Solid State Sciences 160 (2025) 107784

Contents lists available at ScienceDirect

Solid State Sciences

journal homepage: www.elsevier.com/locate/ssscie

Sustainable thermoelectric materials for solar energy applications: A review

Neelam Baghel [a], Anil Kumar [a,b,*]

[a] Department of Mechanical Engineering, Delhi Technological University, Delhi, 110042, India
[b] Division-Clean Energy: Nodal Centre of Excellence in Energy Transition (NCEET), Delhi Technological University, Delhi, 110042, India

ARTICLE INFO

Keywords:
Thermoelectric material
Solar energy
Sustainability
Thermoelectric generator
Environmental impact

ABSTRACT

The growth and implementation of sustainable thermoelectric materials for solar energy applications are investigated in this review article. Subsequently, thermoelectric materials provide a viable means of directly transforming solar heat into electricity, they are essential to improving the sustainability and efficiency of solar energy systems. This paper examines the principles of thermoelectricity, significant material properties, and the most recent developments in thermoelectric materials, such as lead telluride, bismuth telluride, organic, hybrid, and earth-abundant inorganic compounds. Special attention is given to material performance, environmental impact, scalability, and its integration into solar energy systems. Additionally, issues including stability, low efficiency, and a balance between performance and material sustainability are explored. The assessment concludes by outlining potential research approaches and technological advances that will be required to turn thermoelectric materials into an achievable and future solution to the world's energy problems.

1. Introduction

In response to the dramatic shifts in climate, there has been an increased demand for research into alternate renewable energy sources [1]. The usage of fossil fuels for transportation and the generation of energy is primarily responsible for the dramatic changes that have occurred in the climate [2,3]. Many nations throughout the world have made commitments to decrease the practice of primary energy by increasing the efficiency of their production [4], distribution, and end-use processes, limiting their emissions of carbon dioxide, and increasing their utilisation of renewable energy sources [5]. These commitments are in response to the difficulties posed by climate change [6]. Greenhouse gas emissions have been on the rise across the globe as a consequence of the growing demand for various energy sources , including electricity, heating, refrigeration, and air conditioning [7].

Over the past few decades, a substantial amount of effort has been put forward to investigate and develop alternative technologies to satisfy the ever-increasing need for energy [8,9]. Due to the increasing demand for energy in day-to-day living [10], which is mostly maintained by dwindling fossil fuel supplies such as coal, petroleum, and natural gases [11], the scientific community has been compelled to place a greater emphasis on green energy as a result of globalisation [12]. Solid-state energy transformation has emerged as a highly promising approach to tackle the challenges associated with traditional energy production [10]. Solar energy is a sustainable form of thermal energy [13]. Thermoelectric materials (TEMs) convert heat to electricity through the Seebeck effect, while the Peltier effect is used for refrigeration by electricity [14]. The Seebeck effect defines the process of transforming heat into electricity [15]. Thermoelectric coolers (TEC) [16], thermoelectric generators (TEG) [17,18], thermoelectric heaters (TEH), and thermoelectric dehumidifiers (TED) are some of the applications of thermoelectric materials that have the potential to combat environmental problems [19,20]. Thermoelectric devices, which were first developed in the 18th century, produce small voltages when two metals with different electrical properties are brought together [21]. The technology of thermoelectric has seen rapid development over the past sixty years due to its exceptional qualities that distinguish it from conventional energy generators and coolers [22]. This progress has been facilitated by the introduction of high-efficiency semiconductors [23]. Although the discovery of novel materials is currently ongoing, the fundamental theory that underpins the technologies of thermoelectricity is based on the concepts of the Seebeck effect (which is primarily responsible for power generation) and the Peltier effect (which is mostly responsible for refrigeration) [18,21].

The Seebeck effect was revealed in 1821, which showed that two joint dissimilar metals have different temperatures (ΔT) at the joints. It is referred to as the thermo-current and the thermo-electromotive force, respectively, when the associated current and electromotive force that

* Corresponding author. Department of Mechanical Engineering, Delhi Technological University, Delhi, 110042, India.
E-mail address: anilkumar76@dtu.ac.in (A. Kumar).

https://doi.org/10.1016/j.solidstatesciences.2024.107784
Received 30 August 2024; Received in revised form 30 November 2024; Accepted 2 December 2024
Available online 7 December 2024

are present in the joint circuit are considered to be present. When the voltage difference (ΔV) between two joints is increased, the temperature differential (ΔT) between them also significantly increases [24]. The Seebeck coefficient is the name given to the proportional constant that is associated with the inherent quality of the substance to be discussed. When it comes to materials such as metals, this coefficient is quite low, measuring roughly 0 μV/K [25]. However, when it comes to semiconductors, it would be significantly higher, measuring approximately ±200 μV/K. Seebeck coefficient is the amount of the ability of a material to generate an electric current in the presence of a temperature gradient [26]. It is defined as the ratio between the theoretical voltage difference produced and the applied temperature gradient, as shown in Eq. (1) [27]:

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

The Seebeck effect is utilised in thermoelectric generators, which are also referred to as Seebeck generators [28,29]. Power facilities employ these thermoelectric generators to turn waste heat into electricity [30]. Automotive thermoelectric generators use this effect to improve fuel efficiency in vehicles. Thermocouples and thermopiles employ the Seebeck effect to detect temperature differences between two objects [31].

The Peltier effect, discovered in 1834, occurs when various conductors absorb or reject heat in a circuit based on the current direction [32]. The difference in fermi energies between the two materials is primarily responsible for this phenomenon. The ability to absorb or reject heat depends on the conductivity properties and joint temperature [27]. The dimensionless quantity ZT is commonly used to evaluate the performance of thermoelectric materials [33]. It is a key figure of merit that determines the efficiency of a thermoelectric material in energy conversion [34], whether for generating electricity (Seebeck effect) or for cooling/heating (Peltier effect) is given by Eq. (2) [10,26].

$$ZT = \frac{\alpha^2}{k}\,\sigma T \tag{2}$$

Where, k is the thermal conductivity, which is separated into two portions (k_e and k_1, the electrical and lattice conductivity, respectively), T is the temperature, and α is the Seebeck coefficient. Consequently, the Seebeck and Peltier categories of thermoelectric technology are expressed as TEG for power generation [35], if two materials are exposed to different temperatures and the other is TEC for cooling if two materials are exposed to additional voltage. The TEG efficiency is determined by using Eq. (3) [9,36]:

$$\eta_{max} = \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}} \tag{3}$$

Where, T_C is the cold side temperature and T_H is the hot side temperature.

The TEC's maximum coefficient of performance (COP) can be given by Eq. (4) [37]:

$$\eta_{max} = \frac{\sqrt{1+ZT}-\frac{T_H}{T_C}}{\sqrt{1+ZT}+1} \tag{4}$$

When the ZT is infinite, the efficiency, also known as the COP, is expressed as the Carnot, as stated by Equations (3) and (4). Consequently, there is a theory that asserts thermoelectric generators are not hot engines, in which electrons serve as the working medium when they are in operation.

According to Thomson, thermal energy is either created or spent in the metal structure as the current flows across unequally heated conductors. Thomson effect refers to the production of reversible heat when an electric current is applied to a conductive substance that is exposed to a temperature gradient. Thomson effect occurs when a substance loses heat due to a current passing through it. This heat transfer is easily visible. In contrast, it is not possible to measure the net effect of two distinct materials as with the Peltier and Seebeck effects.

1.1. *Thermoelectric utilisation of solar energy*

Thermoelectric devices are used directly to transform solar energy into electrical energy [38,39]. The Seebeck effect produces an electric voltage when two sides of a material have different temperatures [40]. This can be utilised to generate electricity when the temperature difference is high [41,35]. Approximately fifty percent of the light spectrum that the sun provides is used by conventional PV solar cells [42]. Infrared radiation is utilised for the thermoelectric power generation [43]. Instead, the PV cells get heated by the infrared radiation [44], which lowers the cell's efficiency [45]. The range of electromagnetic energy that the sun emits, from the ultraviolet to the infrared, is known as the solar spectrum [46]. The quantity of energy that reaches the earth's surface is known as solar irradiance, whereas solar radiation is the sun's direct energy emission [47]. The ultraviolet (UV), visible, and infrared (IR) are the three primary sections that make up the solar spectrum [48]. Sunlight with a wavelength of less than 400 nm (nm) is included in the ultraviolet spectrum [49]. Energy range of UV photons is roughly 3–5 electron volts (eV). The 400–700 nm range is the visible zone. Photons having energy between 1.8 and 3 eV are found in this region. Last but not least, light with wavelengths longer than 1000 nm and photons with energies ranging from roughly 0.35 eV–1.8 eV make up the infrared area as shown in Fig. 1.

