without optical concentration shown in Fig. 22-d. Through a careful optimization, they were able to achieve a peak electrical efficiency of 5.2% with available commercial TEGs. Moreover, the authors showed that the proposed system was capable of providing 165% of a small house electricity and fully satisfying the domestic thermal energy (with a 35-50℃ temperature) in a simple and economically beneficial manner. The study shows that the potentials of STEGs mentioned in the earlier part of this section are realizable in real applications; it also shows the importance of a good design, and should be a guide for future works in cogenerating STEG systems.

6.3.4. Solar TEGs cold side management

Cooling the cold side of a STEG is another challenge, and because of the amount of the heat rejected to the cold side, it will always be a challenge for thermoelectricity. Among different cooling methods of the cold side of TEGs, convective cooling is probably the most recommended since it offers the side product of hot water. However, if the system's preference is to generate electricity, considering other options that enhance the electrical performance of the system would be helpful. M. Ge et al. [181] proposed a high concentration (165) STEG system and analyzed its performance under spray cooling (Fig. 23-a). According to the results, a 31.3% higher net efficiency was achieved compared to a system using water cooling, leading to a maximum efficiency of 13.203% for a zT value of unity. Although the reported efficiency may be overestimated because of the simplifying assumptions by the authors and also finding a TE material to have an effective zT value of unity at a 1000 K temperature difference would be challenging, the study shows the effectiveness of spray cooling. The authors declared that the system's significant improvement with spray cooling was due to the higher heat transfer coefficient, lower power consumption, and zero contact thermal resistance. M. Al-Nimr et al. [182] investigated the effect of evaporative cooling on an air heating direct absorption flat plate solar collector integrated with a TEG (Fig. 23-b). The evaporative cooling was realized employing a wetted porous media. The results showed a 19.13% enhancement in the system's overall efficiency under a concentration ratio of 20 suns. Moreover, the authors concluded that TEGs with lower thermal conductivity would be more suitable for these systems as the high heat transfer rate created by the evaporative cooling may have a negative effect on hot air production. The idea of using evaporative cooling for the proposed system is more interesting than the previous system because the production of mid-temperature air already meets the cogeneration purposes. These studies show that employing a better heat transfer mechanism can enormously improve the system's electrical performance; although methods like evaporative cooling can reduce the overall efficiency of the system by taking away the cogeneration opportunity.

6.4. Thermoelectric generators for off-grid power generation in deprived locations

In remote areas, the accessibility of electric power is a well-known problem. Moreover, in such areas, households' thermal energy demand is mostly produced through burning available fuels in stoves and chimneys for cooking, heating, hot water production, and so on. TEGs can be used to generate minor but useful electricity without really affecting the efficiency and main purpose of these systems. Although, as we mentioned before, these demands can be satisfied through the employment of solar energy, solar energy holds its own challenges of being affected by incontrollable natural factors. Nevertheless, using stoves is not the ultimate solution; there are environmental and health concerns about burning biomass fuels, which are the most available type of fuel in these areas[183]. However, in underdeveloped countries, these systems are the most common, and these problems, along with electricity shortage, must be addressed. L. Kütt et al. [183] reviewed the TEG applications for energy harvesting in domestic boilers and biomass stoves. They provided a state-of-art summary and concluded that TEGs with high-temperature sustainability would be attractive for domestic boilers and heating systems to produce high powers. However, powers

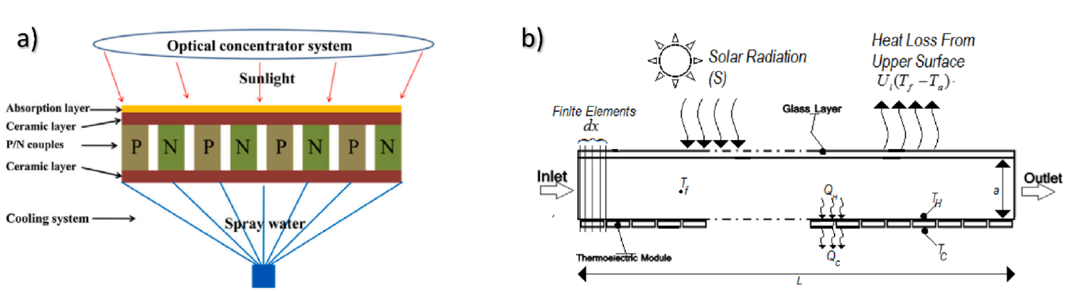

Fig. 23. Schematic view of STEG systems with novel cooling methods: a) M. Ge et al. [181], and b) M. A. Al-Nimr et al. [182].

in the range of 30–70 W would be enough to run the pumps of a heating system, making it a self-powered system; the potential is there to produce powers even more than 1 kW using such systems. Regarding the stove attached TEGs, they indicated that the system cost should be as low as possible, while the robustness and durability are essential for these systems to become competitive in developing countries. They also highlighted the employment of DC convertors and MPPT algorithms for these systems because of the nature of the TEG output power; using power management systems for these systems is a common task. Since then, new configurations and advancements have been provided by researchers to improve these systems. This section will review the main advances and challenges regarding TEGs' applications in deprived households.

At the moment, the low conversion efficiency is the main drawback for systems employing TEGs. Fortunately, in these systems, the main purpose is heat production, and TEGs are suitable for cogeneration systems. Accordingly, using TEGs to produce just electrical power would be absurd. However, a challenge is how and where TEGs would fit into these systems to operate at their best without major effects on the existing system and its performance. K. Sornek et al. [184] analyzed and compared three TEG systems operating with a wood-fired stove. Two of these configurations were designed to be mounted on the flat surface of