Heat required for thermoelectric power generation is typically produced by infrared wavelengths (700 nm –1 mm), especially in waste heat [51] and solar-thermal applications [52]. To generate the required heat for thermoelectric power, the most pertinent wavelengths are those that fall within the mid-infrared (MIR) and far-infrared (FIR) ranges, specifically between 3 μm and 1 mm. These wavelengths correspond to the normal heat radiation that originates from solar heat, industrial waste heat, and natural thermal sources [53]. Spectral splitting concept of PV cells and thermal absorbers is shown in Fig. 2. Sun spectrum generates heat by irradiating thermoelectric materials and raising their temperature [54], when the environment or a designed heat sink offers a colder surface, resulting in the required temperature gradient [55]. Absorbing more of the spectrum of sunlight increases the potential temperature rise, which in turn increases the efficiency of power generation [56]. Advancements in thermoelectric materials concentrate on optimising their capacity to efficiently absorb particular segments of the sun spectrum [57]. Nanostructured materials are now being researched to improve their ability to absorb infrared radiation and convert it into heat. This has the potential to either boost power generation or raise the temperature gradient.

This review focuses on the correlation between environmental sustainability and the advancement of thermoelectric materials, particularly concerning solar energy applications. This paper takes a unique approach by highlighting the importance of developing thermoelectric materials that are both eco-friendly and capable of efficiently harnessing solar energy. Unlike previous reviews, which have mainly focused on performance optimisation. This study aims to fill the gap by emphasising versatility and effectiveness. This review provides an in-depth analysis of the recent developments in sustainable thermoelectric materials, assessing their suitability for solar energy applications. It takes into account various factors such as material science, environmental impact, and implementation strategies, offering a holistic viewpoint. This comprehensive approach offers new perspectives and sets the stage for future studies that concentrate on achieving net-zero emissions.

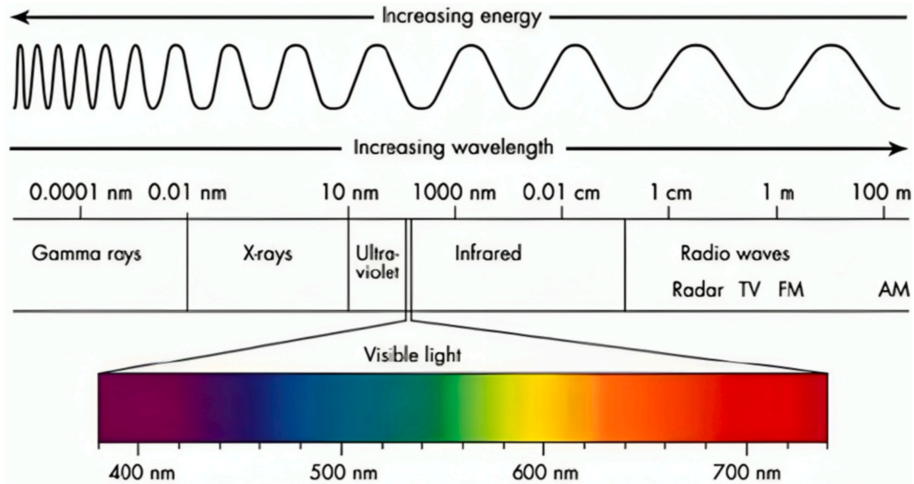

Fig. 1. Spectrum of solar radiations [50].

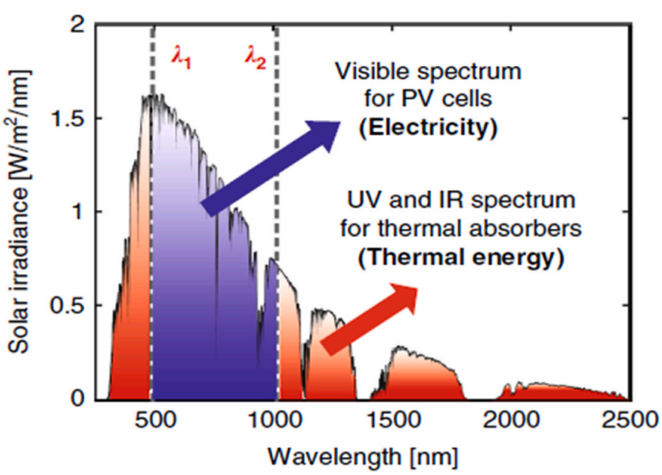

Fig. 2. Wavelength utilised for thermoelectric power generation [58].

2. Recent advances in thermoelectric material for solar energy applications

The Seebeck effect is used in thermoelectric materials to turn heat into electricity and vice versa. These materials need to demonstrate high thermoelectric efficiency, stability under operating circumstances, and sustainability to be used in solar applications. Thermoelectric materials can be classified based on their chemical composition, application, temperature of application, and other methods. This evaluation categorises materials based on their composition and, to a lesser extent, on the temperature at which they are used. Mainly thermoelectric materials can be classified into three temperature ranges i.e., low temperature range, medium temperature and high temperature range [59].

Low-temperature range: It included a temperature range of up to 600 K. Wearable and medical gadgets are common examples of low-temperature applications since they operate at or near ambient temperature. Microelectronics applications, including nodes for WSN devices, may fall within this category due to their minimal heating requirements.

Medium temperature range: Thermoelectric materials suitable for medium temperature range applications which typically fall within 600 K–1000 K, must strike a compromise between achieving strong thermoelectric performance and maintaining robustness at these higher temperatures. These are widely used in the automotive industry, where waste heat can be transformed directly into electrical current from the engine in the former and plants (e.g., heat pipes).

High-temperature range: Thermoelectric materials for high-temperature applications (beginning at 1000 K and above) are intended to survive harsh environments while maintaining resilient thermoelectric performance. To attain high thermoelectric efficiency, these materials must have high Seebeck coefficients as well as strong electrical conductivity and low heat conductivity. This area of application is primarily concerned with the aerospace sector, as it is used to generate energy for space missions and the exploration of outer space in scenarios where photovoltaic energy harvesting is unavailable [60].

Fig. 3 shows different kinds of thermoelectric materials that are employed in solar energy applications. Bismuth telluride and its alloys are extensively utilised as materials for thermoelectric cooling [61]. Additionally, these materials are optimal for utilisation in thermoelectric generators under conditions of moderate heat source temperatures [62]. Bi_2Te_3 and its alloys are said to have the highest figure of merit, as they can function up to 600 K [63]. This material is chosen by the majority of businesses because its commercial uses are close to room

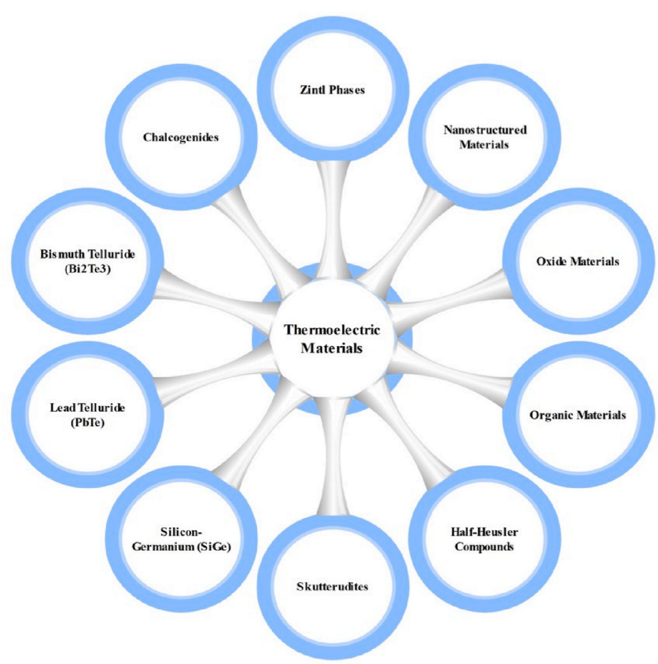

Fig. 3. Classification of thermoelectric materials for solar energy applications.

temperature. PbTe, which stands for lead telluride, is the second material in this classification. It is utilised at temperatures that are greater than those of bismuth telluride, reaching temperatures of up to 900 K. Additionally, PbTe is a chalcogenide, showing the promising potential of this material class.

The primary components of conventional thermoelectric materials are inorganic compounds, such as alloys of bismuth telluride (Bi_2Te_3), lead telluride (PbTe) and related alloys, silicon-germanium (SiGe) alloys, antimony telluride (Sb_2Te_3), and tin selenide (SnSe). Originally developed in the early boom of thermoelectric research in 1950–1960, these inorganic thermoelectric materials especially Bi_2Te_3, SiGe and PbTe have been shown the greatest ZT value of the discovered inorganic thermoelectric materials stayed close to unity until the mid-1990s, this was not cost-effective in most applications [64]. However, developments in science and technology as well as knowledge of fossil fuels pose a huge readiness to raise the thermoelectric material performance (ZT). Table 1 shows the different types of materials, types, their operating temperature and their ZT value.

Research in the thermoelectric field has thus mostly concentrated on increasing thermoelectric properties of the inorganic thermoelectric materials employing enhanced Seebeck coefficient and thermal conductivity since the mid-1990s [65]. For operation at normal temperature (300–400 K), Sb_2Te_3, Bi_2Te_3, Bi_2Se_3 and related alloys have been the most promising inorganic thermoelectric materials since the 1950s. Tellurium (Te) is found in the crust of the earth with a concentration of approximately 0.001 parts per million (ppm), which is even lower than the concentration of gold (Au) in the crust, which is 0.004 ppm. As a result, it is of the utmost importance to search for great alternatives that are free of Te and operate efficiently at room temperature.