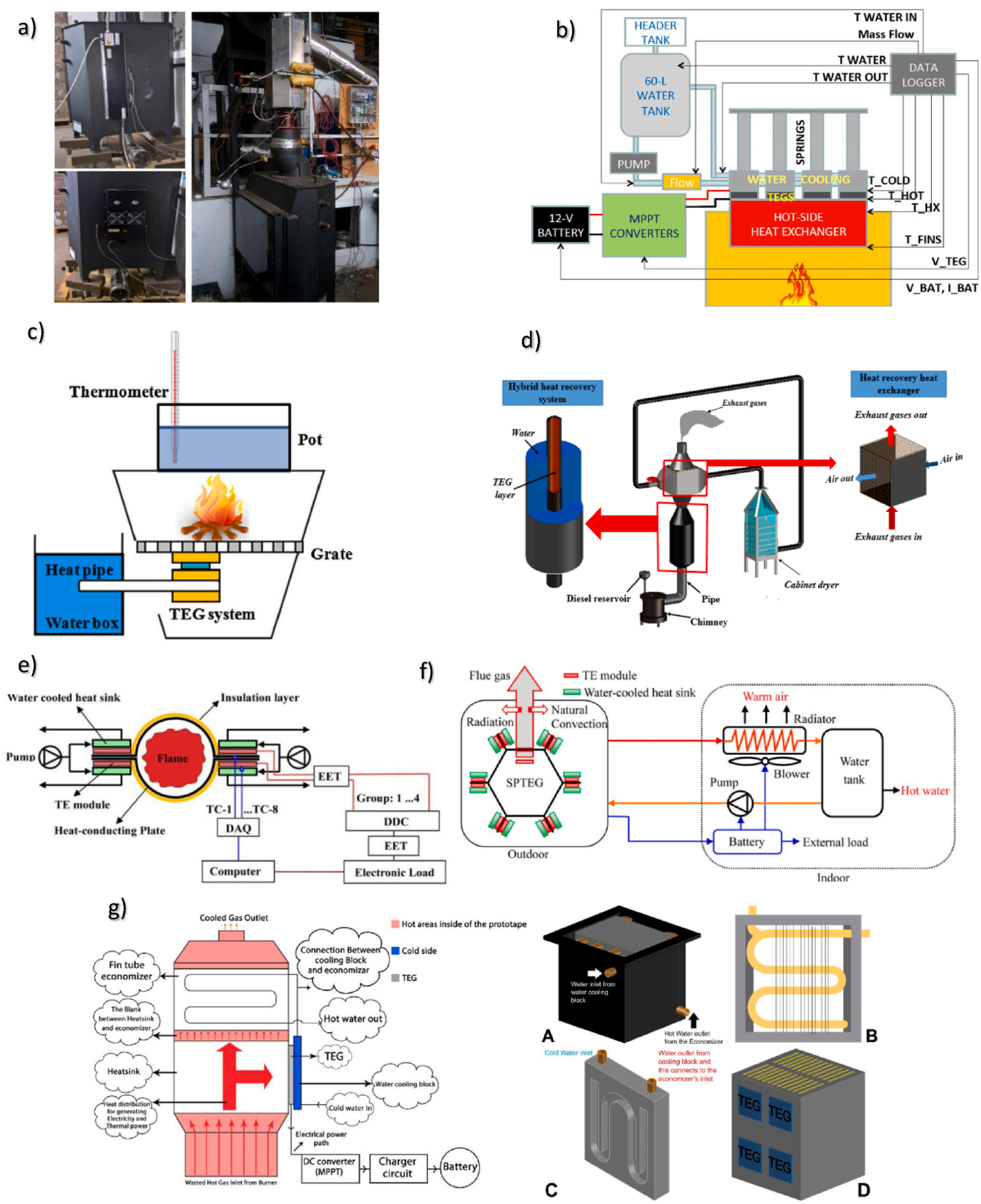

Fig. 24. TEG systems for off-grid power generation in deprived locations: a) Views of the water and air-cooled TEGs mounted to the surface a wood-fired stove and the water-cooled TEG mounted to the flue gas of the stove, K. Sornek et al. [184]. Schematic diagram of the systems used by b) A. Montecucco et al. [185], c) R. Sakdanuphab and A. Sakulkalavek [186], d) H. Jaber et al. [187], e) G. Li et al. [188], f) G. Li et al. [189], and g) S. Zarifi et al. [190] (overall and component views).

the stove with air and water cooling on the cold sides, respectively, whereas the third configuration was designed for mounting on the flue gas channel of the stove (see Fig. 24-a). Experimental results showed that the TEGs produce no more than 41.7% (45 W), 31.2% (100 W), and 7.2% (350 W) of their nominal power, respectively. Moreover, the authors found that the flue gas mounted TEG has the strongest effect on the performance of the stove, while the two others were reported to have minor effects on it. Also, through considering different factors like overall cost and system performance, the authors concluded that the air-cooling TEG is the most likely to be used in practical applications. A. Montecucco et al. [185] investigated the performance of a TEG integrated with a solid-fuel stove for combined heat and power production. The system included four TEG modules cooled by water, and the extracted heat was stored in a tank (see Fig. 24-b). Experimental results showed that during an operation time of 2 h, the average power of 27 W (42 W peak) is generated by the system, and the temperature of the water in the tank increases around 20℃. The authors indicated that the generated power could satisfy the demand of the pump and two high-power USB devices, leading to a yearly saving of €96. Although the system's effect on the stove's performance was not mentioned, the study revealed the potential of such systems with relatively simple designs. R. Sakdanuphab and A. Sakulkalavek [186] introduced an interesting design for a TEG system attached to a cooking stove for CHP production. This system, shown in Fig. 24-c, consisted of a TEG module connected to the bottom of a cooking stove and a heat pipe immersed in a water tank used as the cooling system for the cold side of the TEG. According to the results, the system is capable of producing up to 8 W electrical power as well as hot water with temperatures up to ~ 58℃. Moreover, they reported a minor efficiency decrease of 5% for the stove because of the integration of the TEG. Overall, the system design has an excellent idea: producing hot water and electricity using a fully passive system. The possibility of extending such systems could be considered for the future studies. The type of fuel used in the system could extremely affect its performance. H. Jaber et al. [187] theoretically estimated the potential of a thermoelectric cogeneration drying system for domestic applications. Three case studies were conducted with three different fuels of diesel, coal, and wood. The system consisted of two-stage heat recovery systems recycling the waste heat from the flue gases of a chimney for space heating. The first stage recovery system was composed of 100 TEG modules and a water pipe surrounding them, whereas the second was a heat recovery heat exchanger to produce hot air for drying purposes (see Fig. 24-d). Referring to the results, a maximum electrical power of 240 W and hot water with temperature of 75℃ were achievable using coal and diesel as the fuel, while these values for the wood burning system were 94 W and 58℃, respectively. Moreover, with respect to the results, the system was capable of recovering 20, 42, and 84% of the energy lost through the exhaust gases of diesel, coal, and wood burning systems, respectively; the difference was explained to be the properties of the exhaust gases. Although the results could be well overestimated because of the assumptions made, the system shows good potential for further studies. G. Li et al. [188] investigated the performance of a stove-powered water-cooled TEG for electrical power generation. They employed a heat collector for the hot side of the TEG in their system to absorb and conduct the heat from the stove to its outer flat plate, where TEGs were installed (Fig. 24-e). Results showed that the new system generates 51.2 W net power using 20 TEMs. However, the main downside of such a system is that it could not be used for existing stoves, and the stove should be specifically designed to use this system. Moreover, the cooling water is abandoned with a temperature of 33℃, which leads to a good cooling temperature at the cold side because for CHP systems, a higher water temperature is desired, resulting in a degradation in the performance of the TEGs. In another study, G. Li et al. [189] comprehensively investigated the performance of a stove-powered TEG for CHP production. This system similarly employed a heat collector with a different shape to absorb and conduct the heat from the stove to the TEG; the difference was that the cooling water outlet is used for heating purposes in this system (see Fig. 24-f). According to the results, a maximum output power of 252 W with an average charging power of 118 W as well as a heating power over 9.8 kW were achieved during the experiments. Moreover, the authors concluded that the heat collection efficiency of the system is low and could be improved using better designs. The authors also found the system costly with low-profit and suitable for off-grid areas and suburbs under emergency conditions. Nevertheless, the study is great in the sense that includes almost all steps for a new system from design to real application and can be an example for future studies. The challenge of low heat collection in these systems is a drawback for real applications; if the heat collection is to be higher, the cold side temperature of the TEGs would be affected, and if the optimization goal is to generate a high electric power, the heat collection would be low. S. Zarifi et al. [190] recognized this challenge and proposed a solution by employing a finned tube economizer. They proposed a two-stage heat recovery system applied to the flue gas of a chimney. The exhaust gases enter a recovery channel and lose a fraction of their thermal energy to the hot side heat exchanger of the TEGs and then, pass to a finned tube heat exchanger, where another fraction of the thermal energy is transferred to the water flowing in the tubes (see Fig. 24-g). Employing this configuration provided two advantages for these systems; first, the higher rate of cooling water resulted in better cooling of the TEGs, i.e., a higher power production, and second, the hot water at the system outlet had higher temperatures. The Experimental results showed that this system is capable of generating 44 W electric power (4 TEMs) and hot water with 48℃ temperature with an overall thermal efficiency of 90%. The authors concluded that the system can be applied to any flue gas at a low cost. However, for more electricity, the number of TEGs can be increased, but the cost of the system would increase significantly because the TEGs constitute the main costs for such systems. Furthermore, the effect of adding this system on the combustion process should be analyzed along with some other parameters to prove the feasibility of the system. To sum it up, the TEGs are a potential candidate to be used in the mentioned systems. These systems should be considered for combined heat and power production to be beneficial as much as possible. Also, there is much room for improvement regarding system designs to reduce the costs and improve the performance. With proper design and management, these systems can be an excellent solution for heat and power production, notably in restricted areas.