MgAgSb has drawn a lot of interest because of its lower cost, less toxicity, better thermal stability, and lower thermal conductivity than Bi_2Te_3 alloys [66]. PbTe alloys including PbSe and SnTe displayed a ZT of ~1 and were applied in power generation. Since Selenium is 0.5 ppm and Tellurium is less than 0.001 ppm in the crust of Earth, PbSe is seen as a substitute for PbTe. Although both ZT values are lower than those of excellent PbTe alloys, the ZT values of 88 aluminium-doped PbSe (n-type) and Sodium-doped PbSe (p-type) at 577 °C are significantly lower than those of excellent PbTe alloys. Widely investigated for use in power generation, skutterudites are another possible thermoelectric material with reduced thermal conduction because of their complicated crystal structures. Skutterudites have MX_3 as their chemical formula, M is Co, Rh or Ir, X is P, As or Sb. Large spaces in the crystal cage structure drive the assimilation of tiny guest ions into their natural locations, hence forming the filled skutterudites (TyM_4X_{12}). Table 2 shows various properties of different thermoelectric materials and their ZT value along with the wide variety of applications.

At low temperatures, the ZT values of the majority of thermoelectric materials, except for Bismuth Telluride, are lower as a result of a decrease in electrical conductivity and Seebeck coefficient, as well as comparatively stable or only slightly dropped thermal conductivity. Materials such as Skutterudites, Lead Telluride, and Half-Heusler compounds are most effective within the medium temperature range

Table 1
Thermoelectric materials, its type, operating temperature and ZT value.

Operating Temperature (°C)	Type	Material	Maximum ZT
<150	P	$Bio_{0.5}Sb_{1.5}Te_3$	1.4
	n	$Bi_2Se_{0.3}Te_{2.7}$	1.0
	P,n	Bi_2Te_3	0.8
150–500	P	Zn_4Sb_3	–
	P, n	PbTe	0.7–0.8
	P	TeAgGeSb	0.7–0.8
500–700	P	$CeFe_4Sb_2$	1.1
	ti	$CoSb_3$	0.8
700–900	P, n	SiGe	0.6–1.0
	P	LaTe	0.4

Table 2
Materials and their ZT values, properties and applications.

S. No.	Material	ZT Value	Properties	Applications
1.	Bismuth Telluride (Bi_2Te_3)	1.0 at room temperature	Density: Approx 7.7 g/cm^3. Melting Point: 585 °C (1085 °F). 0.13 eV bandgap	Used in Peltier coolers and thermoelectric generators.
2.	Lead Telluride (PbTe)	0.8-1.0 at around 700 K	Performs well at higher temperatures such as 500–900 K.	Utilised in thermoelectric generators for waste heat recovery as well as mid-temperature range solar applications.
3.	Silicon-Germanium (SiGe)	0.6-1.0 at high temperatures (900–1300 K)	Highly effective at high temperatures.	Space applications and concentrated solar power systems, radioisotope thermoelectric generators.
4.	Skutterudites ($CoSb_3$-based)	1.0–1.5 (500–900 K)	Complex crystal structure that helps in reducing thermal conductivity while maintaining high electrical conductivity	Suitable for mid to high-temperature applications such as 500–900 K.
5.	Half-Heusler Compounds (e. g., ZrNiSn-based)	1.0 at elevated temperature range between 700 and 1000 K	High thermal stability and good thermoelectric performance at elevated temperatures.	Used in automotive waste heat recovery and high-temperature solar applications.
6.	Tin Selenide (SnSe)	2.6 at 923 K (single crystal form)	Exceptionally high ZT values at high temperatures.	High-temperature thermoelectric applications, including solar thermoelectric generators.
7.	Organic Thermoelectric Materials	Up to ~0.4 at room temperature	Flexible, low-cost, and can be synthesized from abundant resources.	Used in wearable thermoelectric devices and low-power solar applications.

components [67]. The increase in ZT values is a result of the advantageous balance that exists between the electrical and thermal properties of these materials as shown in Fig. 4(A) and (B). Tables 3 and 4 show the confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at a cell temperature of 25 °C.

Nazri et al. focused on Photovoltaic-Thermal (PVT)-thermoelectric hybrid systems for enhanced energy efficiency. Integration of thermoelectric with PVT outperforms the traditional PVT strategy [69]. There has been a rise in both thermal and electrical performance from 21.19 % to 57.08 % and 12.55 %–14.09 %, respectively. The growth is proportionate to the acceleration of the air mass flow [70].

Mandev et al. investigated the desalination performance of solar stills after using thermoelectric modules. Water production efficiency is increased by solar stills equipped with thermoelectric modules as shown in Fig. 5. As cooling agents, thermoelectric modules quicken the system's condensation process. The use of thermoelectric modules in the production of freshwater offers a long-term, environmentally friendly

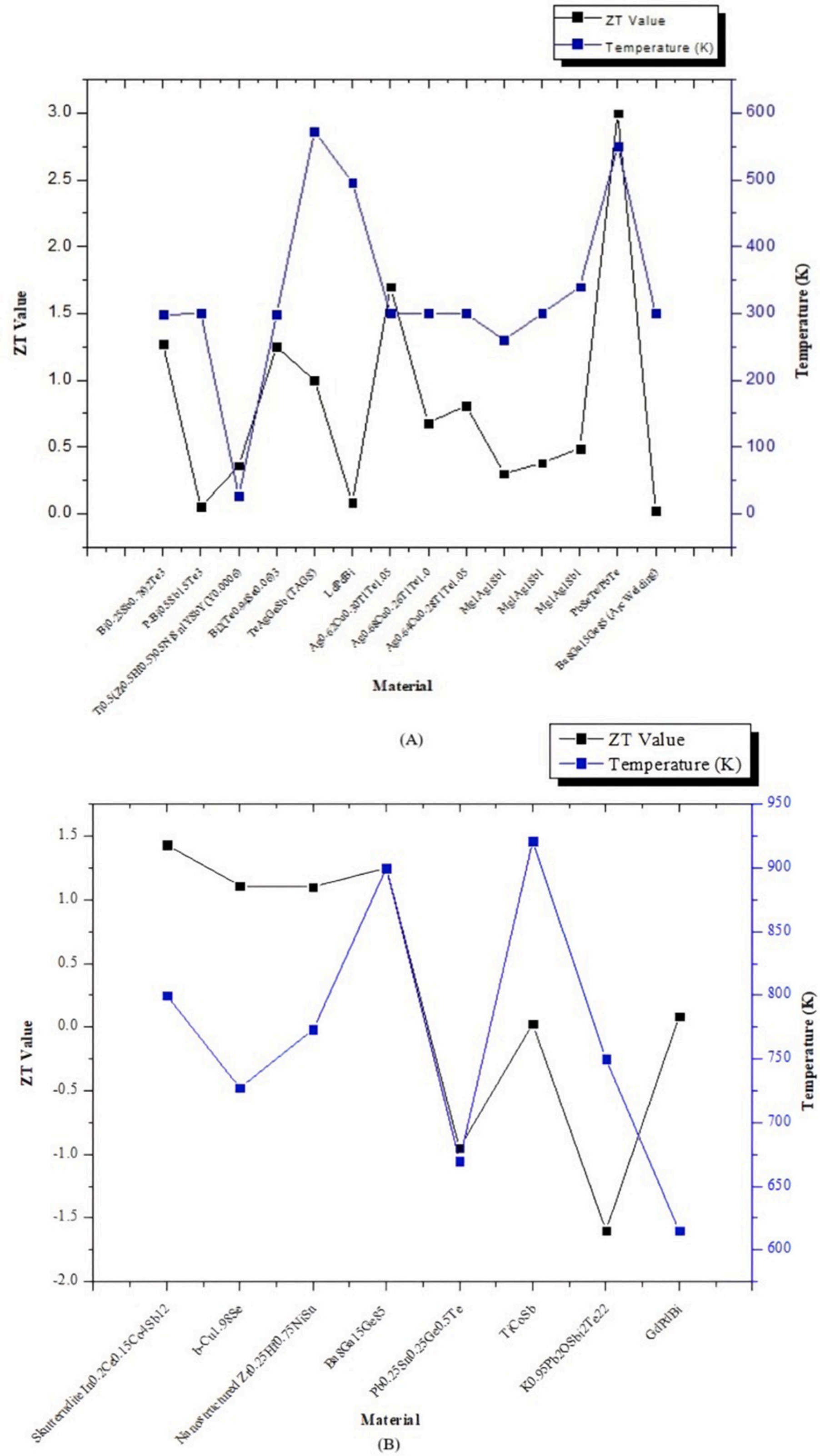

Fig. 4. (A) Effect of low-temperature range on ZT value of various thermoelectric materials (B) Effect of medium temperature range on ZT value of various thermoelectric materials.

alternative [38]. Acir et al. experimentally examined a thermal energy storage unit (TESU) that integrates phase change materials (PCMs) with TEGs using imitated solar radiation. Thermal energy storage units increased maximum power by 11 % compared to non-TESU systems. The outcome demonstrated that a more stable TEG cold surface temperature could be achieved with PCM, leading to more effective TEG systems. Furthermore, it was discovered that increasing the radiation intensity reduced the melting time while increasing the TESE and ECE [71].

Table 3
Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at a cell temperature of 25 °C [68].

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	I_{sc} (A)	Fill factor (%)
a-Si/nc-Si (tandem)	12.2 ± 0.3	14322 (t)	202.1	1.261	68.8
Organic	8.7 ± 0.3	802 (da)	17.47	0.569	70.4
Si (multi-crystalline)	18.5 ± 0.4	14661 (ap)	38.97	9.149	76.2
GaAs (thin film)	24.1 ± 1.0	858.5 (ap)	10.89	2.255	84.2
CIGS (Cd free)	17.5 ± 0.5	808 (da)	47.6	0.408	72.8
CIGS (thin-film)	15.7 ± 0.5	9703 (ap)	28.24	7.254	72.5
CdTe (thin-film)	17.5 ± 0.7	7021 (ap)	103.1	1.553	76.6
Si (crystalline)	22.9 ± 0.6	778 (da)	5.6	3.97	80.3
Si (large crystalline)	22.4 ± 0.6	15775 (ap)	69.57	6.341	80.1

Table 4
Confirmed cell and module results measured under the global AM1.5 spectrum (1000 W/m^2) at 25 °C [68].

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill factor (%)
CIGS (thin-film)	21.7 ± 0.7	0.4972 (da)	0.7963	36.59	79.3
CIGSS (Cd free)	19.7 ± 0.5	0.496 (da)	0.683	37.06	77.8
Cells (silicon) Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7	82.8
Si (large crystalline)	25.0 ± 0.7	120.94 (ap)	0.726	41.5	82.8
Si (large multi-crystalline)	19.5 ± 0.4	242.7 (t)	0.652	39.0	76.7
GaInP	20.8 ± 0.6	0.2491 (ap)	1.455	16.04	89.3
CZTSS (thin film)	12.6 ± 0.3	0.4209 (ap)	0.5134	35.21	69.8
CZTS (thin-film)	8.5 ± 0.2	0.2382 (da)	0.708	16.83	70.9
Perovskite (thin film)	20.1 ± 0.4	0. 0955 (ap)	1.059	24.65	77
Organic (thin film)	11.1 ± 0.3	0.159 (ap)	0.867	17.81	72.2

Fig. 6(A) assessed the effect of thermoelectric heating on solar desalination efficiency. Black Plexiglas was used in the construction of the 400 mm by 60 mm absorber panel of the system, which was designed to absorb solar radiation [73]. The effects of thermoelectric cold side on the freshwater yield in a cost investigation on solar desalination. Solar collector's water temperature increased, and a sprinkler tube allowed the heated water to enter the enclosure. Air blower placed at the back of the sprinkler pipe forced the water vapour into the condenser zone, where it connected to the thermoelectric cooling system to produce enhanced distilled water. The findings show that during the nine-day trials, an average of 1.2 l/m^2 of water was generated (Fig. 6(B)) [74].

Miljkovic and Wang [27] originally suggested a schematic of the hypothetical HSTE device (Fig. 7). Three subsystems make up the hybrid system: a thermosyphon unit, a collection of TEGs, and a solar radiation concentration unit (also known as a parabolic or dish concentrator). A parabolic optical concentrator is seen in the schematic from schematic to gather solar radiation on an absorber-emitter surface. The TEG's high-temperature side receives solar energy through this surface. Next, heat is transferred to the thermosyphon's evaporator zone through heat diffusion through the TEG, which uses the Seebeck effect to produce electricity. In a nutshell, the evaporator zone is the bottom of the thermosyphon, where heat is absorbed and the working fluid evaporates. The vapour then travels to the thermosyphon's upper section or condenser. In this case, the heat is recovered using a heat exchanger for later uses and the condensate of the working fluid passes through the inner walls of gravity through the thermosyphon [75].

Alnajideen et al. designed a concentrated PV-TE system to boost solar energy conversion efficiency, with dichroic mirrors for spectral splitting and beam concentration as shown in Fig. 8. This system harvests "unused energy" in the infrared spectrum. Performance of this hybrid system was tested using the usual one-sun testing procedure. Findings demonstrate that the hybrid system has a total efficiency of 16.9 %, compared to 15.9 % for the same configuration, except the concentrator's reflecting surfaces are aluminium mirrors. Pan et al. described a unique solar-powered CPV-TPG-SOEC system that is intended to considerably increase hydrogen production efficiency by optimising both electrical and thermal energy utilisation. Thermodynamic research demonstrates that the system reaches energy and exergy efficiencies of 0.60 and 0.52, correspondingly, while lowering the optimal operating temperature to around 1173 K, allowing for improved effectiveness at lower temperatures as shown in Fig. 9.

Guo et al. utilised solar concentrators to generate thermal energy for the SMR and PV cells to generate renewable power as shown in Fig. 10. This results in excellent methane conversion and solar energy utilisation efficiency under mild temperature and pressure circumstances. The First-law thermodynamic efficiency and net solar-to-fuel efficiency can be as high as 63.27 % and 26.25 %, respectively (taking into account CO_2 sequestration). Combined with the spectral splitting approach, this system's net solar-to-fuel efficiency might be increased to 33.91 % (taking CO_2 sequestration into account). At 0.16 V, producing hydrogen saves up to 1.29 kg of methane and reduces CO_2 emissions by 3.55 kg.

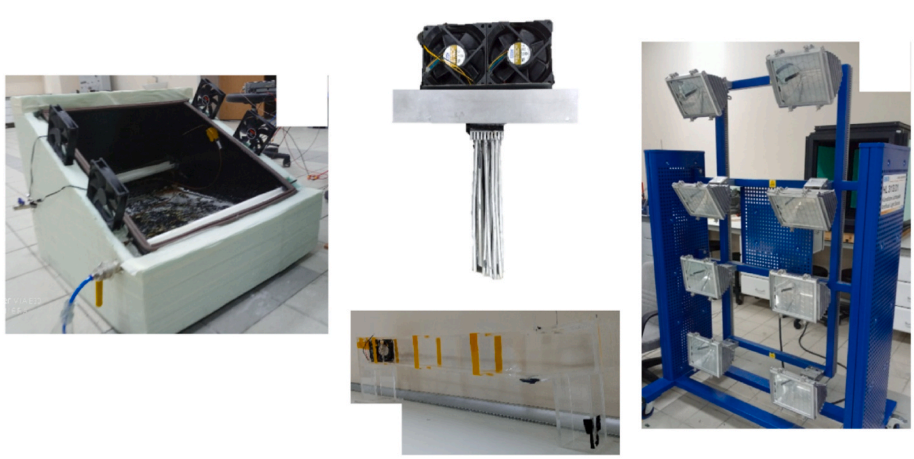

Fig. 5. Solar still uses a thermoelectric module, plexiglass channel, and artificial light source for the experiments [72].

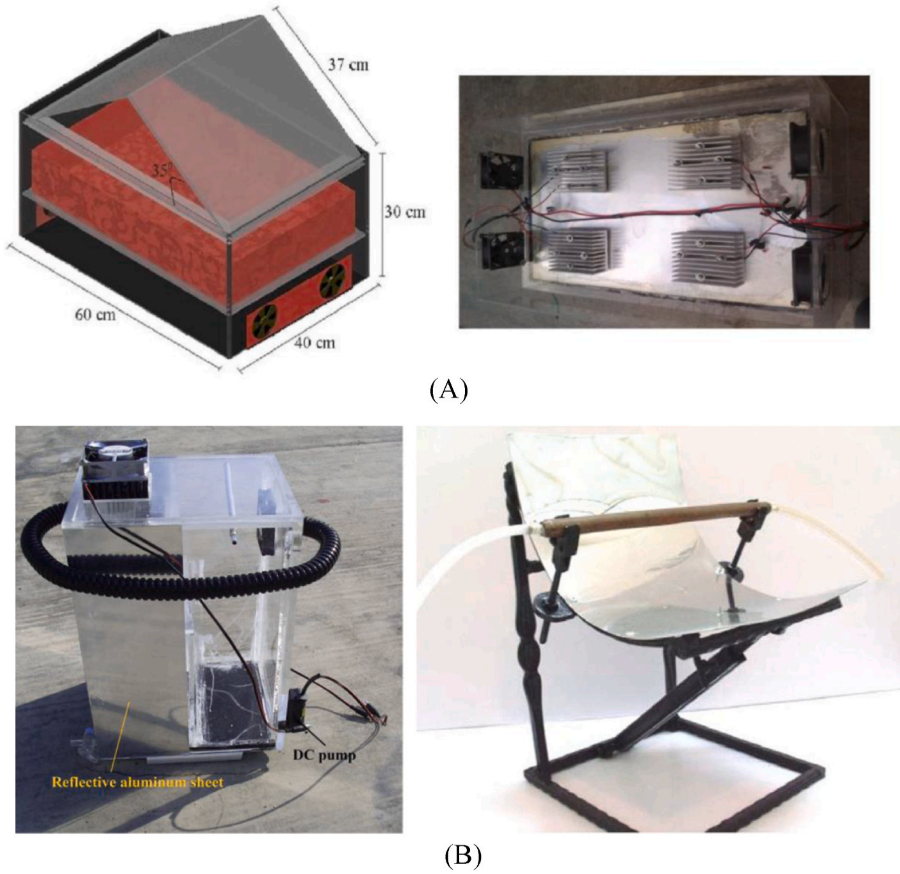

Fig. 6. (A) Solar desalination with four thermoelectric heating devices [73], (B) solar desalination system using thermoelectric cooling module with solar collector [74].