6.5. *Thermoelectricity in portable micro-power generation*

In the past few years, portable power generation has gained much interest because of the need for such power sources with the advent of portable devices. Traditional battery technology has been the primary power source for portable devices; however, batteries are heavy and have low power density. In addition, they do not last long enough, demand long charging time, and when disposed, they release toxic substances to the environment [191]. One way to resolve these problems is to use micro-scale combustors, which offer much higher power density, more reliability, and less environmental effect. With efficiencies around 5%, hydrocarbon fuel-based power generators can provide a six times higher power density compared to advanced electrochemical battery concepts [192]. However, this is not an easy task to achieve; designing combustors with stable flame and a conversion device to convert this heat into electrical power are the main challenges in this regard. N. Kaisare et al. [191] conducted a detailed and comprehensive review of the fundamentals, devices, and applications of micro-combustion, producing useful information on the concept. At the time, they concluded that TEGs are not the best option for portable power generation because of the low-temperature operation which makes them incompatible with high temperatures of combustion. However, since then, some modifications have been made to the micro-combustors, and some system designs have made TEGs one of the best for these applications. Here, we will briefly review the most recent improvements and introduce the unsolved challenges in micro-combustion TEG devices for portable power generation.

Thermoelectric generators can be excellent for these systems because of characteristics like compactness, reliability, low weight, and having no moving parts. Meanwhile, utilizing TEGs in these applications will not be straightforward because of challenges like low conversion efficiency. Moreover, the most popular TEGs are Bi_2Te_3-based, which are for low-temperature operation; this adds another challenge to the design of combustors and heat exchangers. The combustor design faces the main challenges in these systems; the aim would be to have a stable flame while utilizing the produced heat as much as possible. Moreover, the design complexity would increase considering the fuel tank, mixing system, ignition method, cooling system, and so on. T. Singh et al. [193] investigated the performance of a non-catalytic self-aspirating *meso*-scale premixed burner integrated with a TEG for portable power generation. The proposed system was mainly composed of a burner, internal heat exchangers, TEMs, and heat sinks (see Fig. 25-a). Propane was used as fuel in this system, and four different configurations were investigated. According to the results, a 3.54 W maximum power is obtained from an input power of 250 W using two TEMs. Moreover, through a comparison of different configurations, the authors found that using more TEMs results in a worse overall system performance because the same input power is shared between more modules. This system is advantageous as it is self-aspirating and utilizes passive heat sinks for the cold side of TEGs, making it a practical design for portable power generation although more compactness is demanded in such systems. B. Guggilla et al. [194] designed and studied a microcombustor-TEG utilizing platinum nanoparticle catalysis micro-channels for portable power generation. The system (see Fig. 25-b) was designed to realize room-temperature self-ignition with stable combustion and to preheat the entering methanol-air mixtures. According to the results, an output power of 490mW (0.1% system efficiency) is obtained with a temperature difference of 62℃, while the estimated power was 1400mW for this design. Moreover, the authors found that increasing the fuel injection rate does not really contribute to the temperature difference across the TEG and mostly affects the exhaust temperature and heat losses. This shows the importance of the combustor design to achieve high thermal collecting efficiencies. In compact designs, the residence time of the exhaust gases is important for thermal collection efficiency, which is affected by different factors, including the channel's geometry and mixture flow rate. H. Gao et al. [195] developed a *meso*-scale combustion-powered TEG for portable power generation. The overall configuration of the proposed system is shown in Fig. 25-c. In accordance with the results, a maximum output power of 1.88 W is achievable with system and TE efficiencies of 1.74 and 2.31%, respectively. The hot side temperature was kept under 100℃ during the experiments; however, because of the design, a proper heat collection of 77.4% was achieved. The authors concluded that the main limit for the efficiency of the system is the TE efficiency. Nevertheless, the TEGs were not working at their full potential, which further affected their low efficiency. B. Aravind et al. [196] developed an efficient compact microcombustor-TEG system for portable power generation. The proposed system utilized a stepped geometry and porous media for better and stable