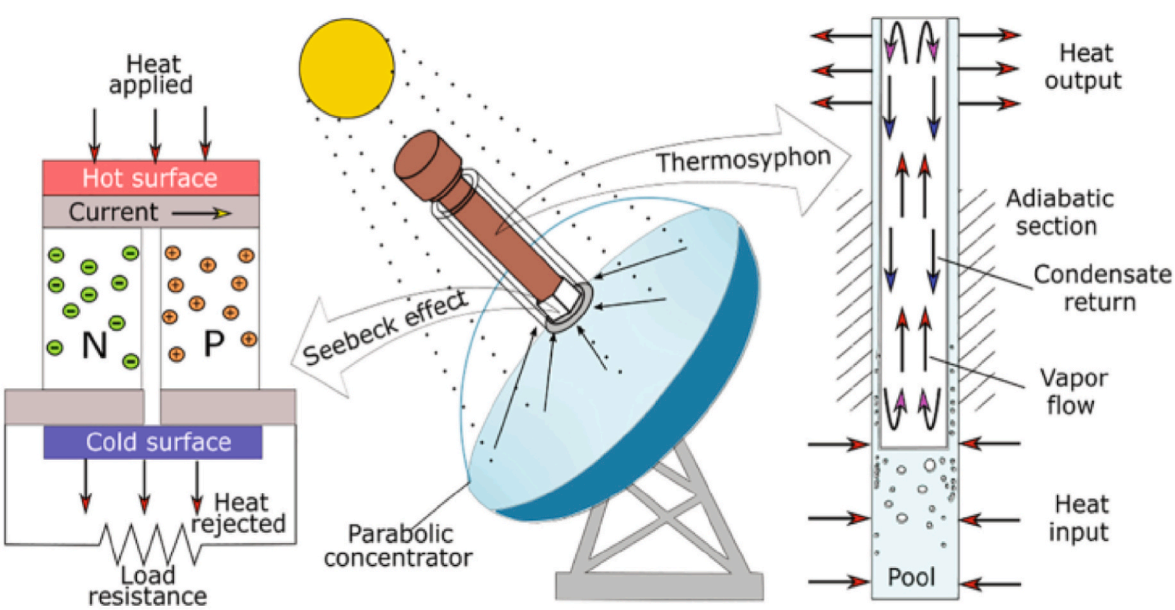

Fig. 7. Hybrid Solar Thermoelectric (HSTE) system proposed by Miljkovic and Wang [74].

Recent breakthroughs in thermoelectric materials for solar energy applications have considerably increased the possibilities for sustainable sources of energy. It is now possible to convert solar heat into electricity with the discovery of highly efficient thermoelectric materials such as nanostructured semiconductors, organic-inorganic hybrids and topological insulators. Material design innovations, such as optimising thermal conductivity and electrical characteristics, have enabled improved performance throughout a wide temperature range, making them more practical for real-world applications.

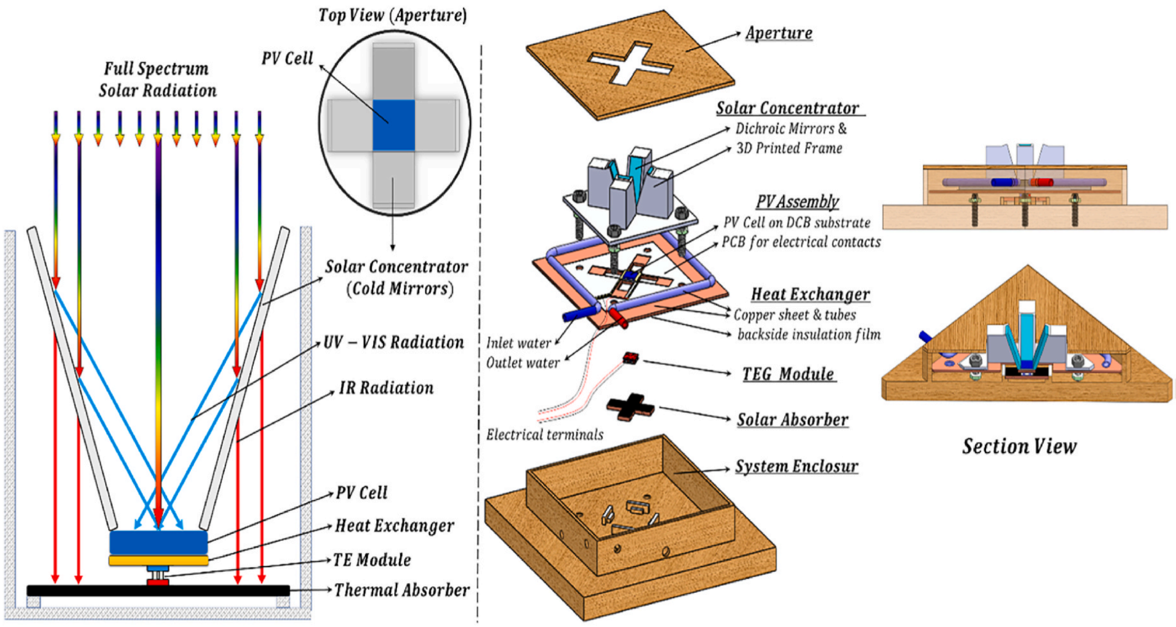

Fig. 8. Novel hybrid PV-TE with spectral splitting solar concentrator [76].

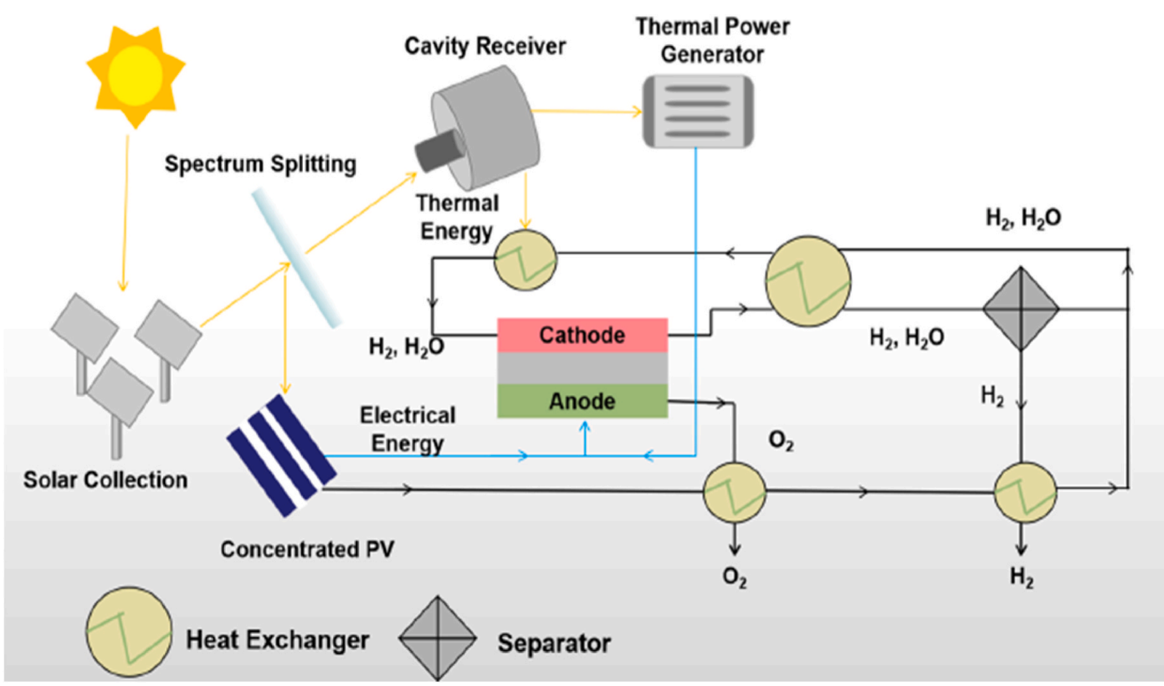

Fig. 9. Layout of concentrated photovoltaic-thermal power generator-solid oxide electrolysis cell system [77].