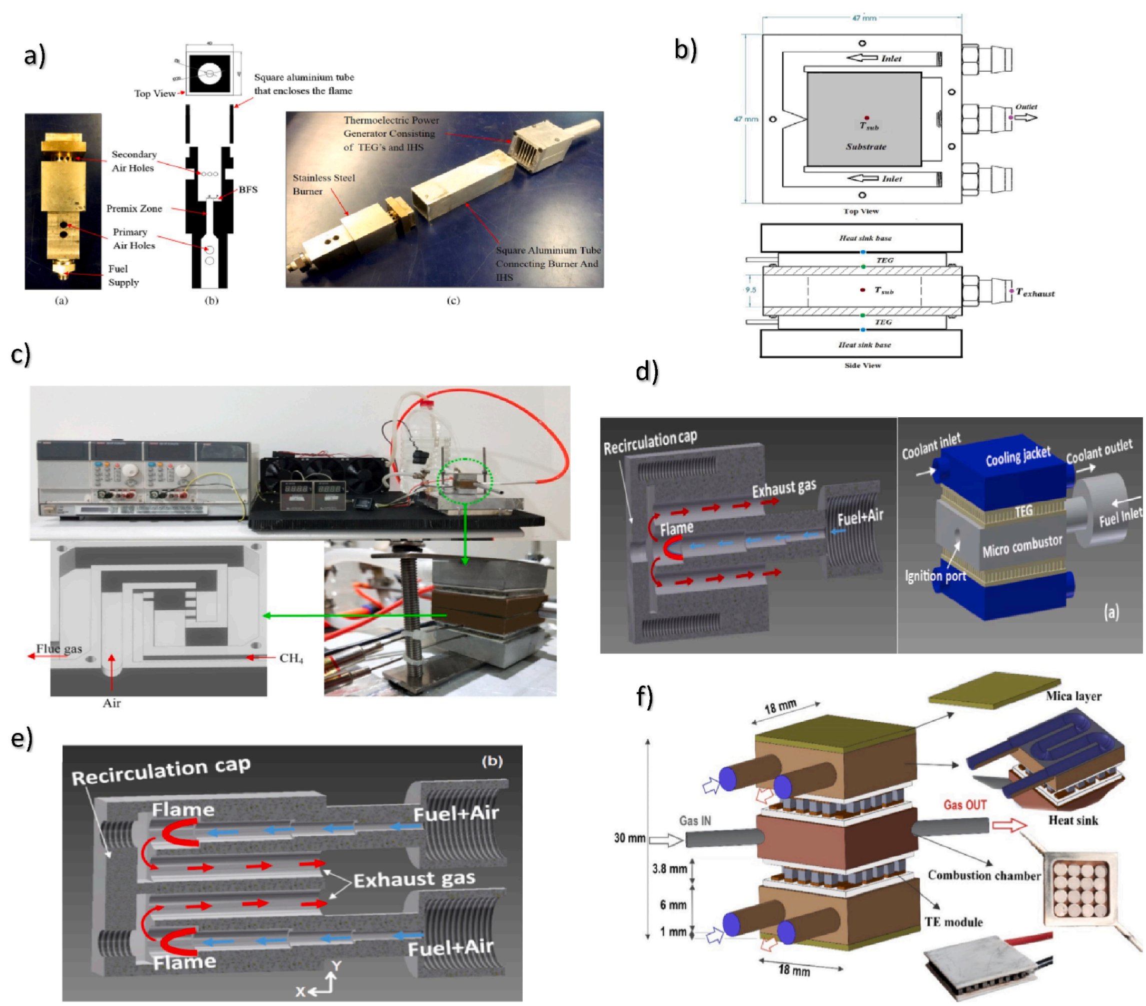

Fig. 25. Schematic and prototype views of micro combustion-based TEG systems for portable power generation proposed by: a) T. Singh et al. [193], b) B. R. Guggilla et al. [194], c) H. Gao et al. [195], d) B. Aravind et al. [196], e) B. Aravind et al. [192], and f) H. Abedi et al. [197].

combustion with a heat recirculation channel for exhaust gases (see Fig. 25-d). The results showed that using two TEMs and water-cooling jackets, maximum output power and efficiency of 3.98 W and 4.03% are achievable by this system, respectively. The combustor design was compact, which resulted in a high power density for the proposed system; however, this is without considering the auxiliary components like air and fuel tanks and their mixing system and the water circulation system. Moreover, although a large portion of the generated heat is still wasted in exhaust gases, the system shows great potential in terms of efficiency and compactness of the combustor design. In order to further improve the system performance, B. Aravind et al. [192] proposed a similar system with dual combustion. The only difference was the geometry of the combustor compared to their previous study (see Fig. 25-e). The results indicated an improvement in the temperature distribution and the heat collection performance of the system, which led to higher output power and efficiency of 4.52 W and 4.66%, respectively. Moreover, the authors showed that the auxiliary input power is negligible compared to the system's output power; however, in systems with lower output power, this may become a decisive factor. Although an improvement in the system's overall performance was obtained, a large portion (~60%) of the generated energy was lost through exhaust gases, which indicates that there may still be room for more improvement in these systems. H. Abedi et al. [197] investigated the performance of a small size thermoelectric power supply as a battery backup. The proposed system (see Fig. 25-f) employed a catalytic micro-combustor as the heat source with two TEMs and a water-cooling system. Results showed that a TEG efficiency of 3.4% with an electrical power output of 5.3 W is achievable for this system. Moreover, the authors deduced that the system's output is more than enough to satisfy the charging need of different AA type batteries. Furthermore, the cold side heat exchanger was one of the critical components in these systems. Because of high heat fluxes while having compact and small geometries, a heat exchanger is needed to create a high heat transfer rate to drag the heat through the TEG as much as possible. On the other hand, for the sake of portability of the system, the heat exchanger has to be as simple as possible. However, this issue has not been studied much. B. Aravind et al. [81] investigated the role of three types of heat sinks in developing an efficient combustion-based TEG. A dual combustor was used by the authors to investigate the effect of heat sinks. The authors used three simple fin, fin-fan, and water circulating heat sinks and compared them from different viewpoints. According to the results, the water cooling showed superior performance compared to the air-cooling heat sinks, while it consumed less power than the fin-fan heat sink. However, for portable power generation, carrying water might be a downside. More studies on other heat sinks should be conducted for a distinguished perspective of the demanded characteristics in such systems. To sum it up, TEGs show great potential for portable power generation from micro- and *meso*-scale combustors in terms of output power, efficiency, compactness, power density, and so forth. However, more investigations are necessary for an application-level comprehension of these systems like cost and lifetime investigations and more compact overall designs for portability, which favors self-aspirating and self-igniting systems with simple cooling methods.

6.6. Thermoelectric generators for space applications

Another application of thermoelectric power generation is in space missions, where advantages like compactness and high reliability are in need, especially in deep space exploration. These properties are the main reasons why many space missions have used radioisotope thermoelectric generators (RTGs) for more than 50 years now. Radionuclides are a sustainable energy source with an extremely high specific energy in the order of 10^6 MJ/ kg; they are capable of producing high-grade thermal energy during their decay for several decades [198]. The produced thermal energy should be converted into electricity utilizing a converter. Thermoelectric generators have been a famous success in space applications. X. Wang et al. [198] reviewed the critical design features of thermal-based radioisotope generators, including RTGs. They showed that at the moment, thermoelectric generators are considered as the most reliable option with efficiencies of 6.6% and that with the new developments, it is possible to achieve system efficiencies above 15%. Although new developing technologies with other converters possess higher efficiencies, the challenges for such systems are long-life reliability and complex system designs. Furthermore, the authors concluded that a range of generators in diverse sizes can be used from power supply on Moon and Mars and deep space explorations to terrestrial applications on boats, underwater, and in the Polar Regions. Accordingly, there is a plethora of opportunities for RTGs, at least in the applications that are not in close interaction with humans or other living species. K. Liu et al. [199] experimentally optimized a small-scale structure-adjustable RTG, developing two types of structures for TE legs (see Fig. 26-a). The results revealed that the fan-shaped and annular RTGs achieve maximum powers of 1.9 mW and 3.93 mW at 398.15 K, respectively. Moreover, the authors concluded that the developed system is capable of providing stable and real-time volt-level voltage and milliwatt-level power, which could serve for a vast area of applications from meteorological monitoring equipment and seismometer to microsatellites. The main challenges for RTGs are their low efficiency and safety; it should also be noted that radioisotopes, if disposed, can lead to hazardous results. This may be the reason why not many RTGs are used in terrestrial applications unless there is a need for reliable power in special circumstances. Moreover, there is not much information about the financial aspect of these systems although for such applications, economics is not a priority. There have been other TEG systems for onboard power generation in space applications. T. Kwan and X. Wu [200] investigated the performance of a hybrid PV-TEG system for outer space applications. They proposed a simplified model for the optimization of mass and power of one/two-stage TEG integrated into a PV panel. The results showed that the addition of the TEG can improve the overall power and efficiency of the system at the expense of added weight. They also showed that the main source of added weight is the cold side heat exchanger. Although the simplifying assumptions made by the study may lead to an overestimation of system performance, the study reveals the effect of different design parameters on the performance of the system. Furthermore, the reliability of such a design is limited by the presence of sunlight. In the meantime, because of the absence of an atmosphere on some planets and also for applications like satellites orbiting the earth, the presence and absence of the sun can drastically change the thermal environment of the satellite or spacecraft, leading to great thermal fluctuations. W. Zhu et al. [201] proposed a system to utilize these fluctuations for power generation. The proposed system was mainly composed of TEG and PCM storage (see Fig. 26-b), where the TEG produces power from the heat flow in- and outside of the PCM when thermal conditions of the environment change. Assuming a cyclic temperature change from + 100℃ to −50℃, each lasting for 30 min, the authors optimized the mass and melting temperature of the PCM. They concluded that a small size of harvester can supply the power requirement for the practical space application and lead to significant space and mass reductions. So far, the RTGs have been the most reliable power source for space applications, especially for missions during which, the sunlight might not be available. Moreover, RTGs guarantee a stable and reliable power supply, while others can be affected by the conditions. On the other hand, systems like the latter one has advantages of being much simpler and easier to implement. Altogether, TEGs are in an advanced position for space applications because of their standout characteristics and as it stands TEGs will continue to be the first choice for these applications.

6.7. Thermoelectric devices integrated with fuel cells

Fuel cells (FCs) are high-efficiency electrochemical conversion devices that generate electricity and heat during an electrochemical

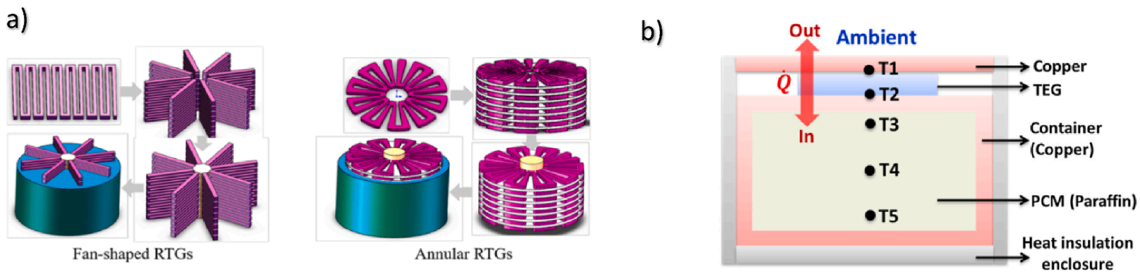

Fig. 26. Schematic views of a) small scale structure-adjustable RTGs, K. Liu et al. [199] and b) PCM based thermoelectric harvester, W. Zhu et al. [201].

reaction between hydrogen and oxygen. There are different types of FCs with different operating temperatures (~50-1000℃), which are suitable for large and small-scale power generation [202]. Simultaneous generation of heat and electricity makes FCs a good source for multi-generational applications. Fuel cells can be hybridized with different systems to produce more electricity, heating and cooling loads, desalinated water, etc. on different scales [203]. T. H. Kwan et al. [203] comprehensively reviewed different energy systems integrated with FCs, including thermoelectric devices. They concluded that TEGs have the potential to operate with small-scale and low-temperature FCs to further increase the electrical efficiency. Moreover, for higher temperatures, they recommend segmented TEGs. They also recognized an enormous difference between the numerical and the few experimental performances reported for FC-TEGs in the literature, which indicates the need for more investigations. However, TEGs potential in these applications needs good assessment, while literature is not rich enough to come to a conclusion for these hybrid systems, probably because of higher achievable efficiencies with other hybrid systems. Here, with the introduction of some of the systems and configurations of FC-TEG systems, we aim to review the applicability of TEGs in these systems.

S. Wu et al. [204] assessed the performance of a molten carbonate fuel cell (MCFC) integrated with a thermoelectric generator; using a numerical model they found that more than 30% improvement in power density and the corresponding efficiency is achievable compared to the stand-alone MCFC. Moreover, compared to other hybrid MCFCs from the literature, they showed that at the operating temperatures (~870–930 K), the system integrated with TEG has a better performance compared to thermionic generator, Stirling, and Rankine heat engines. In a similar study, H. Zhang et al. [205] investigated a two-stage TEG's performance integrated into a solid oxide fuel cell (SOFC). Because of the high operating temperatures, a two-stage TEG was considered for this study, while this might be absurd because of the assumptions and modeling of the system studied. According to the results, more than 35% improvement was achievable compared to a stand-alone SOFC with operating temperatures slightly lower than 1000 K. However, the improvement dramatically decreased for higher operating temperatures. In another similar study conducted by X. Guo et al. [206], the performance of a high-temperature polymer electrolyte membrane fuel cell (PEMFC) integrated with a TEG was assessed. This type of FC might be more suitable for TEGs because of relatively lower operating temperatures (~100-200℃). According to the results, the combined system's maximum power density and corresponding efficiency improved by 21.13% and 15.54%, respectively. The three mentioned studies achieved useful improvements by integrating TEG into FCs. However, some of the researchers' assumptions are not realistic, which may lead to the overestimation of the performances. The studies show the potential of these systems, but for better understanding, there is a need to more realistic investigations, at least from the TEG point of view. T. Kwan and Q. Yao [207] analyzed a CHP system consisting of fuel cell and TE devices. In this study, the TE devices were used for two purposes depending on the state of the FC. If the FC works under the ideal conditions, the TE device is used as a generator to produce electricity from the FC's heat, and if the FC operating temperature is not ideal, the TE device is used either as a cooler or heater. According to the results, the system's exergy efficiency was improved up to 2% using this new configuration. The authors concluded that using TE devices in cooling or heating mode would decrease the exergy efficiency, and should be used only for providing rapid transient changes. In a different configuration, H. Zhang et al. [208] used TE devices for space cooling from the waste heat of a SOFC. In their system, a TEG was used to generate electricity from hot products of the SOFC, and the generated electricity was used to run a TE cooler for space cooling. According to the results, 2.3% and 4.6% improvements in power density and efficiency of the system were achieved compared to the stand-alone SOFC. This configuration could be suitable for micro power generations in deprived households to have electricity, heating, and cooling within a system. Altogether, seemingly, using TE devices with fuel cells is far away from real applications; although the studies show the potential of these systems, more experimental investigations are needed to prove the feasibility of such combinations. Nevertheless, with advancements in the systems design and improvement of TE materials, such a combination could introduce a compact, reliable, and multi-production system, especially on small scales, where TEGs would offer numerous advantages compared to other systems.

6.8. *Thermoelectric generators as a component in power plants*

We have discussed the importance of using renewable energy sources for the future. One of the recent literature trends for reducing the reliance on conventional power sources and their environmental effects is utilizing solar, geothermal, biomass, and fuel cell-based poly-generation plants. There are countless studies on the design and optimization of such plants for different applications. Thermoelectric generators can be considered a potential candidate for waste heat recovery from these systems or as one of the main components. As mentioned before, TEGs are compatible with different scenarios, spaces, operating temperatures, heat exchangers, etc. Moreover, in these power plants, there are different heat exchangers with different operating temperatures and thus, many options for TEGs. TEGs have been considered for low-grade waste heat recovery in different systems. They have been utilized in lieu of condensers in ORCs [209-212], kalina cycles [213,214], absorption chillers, and ejector refrigeration cycles [215-217], or in the last stages of gasifier-based system's exhaust [211], or for heat recovery of a geothermal based system [214] with TEG output powers in a range of 100 W to more than 1000 kW. In these studies, the integration of TEGs was reported to positively affect the efficiency and output power of the systems while improving the plant's financial facet in some cases. This shows the potential of TEGs in these configurations; however, the challenges of operating within these temperature ranges have not been considered in most of these studies, making the results unreliable and unrealistic for the moment. Furthermore, TEGs have been used in higher temperatures and configurations in which the rejected heat from TEGs is consumed in another system like a steam turbine [218] or the evaporator of ORCs [219,220] with output powers in a range of 52.6–160 kW, or for heat recovery from high-temperature products of a SOFC-based system [221]. In such systems, the temperature range would not be the main challenge, but due to the high thermal resistances of TEGs and thus, large temperature drops, a challenge would be the design of heat exchangers and their size. A solution for this type of systems can be the concept of symbiotic generation. However, in the mentioned studies, each component's detailed performance is not the primary objective; these studies are to examine different systems cooperation and optimization of the whole system based on the average and logical assumptions for each considered component. Although, for a better understanding of the feasibility of TEGs in these configurations, more investigations are needed, which would determine the application challenges and effects of adding TEGs on heat exchangers and their heat transfer performance. T. Ma et al. [222] considered a new configuration for such a system. They proposed a new model for recuperators integrated with TEGs and assessed its performance using a numerical simulation; interestingly, in this configuration shown in Fig. 27 the TE legs were used instead of steel fins along the 200 mm long hot side channels. The TE legs were connected to each other electrically in series at the inlet and outlet of the recuperator to generate electricity from the temperature difference between the inlet and outlet gases. A comparison between the traditional recuperator and the novel TE fin recuperator showed that using TE fins rather than steel fins does not have a significant effect on the temperature distribution and heat transfer rate of the recuperator. Feasibility aside, the configuration has a good idea with it, and as the authors reported, a temperature difference of 147 K is achievable with this configuration. However, more examination on the applicability of such configuration is needed to clear some of the questions about practicality and economics.