3. Environmental impact of thermoelectric materials

The assessment of the environmental consequences of thermoelectric materials is crucial, particularly when prioritising sustainability in the context of solar energy applications. Number of published articles containing the words "sustainable" and "Thermoelectric" in the keyword section is examined by Web of Science database. A clear indication of the importance of sustainability in this industry is the exponential tendency, which shows that about seven times as many publications have been viewed now as there were twenty years ago as shown in Fig. 11.

The concept of sustainable development refers to the process of development that satisfies the needs of the present without compromising the ability of future generations to meet their essential requirements [37]. Without a strong resource base, technology cannot be sustained. There is a clear connection between the ratio of reserves to production difficulties and the equality that exists between generations [79]. For example, the static ratio of antimony is only for one generation or less, ranging from 15 to 30 years (reserve and reserve basis). One needs to evaluate the dynamic ratio, particularly when dealing with a now very small yearly production. Analysing the energy consumption of TEG production provides insight into its possibilities for optimisation and serves as a baseline for comparing thermoelectric applications. The following is the order in which primary energy is consumed: Opt. 3b < Opt. 2< Opt. 3a < Opt. 1< TEG 0 as shown in Fig. 12. Across all versions, the biggest part goes to the supply of aluminium for the heat sink. The production of modules and the thermoelectric materials themselves

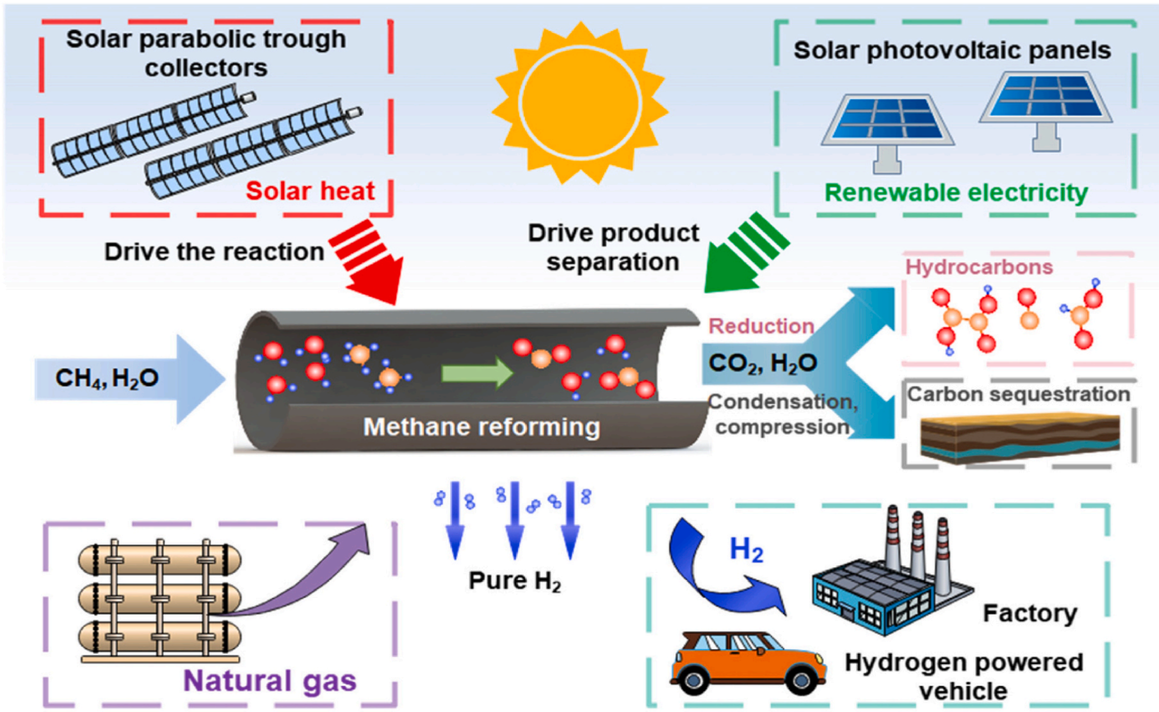

Fig. 10. Novel hydrogen production and solar energy storage with thermoelectrochemically enhanced steam methane reforming system [78].

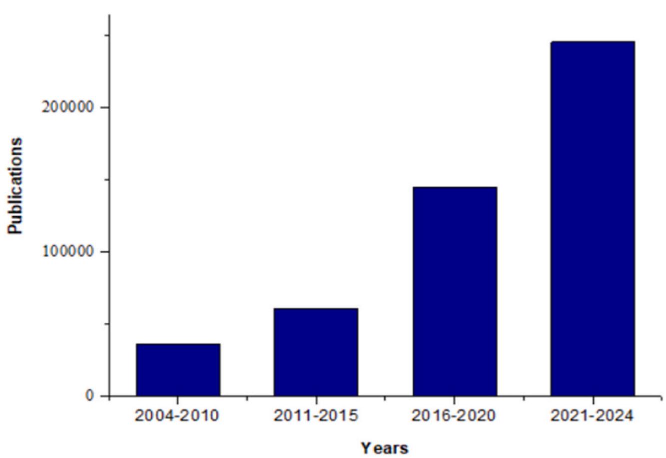

Fig. 11. No. of articles published with the keywords "Sustainable" and "Thermoelectric" according to the Web of Science database.

account for only modest to minor proportions.

According to various scientists, over 70 % of the energy consumption losses in the world are caused by waste heat, which enters the environment and is left unused. Special semiconductors known as thermoelectric materials are capable of transforming the emitted heat into electrical power [81]. Different doping methods can result in different changes to the material's mechanical characteristics. The dopant concentration in n-type PbTe marginally alters the mechanical characteristics. Hardness of PbTe in the p-type exhibits a noteworthy enhancement [82]. Under the manufacturer's specifications, a waste heat recovery system comprising six thermoelectric modules (14 W at a temperature gradient of 200 °C) was constructed and tested in a fixed industrial diesel engine as shown in Fig. 13. The investigation demonstrated that with proper assembly and a significant temperature differential across the modules, optimal performance was achievable. Even at today's relatively low conversion efficiencies, thermoelectric devices play a vital role in increasing the thermal efficiency of heat engines. Waste heat recovery design can considerably boost the thermal efficiency of heat engines. The decrease in greenhouse gas emissions is the

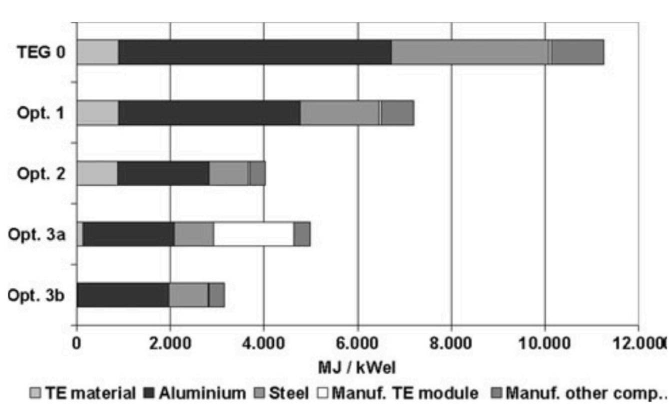

Fig. 12. Primary energy consumption including all conversion losses [80].

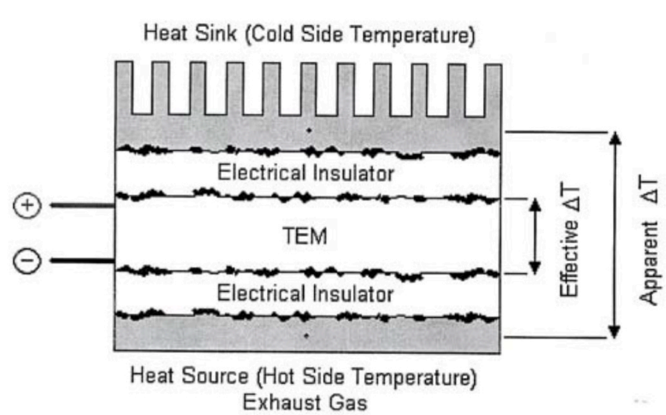

Fig. 13. Waste heat recovery system presenting the locations of four interfaces [83].

most evident result of increased engine efficiency [83].

Thermoelectric systems provide several advantages over other heat recovery systems, including low maintenance needs, low noise production, and compatibility with the abundant available areas within structures. Large-scale thermoelectric solutions make it possible to develop self-sufficient buildings in contemporary architecture. In addition to facilitating space conditioning and energy generation, thermoelectric systems allow for flexible application in a variety of environmental and climatic settings [84]. Iyer et al. investigated the environmental effects of thermoelectric modules for waste heat generation. Life cycle analysis is used to examine thermoelectrics environmental performance and long-term sustainability. The ecological performance of thermoelectrics is slightly impacted by end-of-life scenarios, thermoelectric modules exhibit positive ecological benefits, and current thermoelectrics are appropriate for continuous waste heat applications as shown in Fig. 14.