6.9. Other applications for thermoelectric generators

Thermoelectric generators can be used in different environments; wherever there is a temperature difference, TEGs could be considered a potential technology to produce electricity. This section aims to introduce some of the potential sources for power generation with thermoelectric generators and challenges, and advantages of such systems.

Roads demonstrate a promising locale for energy conversion and potentially could become one of the largest energy sources in the future. Currently, three main techniques exist to harvest energy from roadways: (a) piezoelectricity (converts mechanical energy generated by traffic loads), (b) thermoelectricity (converts the thermal energy collected in pavements), and (c) photo-electricity (converts the incident solar radiation)[223]. In midsummer, the surface temperature of asphalt pavements could reach 70℃, which leads to problems like the urban heat island effect and damages to the structure and lifetime of the pavement [224]. Accordingly, extracting this thermal energy can entail positive outcomes. However, there are challenges of how to extract the collected heat and where to utilize it. Thermoelectric generators are one of the candidates to convert the collected heat into electricity, which will lead to lower temperatures of the pavement while producing an additional power that could be very useful for different applications like online monitoring of the roads. X. Zhu et al.[224] comprehensively reviewed different aspects of road pavement thermoelectric systems, introduced the potentials and challenges ahead of these systems, and made future research recommendations. Although the temperature difference would be small, and there would be challenges of extracting the thermal energy, if realized, it would be a big step in the future energy market. For instance, L. Guo and Q. Lu [225] showed that assuming 0.15 efficiencies for the thermal energy collection of a pipe system and 8% conversion efficiency for TEGs, 55GWh electrical energy per day is collectible from the entire Florida roadway network. In another study with more realistic assumptions, W. Jiang et al. [226] showed that 160 kWh of energy could be obtained during 8 h and from a road which is 1 km in length and 10 m in width. It should be noted that using thermoelectric generators in asphalt pavements is a relatively new subject; more investigations are required in terms of real-time performance, system designs, feasibility, effects on the structure of the pavement, financial aspects, etc. to show a clear prospect of such systems.

Geothermal is another attractive renewable energy source that is conventionally used as a source for different multi-generation cycles. Considering the thermoelectric generators' low conversion efficiency, they are not competitive with existing systems and are mainly added to these systems as a WHR component, as mentioned earlier. However, the characteristics of TEGs can be useful under certain circumstances. L. Catalan et al. [23] studied the performance of an entirely passive TEG system in shallow hot dry rock (HDR) fields, which are defined as geothermal fields with high-temperature compact rocks. These types of geothermal fields cannot be used as a source for the traditional geothermal systems since there is neither a reservoir nor a fluid to operate as a heat carrier. The newly developed system (see Fig. 28-a) can surpass these restrictions and is mainly composed of two two-phase thermosiphons and two TEMs. Utilizing such heat exchangers makes the system robust and reliable with no maintenance need while having a better performance than other passive or active heat exchangers[227]. After modeling and optimizing the proposed system, the authors conducted a case study for two HDR areas within Timanfaya National Park, which indicated a potential power generation of 681.53 MWh/ year. The study clearly shows the potential of TEGs in this type of geothermal resources with minimum environmental impact. K. Wang et al. [228] investigated downhole geothermal power generation from mature oil and gas wells using TEGs. Oilfields possess adequate candidate wells for geothermal development; particularly, mature oilfields contain a large number of high water-cut wells and abandoned wells that could be transformed for geothermal power generation. The proposed system utilizes this availability for downhole power generation where the produced fluid (oil or gas) has temperatures up to 120℃, and the injected water could be used as cold side fluid with temperatures around 20℃. To achieve high temperature difference the authors proposed a new configuration (see Fig. 28-b) and showed that a maximum output power of around 8.5 kW with conversion efficiency of 4.1% is achievable. Later, in a similar study K. Wang and X. Wu [229] investigated a similar configuration for horizontal wells (see Fig. 28-c). In the horizontal wells, the high-temperature fluid is more available and thus, the opportunity for power generation is bigger. Similar to the previous study, the authors estimated the total output power of approximately

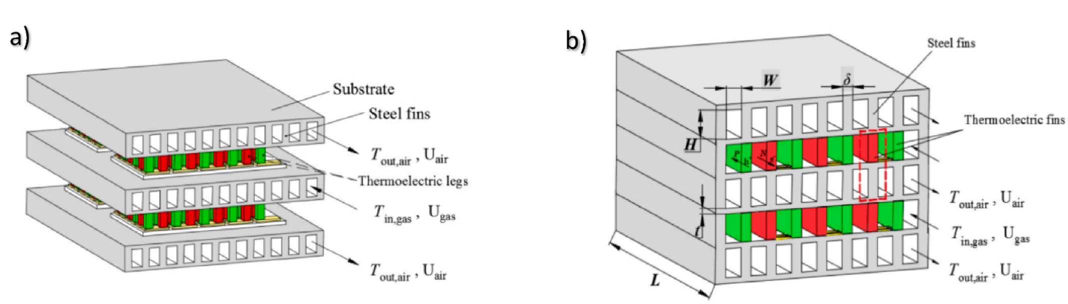

Fig. 27. Schematic of: a) Traditional TEG recovery heat exchanger and b) Novel TEG recuperator, from T. Ma et al.[222].