Using a life cycle assessment tool called GaBi v.4.4, the current study aims to evaluate the life cycle implications of thermoelectric materials at the production stage. Inorganic, organic, and hybrid forms of thermoelectric materials were distinguished. Resource consumption, emissions, waste, primary energy demand, and global warming potential were the five impact categories that were the subject of the investigation. They indicated that compared to the other two categories, the inorganic type had a noticeably bigger negative influence on the ecosystem. Only Bi_2Te_3 was an inorganic material that did not harm the environment. It was by far the least harmful of all the thermoelectric materials that were tested [86]. In the quest for sustainable energy solutions, the environmental effects of thermoelectric materials provide challenges as well as opportunities. On the one side, thermoelectric technology provides a clean and efficient method for converting waste heat into electricity, potentially lowering greenhouse gas emissions and energy consumption. However, the manufacturing and disposal of some thermoelectric materials pose environmental issues, especially those that contain rare or hazardous metals like lead, tellurium, or bismuth. Advances in the development of more environmentally benign, plentiful, and recyclable materials are critical to mitigating these concerns. As research continues to focus on reducing thermoelectric materials' environmental footprint while improving their performance, it will be critical to evaluate their advantages against the ecological challenges associated with their lifecycle. Sustainable innovation in this particular area may lead to economically and environmentally responsible energy options in the future.

4. Key challenges and opportunities of thermoelectric materials

Thermoelectric materials have enormous promise for transforming waste heat into power, particularly in solar energy applications. The availability of high-performing thermoelectric materials is still limited in the case of organic and hybrid organic-inorganic materials [87]. To facilitate the creation of cutting-edge thermoelectric materials for the coming decades, it is crucial to gain a deeper comprehension of the underlying processes of doping, as well as thermal and electrical transport. This task is particularly challenging due to the intricate nature of these systems, which often consist of multiple components and a combination of ordered and disordered phases [28]. Due to significant problems that arise in real-world applications, the development of

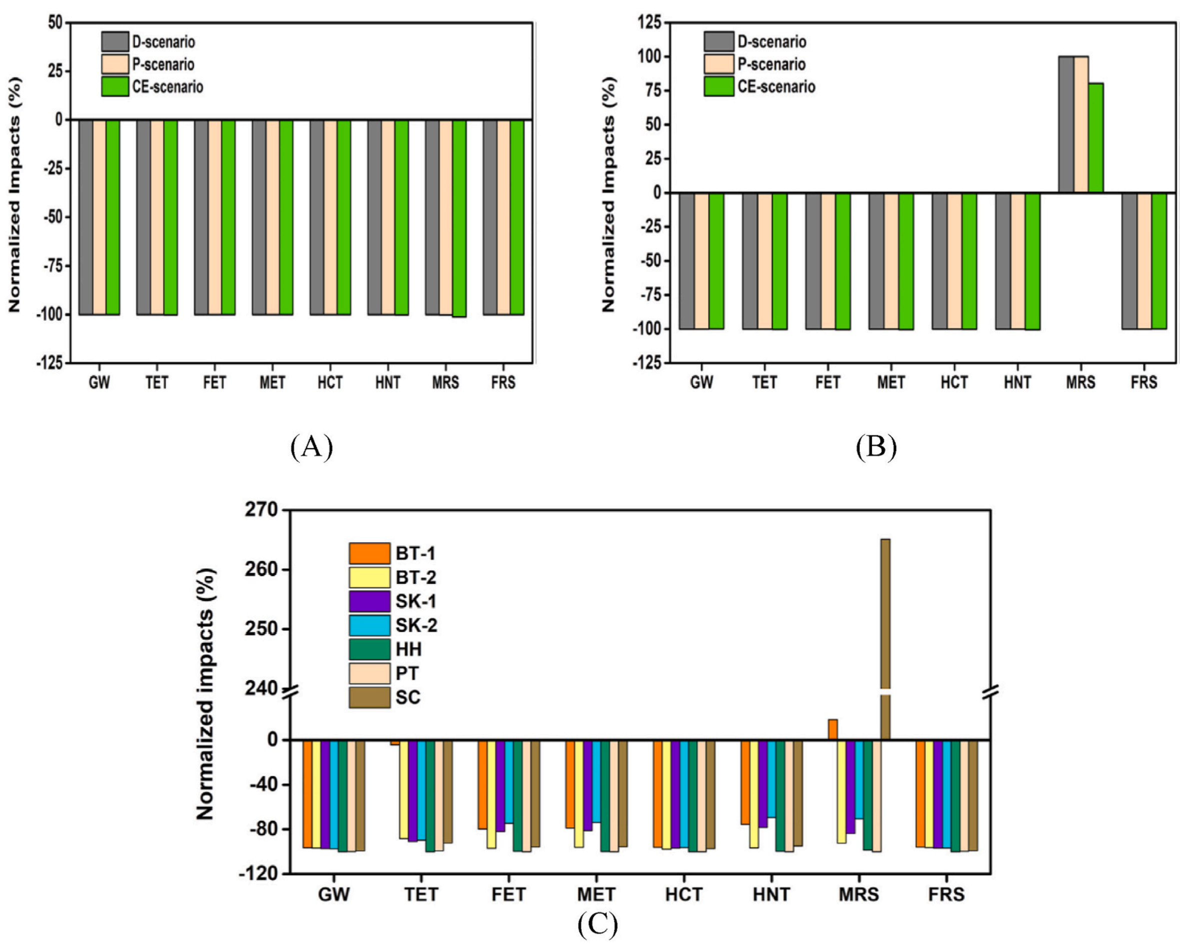

Fig. 14. (A) Life cycle environmental impacts of Half-Heusler (HH) module under different end-of-life scenarios (B) Life cycle environmental impacts of silicide (SC) module under different end-of-life scenarios (C) Life cycle impacts of various thermoelectric modules [85].

thermoelectric devices based on these nanoparticles is developing more slowly than that of thermoelectric nanomaterials with high ZTs. When it comes to nanowires, modules that rely on individual nanowires can only serve as platforms for evaluating physical attributes. However, it is unlikely that these modules will have any practical applications. The sole options for fabricating useful devices are nanowire bundles or arrays [88].

The Mg_3Sb_2 series possesses a significant benefit in terms of the abundant availability of Mg. However, it faces challenges in the fabrication process due to the vulnerability of Mg to oxidation. There is currently an absence of p-type Mg-based thermoelectric materials that can be synthesized at room temperature without the use of noble metals. As a result, the development of room-temperature thermoelectric materials that are both Te-free and rich in Mg continues to be in its earliest stages [89]. Artini et al. analysed that the anode temperature can reach 500 °C, complete concept deployment requires the discovery of materials that have greater operating temperatures, as commercial TEGs are currently based on Bi_2Te_3, which has a limited maximum working temperature (~280 °C). Ultimately, one of the most crucial elements of enhancing the efficiency of hybrid power generators is the reduction of heat losses [90]. The thermoelectric performance has been enhanced by the substantial reduction of thermal conductivity achieved through the use of nanostructures and artificial superlattices. The complexity of the multi-component phase equilibrium makes it difficult to maintain their structural stability at high temperatures, though. Consequently, authors put up the notion of a "natural superlattice" which is created by integrating an SnS layer into the layered TiS_2 van der Waals gap [91]. According to the findings of Fiedler et al., who compared the transport behaviours of solution-processed materials with those of their solid-state equivalents, solution-processed thermoelectric materials often exhibit poorer electrical conductivities at room temperature. In addition, the conductivity tends to rise with temperature rather than decrease, which is the temperature-dependent tendency [92]. Some outline of the key challenges and opportunities linked with thermoelectric materials are as follows.

- The figure of merit ZT indicates the efficiency of thermoelectric materials, which is typically low, often less than 1. This reduces their capacity to effectively convert heat into electricity. Many thermoelectric materials have excellent thermal conductivity, which minimises the temperature gradient essential for successful energy conversion [93].
- It is difficult to achieve the desired equilibrium of features such as the electrical conductivity, Seebeck coefficient, and low thermal conductivity. Temperature gradients must be maintained by effective thermal insulation, however doing so without affecting other elements of the system can be difficult [94].
- Current investigations into novel thermoelectric materials, including organic, hybrid, and nanostructured materials, are promising in terms of cost reduction and efficiency enhancement. One major possibility to lessen the negative ecological effects of these technologies is to accelerate the creation of thermoelectric materials that are abundant, non-toxic, and recyclable.
- Reducing heat conductivity while maintaining or increasing electrical conductivity is one way that nanostructuring thermoelectric materials can greatly improve their performance. Heat exchangers, air conditioning systems, power plants, and other energy-related systems can all benefit from the integration of thermoelectric materials to increase efficiency.
- By increasing the effectiveness of renewable energy sources and lowering dependency on fossil fuels, thermoelectrics can support global decarbonisation initiatives.

5. Conclusions

The substantial potential of sustainable thermoelectric materials to improve the effectiveness and ecological impact of solar energy applications is highlighted in this review. Even while the development of high-performance, environmentally friendly thermoelectric materials has advanced significantly, there are still several obstacles to overcome, most notably in the areas of efficiency, stability, and scalability optimisation. A viable path to sustainable energy conversion is provided by the integration of these materials into solar energy systems; however, addressing the trade-offs between material performance and sustainability will require ongoing interdisciplinary study.