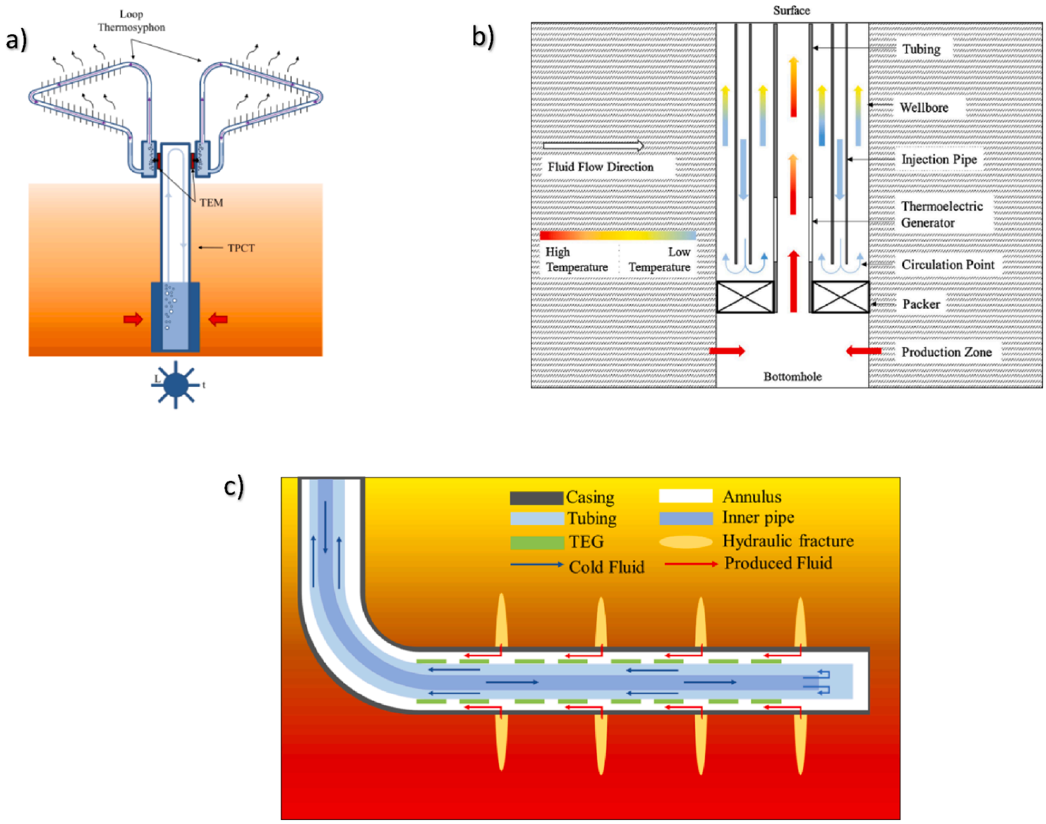

Fig. 28. Schematic view of some of the TEG-geothermal systems: a) Fully passive configuration for HDR fields, L. Catalan et al. [23], b) Downhole thermoelectric generation from vertical wells K. Wang et al. [228], c) Downhole thermoelectric generation from vertical wells, K. Wang and X. Wu [229].

128 kW and overall conversion efficiency of 5.2%. These two studies show the potential of TEGs in unconventional downhole power generation, which could be useful in the oilfields to operate the auxiliary components and reduce the cost and energy demands by generating reliable power from a renewable source. However, there are lots of question marks that should be investigated to clarify such systems' economic feasibility and practicality, but this can be a starting point for oilfields and other applications like conventional geothermal systems. Furthermore, TEGs can also be used in conventional geothermal sources and be advantageous in terms of reliability, simplicity, and compactness. C. Suter et al. [230] optimized a 1 kW TEG stack for on-surface geothermal power generation. The authors considered two optimization scenarios of highest conversion efficiency or highest power density. According to the results, they were able to achieve a 1 kW net power with maximum efficiency of 4.2% (0.0135 m^3 stack volume) or in the second case, with a minimum volume of 0.0021 m^3 (2.1% efficiency). Using such a system would significantly reduce the complexity and maintenance needs of traditional geothermal systems which may be suitable for some geothermal sources.

Another field in which thermoelectric generators have gained lots of attention is wireless sensing and monitoring. In such applications, TEGs offer lots of benefits over other energy converters and batteries. Although it may be of minor quantity and quality, thermal energy is widely available in most of the applications one can imagine. On the other hand, batteries can not offer the reliability and durability of TEGs. Moreover, with vast improvements in MEMS technology, there is a need for power supply in a range of milli-Watt to Watt for these systems. We have already introduced some of the applications that employed TEGs to supply power for monitoring and sensing devices from roads to ecological and space applications; nevertheless, the opportunity is much bigger than previously mentioned. Thermoelectric generators can offer power supply on every sensing node with high reliability and compactness, which is desirable for wireless sensing and monitoring applications. A. Rodriguez et al. [231] experimentaly evaluated the applicability of TE-driven autonomous sensors in a biomass plant. Envolving some batteries to save the continious power generation of TEGs, the authors were able to power the required sensors and transmitt the data at least every 2.6 s. In a similar study Y. Wu et al. [232] proposed a segmented TE energy harvester for a gas turbine (GT) sensing and monitoring system; the TEG was embedded in the isolation layer of the GT and was cooled using two heat pipes. The authors found that the power supply by a TEG module was more than enough to run the few wireless sensors in a GT. T. Tuoi et al. [233] investigated the performance of a TEG-PCM system and showed that it could produce sufficient power for wireless Internet of Things (IoT) sensing systems. The proposed system employed the ambient temperature change to drive the heat through the TEG and in and out of the PCM container for power generation. Y. Xie et al. [234] assessed a TEG's performance for power production from deep-sea hydrothermal vents. The proposed system employed a heat pipe to drag heat from the hydrothermal vents and produce power from the available temperature difference between the heat pipe condenser and seawater using four TEMs. The authors reported a continuous power output of 2.6–3.9 W during the field tests and concluded that this power would be enough for seabed observation equipment. Overall, these studies suggest that TEGs in cooperation with passive heat exchangers are in an advanced position for the mentioned applications. Nevertheless, these applications demand unique designs and engineering to improve in directions like more compactness and reliability as the sensing equipment are moving in the same directions. There is much more research regarding the application of TEGs in monitoring and sensing. However, considering the context of this paper, we see it enough to mention two of the recent reviews done by E. Liu et al. [235] and Z. Fan et al. [236] on the matter of flexible thermoelectric generators for applications including wearable devices that employ TEGs for power production from the thermal energy of the human body which can be used in healthcare sensors or other portable and low-power electronic gadgets.

7. Conclusions

Precisely, two centuries have passed from the discovery of first thermoelectric effect. During this period, countless effort and dedication has been put into the development of thermoelectricity, and although slowly, thermoelectricity has overcome many setbacks on the road. Over the past two decades, great improvements has been achieved in thermoelectric materials, devices, and applications, leading to a rich literature on each thermoelectricity's branches. However, there seems to be a disconnection between the mentioned areas of research. In the present review, it was tried to build a connection between these areas by gathering useful information on modeling approaches, thermoelectric materials, device-level designs, and system-level designs. Based on such fundamental information, it was possible to review the applications of TEGs from a comprehensive and realistic viewpoint. The main conclusions and outlines for future research can be summarized as follows.

- Improving thermoelectric materials in terms of costs and performance is an essential primitive for the practicability of TEGs. Encouraging achievements have been reported throughout the past decade (as summarized in Fig. 4), and the field is still active and progressing. Thanks to the development of Cu_2Se and SnSe based materials with exceptional thermoelectric performances, zT values well over 2 especially for medium temperature ranges has been achieved in recent years, and just recently, the record zT value for a bulk thermoelectric material was improved reaching peak and average values over 3 and 2. Nevertheless, if thermoelectricity is to compete with other technologies, more effort is necessary; especially, considering the wide availability of medium-to-low temperature heat in most of the potential applications for TEGs, finding new materials and improving the existing ones for this temperature range should be at the top of this field's agenda.
- Many achievements have been accomplished on thermoelectric device design and optimization, the effect of geometrical parameters is now well-understood, and different structures and shapes, including annular, cylindrical, segmented, and cascaded have been evaluated for thermoelectric generators each offering special advantages for certain applications. Additionally, studies on the effects of electrical contact resistance and thermal insulation of the gaps in TEMs have improved the overall performance of TE devices. However, most of the studies have been theoretical, and more experimental evaluations are in need. Furthermore, new and high-performance thermoelectric materials have not been used in most of the recent designs, and for a faster development of high-performance devices, it is essential for device-level designs to catch up with the improvements in thermoelectric materials.
- Tangible experience exists on heat exchanger designs, thermal design and optimization, and electrical management of TEG systems. Having a well-designed thermoelectric device, it is essential to employ it in the best possible manner. In that regard, choosing the type of heat exchanger, design optimization of heat exchanger, optimizing the number and arrangements of modules, and surmounting the effect of contact thermal resistance are of the main challenges. The selection of heat exchangers mainly depends on the application demands. Some incredible achievements have been reported using phase change passive heat exchangers, water circulating blocks, nano- and microfluid heat exchangers, direct contact configurations and spray cooling techniques. However, from a general perspective, high-performance passive heat exchangers like heat pipes and thermosiphon are the first choices as they protect the interests of the whole system in being reliable and low maintenance while demanding no auxiliary consumption. All in all, it is necessary to consider the whole system as a unit and assess its feasibility in comparison to other options. Moreover, economic analysis would be helpful for future improvements although thermoelectric technology is not fully established yet, which can make the economic analysis somewhat difficult.
- Industrial waste heat recovery holds promising potentials for TEGs. Characteristics of TEGs gives them the advantage of being implemented in existing industrial systems with high flexibility. Especially for unconventional waste heat sources including furnace walls and casting products thermoelectric generators seem to be the first choice. Although the conducted studies show the great potential of thermoelectric generators in these applications, there is a need for more field tests and experimental studies. Moreover, based on the potential of thermoelectric generators for waste heat recovery from untapped and unconventional sources in industrial process, investigating the recognition of these sources and designing the recovery systems should be expanded.
- Application of vehicle exhaust TEGs is highly uncertain with the push for EVs. Although some promising results are reported on the feasibility of vehicle exhaust TEGs, there is a lot of complexity in evaluating the effect of TEGs on vehicles. In the aggregate, the ATEGs are better performing on extra-urban driving cycles and heavier vehicles. Nevertheless, the rich literature on this topic can offer a lot of useful information on heat transfer designs and transient waste heat recovery which can be applied to similar systems like flue gases.
- Hybrid PV-TEG systems are complex mixture of promising results and disappointment. Adding TEG to unconcentrated PV cells does not show any signs of improvement, and it seems that the fact is not going to change even with improvement of thermoelectric materials. PV-TEG systems with thermal and/or optical concentration give better results but they are most likely uneconomic compared to other photovoltaic-thermal systems. Additionally, the opposite response of TEG and PV to a temperature rise in the cell results in a complexity of design for these systems. Nevertheless, some configurations have been proposed to eliminate this effect. A promising solution is employing spectrum splitter; however, such studies are limited and all are theoretical. Altogether, more theoretical and experimental investigation on CPV-TEG systems with novel configurations is recommended.
- Solar TEGs are one of the promising alternatives to solar PVs, and in some cases, STEGs offer a better economic aspect. Challenges for solar TEGs include design of absorbing systems for high solar concentrations and low efficiency for low solar concentrations. Moreover, because of the low efficiency a considerable part of the absorbed heat needs to be dissipated at the cold side of TEG; therefore, theoretically, these systems are suitable for combined heat and power generations in different scales with high reliabilities. Nevertheless, there is still many rooms for investigation regarding the practicality of these systems, absorbing system design, and large-scale feasibility.
- Electricity problem in deprived areas can be partially solved by thermoelectric generators. The studies on stove powered TEGs show that with an effective design they can produce enough power for running the pumps of a heating system or provide power for portable devices. However, economic considerations will play a big part in development of these systems and more studies are necessary to determine their economic feasibility.
- Micro combustion TEGs offer advantages of higher power density and higher reliability over batteries. Accordingly, they seem perfectly suitable for portable power generation in small scales. However, there is still a lot of challenges to be addressed; although the combustor and TEG design are compact, the effects of cooling water and fuel tanks are not considered in the conducted studies. Therefore, more compact designs with more suitable heat exchangers are necessary for development of these systems.

- Space applications were one of the main reasons for recognition and development of thermoelectric generators in 1950 s. TEGs with radioisotope heat sources still are the most reliable option for deep space missions and they are highly likely to stay as the best option with the advancements in thermoelectric materials. Although the market for such a niche application is very small, it can be widened considering the new opportunities with development of satellites and sensing equipment for harsh environment. Small sized and modular radioisotope TEGs can be highly beneficial even for terrestrial applications if safety concerns are resolved. Moreover, the large temperature fluctuations in space provides another opportunity for thermoelectric power generators. All in all, there is some interesting and realistic opportunities for TE power generation in different space applications.
- The integration of TEGs with fuel cells is a new trend in the literature; such a combination, especially at kW level, can offer great advantages for off-grade multigeneration in developing countries. The conducted studies indicate the high improvement of different types of FCs due to hybridization with TEGs; however, the simplifying assumptions used by these studies suggests that the results are somewhat overestimated. Nevertheless, there is a need for more realistic theoretical assessment and especially experimental studies for a better judgment.
- There is a huge opportunity for thermoelectric generators as a component in power plants. TEGs can be added to different types of heat exchangers in power plants for waste heat recovery during the condensation process of a fluid or as a conducting part of the heat exchanger in other processes. However, effect of the TEGs on these heat exchangers and feasibility of these configurations is not fully obvious. Such an idea should be further investigated to evaluate the challenges and advantages of designing compact heat exchangers containing thermoelectric materials in their structure.
- The potential for thermoelectric power generation is endless. Everywhere there is a temperature difference there is an opportunity for thermoelectric power generation. Some of other evaluated heat sources for large-scale TE power generation include the thermal energy collected in asphalt pavements and geothermal energy. Initial assessment of these sources indicates the huge potential of them for power generation; however, practicality of large-scale power generations from these sources needs more investigation. Moreover, small-scale power generation by TEGs can be utilized in sensing and monitoring applications and low power gadgets, which are already in practice.
- A survey on applications of thermoelectric generators and specially the experimental studies shows that there is a big gap between applications and theoretically proven ideas. Neither the materials nor device level or system-level design improvements are fully practiced in the applications of thermoelectric generators. The reason behind this can be the vastness of the thermoelectric research area, interdisciplinary nature of the field, or the phase-to-phase dependency of applications on readiness of thermoelectric devices and dependency of devices on development of high-performance thermoelectric materials with good mechanical properties. In any case, the present review tries to provide comprehensive viewpoint from the state of the technology, and also, some helpful fundamentals and guidelines for the future research. All in all, it is believed that thermoelectric generators can improve our systems in many sectors applications from industry, transportation, and utilization of different renewable sources, to portable applications, encompassing space explorations and wireless sensing and monitoring systems. The opportunity for thermoelectric generators is huge provided that the applications are well-understood and suitable design procedures are taken.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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