- In the global endeavour to reduce pollution and conserve energy, thermoelectric materials are capable of tremendous help for applications involving solar energy.
- Additionally, there are several ways to increase the Seebeck coefficient, including modulation doping to increase carrier mobility and features that can be employed in alloys to reduce heat conductivity without changing electrical conductivity.
- Future developments are anticipated to concentrate on enhancing the thermoelectric figure of merit (ZT), exploring novel materials with reduced ecological impacts, and developing economical production methodologies.

In the end, a more sustainable energy future may result from the effective use of sustainable thermoelectric materials in solar energy applications, which could be vital in supplying the world's energy needs while reducing their negative effects on the environment.

CRediT authorship contribution statement

Neelam Baghel: Writing – original draft, Methodology, Investigation, Formal analysis. **Anil Kumar:** Writing – review & editing, Visualization, Supervision, Investigation, Conceptualization.

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.

Acknowledgments

Authors are extremely thankful to Prof Yogi Goswami Distinguished Professor and Director, Clean Energy Research Center, University of South Florida, USA for supporting the creation of Centre for Energy and Environment, Delhi Technological University, Delhi (India), where compiling this research work is done.

Abbreviations

COP	Coefficient of performance
CPV	Concentrating photovoltaic
FIR	Far-infrared
HSTE	Hybrid Solar Thermoelectric
PCM	Phase change material
PVT	Photovoltaic-Thermal
MIR	Mid-infrared
SOEC	Solid oxide electrolysis cell
T	Temperature
TEC	Thermoelectric cooler
TED	Thermoelectric dehumidifier
TEG	Thermoelectric generator
TEM	Thermoelectric material
TESU	Thermal energy storage unit
THE	Thermoelectric heater
TPG	Thermal power generator
ZT	Thermoelectric material performance

k Thermal conductivity

Data availability

Data will be made available on request.

References

[1] S. Shoeibi, H. Kargarsharifabad, M. Sadi, A. Arabkoohsar, S. Ali, A review on using thermoelectric cooling, heating, and electricity generators in solar energy applications, Sustain. Energy Technol. Assessments 52 (2022), https://doi.org/10.1016/j.seta.2022.102105. February.

[2] X.F. Zheng, C.X. Liu, R. Boukhanouf, Y.Y. Yan, W.Z. Li, Experimental study of a domestic thermoelectric cogeneration system, Appl. Therm. Eng. 62 (1) (January 2014) 69–79, https://doi.org/10.1016/j.applthermaleng.2013.09.008.

[3] S. Twaha, J. Zhu, Y. Yan, B. Li, A comprehensive review of thermoelectric technology : materials, applications, modelling and performance improvement, Renew. Sustain. Energy Rev. 65 (2016) 698–726, https://doi.org/10.1016/j.rser.2016.07.034.

[4] N. Baghel, K. Manjunath, A. Kumar, Assessment of solar-biomass hybrid power system for decarbonizing and sustainable energy transition for academic building, Process Saf. Environ. Protect. 187 (2024) 1201–1212, https://doi.org/10.1016/j.psep.2024.05.004.

[5] Pradeepkumar Sundarraj, Dipak Maity, Susanta Sinha Roy and Robert A. Taylor, Recent Advances in Thermoelectric Materials and solar thermoelectric generators - a critical review, RSC Adv. 4 (2014) 46860–46874, doi:10.1039/C4RA05322B.

[6] N. Baghel, K. Manjunath, A. Kumar, Performance evaluation and optimization of albedo and tilt angle for solar photovoltaic system, Comput. Electr. Eng. 110 (2023) 108849, https://doi.org/10.1016/j.compeleceng.2023.108849. April.

[7] Z. Li, J. Yang, P.A.N. Dezfuli, Study on the influence of light intensity on the performance of solar cell, Int. J. Photoenergy (2021), https://doi.org/10.1155/2021/6648739.

[8] A. Rehman, A. Ali, S. Ikram, K. Mahmood, A. Al, Emerging pathways in thermoelectric : chemical bath deposition of magnesium selenide thin films for sustainable energy harvesting, Ceram. Int. 50 (2024) 20758–20763, https://doi.org/10.1016/j.ceramint.2024.03.204. March.

[9] X.F. Zheng, C.X. Liu, Y.Y. Yan, Q. Wang, A review of thermoelectrics research – recent developments and potentials for sustainable and renewable energy applications, Renew. Sustain. Energy Rev. 32 (2019) 486–503, https://doi.org/10.1016/j.rser.2013.12.053. May.

[10] C. Shen, G. Lv, S. Wei, C. Zhang, C. Ruan, Investigating the performance of a novel solar lighting/heating system using spectrum-sensitive nanofluids, Appl. Energy 270 (2020), https://doi.org/10.1016/j.apenergy.2020.115208. January.

[11] H. Alghamdi, et al., From sunlight to power: enhancing 4E performance with two-stage segmented thermoelectric generators in concentrated solar applications, J. Clean. Prod. 429 (October) (2023) 139314, https://doi.org/10.1016/j.jclepro.2023.139314.

[12] K. Dhandapani, H. Fattahimoghaddam, I. Ho, D. Mani, Black TiO_2 -infused polydimethylsiloxane composites for efficient solar-assisted water evaporation and thermoelectric energy generation, Separ. Purif. Technol. 343 (2024), https://doi.org/10.1016/j.seppur.2024.127026. March.

[13] L. Yang, Z.G. Chen, J. Zou, High-performance thermoelectric materials for solar energy application, Emerging Materials For Energy Conversion And Storage 3-38 (2018), https://doi.org/10.1016/B978-0-12-813794-9.00001-6.

[14] M. d'Angelo, C. Galassi, N. Lecis, Thermoelectric materials and applications: a review, Energies 16 (17) (2023), https://doi.org/10.3390/en16176409.

[15] Z. Soleimani, S. Zoras, B. Ceranic, S. Shahzad, Y. Cui, A review on recent developments of thermoelectric materials for room-temperature applications, Sustain. Energy Technol. Assessments 37 (2020), https://doi.org/10.1016/j.seta.2019.100604. September 2019.

[16] M. Bozorgi, S.H. Tasnim, S. Mahmud, Experimental and numerical study on the integration of solar-driven desiccant and thermoelectric Systems for Sustainable Thermal Comfort, Appl. Energy 376 (2024) 124253, https://doi.org/10.1016/j.apenergy.2024.124253.

[17] F.J. Montero, R. Lamba, A. Ortega, W. Jahn, W.H. Chen, A.M. Guzmán, A bidirectional solar thermoelectric generator combining heat storage for daytime and nighttime power generation, Appl. Therm. Eng. 224 (2023), https://doi.org/10.1016/j.applthermaleng.2023.119997. January.

[18] N.P. Bayendang, M.T. Kahn, V. Balyan, Thermoelectric generators (TEGs) and thermoelectric coolers (TECs) modeling and optimal operation points investigation, Adv. Sci. Technol. Eng. Syst. J. 7 (1) (2022) 60–78, https://doi.org/10.25046/aj070107.

[19] G. Kidegho, R. Kinyua, C. Muriithi, F. Njoka, Innovative solar photovoltaic and thermoelectric power generator for a recirculating aquaculture system, Int. J. Renew. Energy Resour. 10 (3) (2020).

[20] M. Elgendi, J.A.L. Tamimi, A. Alfalahi, D. Alkhoori, M. Alshanqiti, A. Aladawi, Wall panels using thermoelectric generators for sustainable cities and communities: a mini-review, IOP Conf. Ser. Earth Environ. Sci. 1074 (1) (2022), https://doi.org/10.1088/1755-1315/1074/1/012003.

[21] R. Ahıska, H. Mamur, A review : thermoelectric generators in renewable energy, Int. J. Renew. Energy Resour. 4 (1) (2014).

[22] Y. Köysal, Y. Yakut, S. Özbektaş, H. Bülbül, T. Atalay, F. Şahin, Evaluation of energy efficiency of thermoelectric energy generator system with heat pipes, solar tracker, Fresnel lens and nano-particle fluids, Appl. Therm. Eng. 246 (2024), https://doi.org/10.1016/j.applthermaleng.2024.123027. March.

[23] E.A. Khera, et al., First principles exploration of structural stability, optoelectronic and thermoelectric properties of BaXO3 (X = Hf, Ti, V) for solar cell applications, Mater. Today Commun. 39 (2024) 1–11, https://doi.org/10.1016/j.mtcomm.2024.108629. March.

[24] S.K. Bhukesh, A. Kumar, Simulation, modeling and experimental performance investigations of novel giant water lens solar thermoelectric generator, Energy Convers. Manag. 295 (2023) 117656, https://doi.org/10.1016/j.enconman.2023.117656. July.

[25] H. Liu, et al., Effects of SnSe addition on the thermoelectric properties of Bi0.85Sb0.15Se, Solid State Sci. 154 (2024) 107599, https://doi.org/10.1016/j.solidstatesciences.2024.107599. May.

[26] J.C. Zheng, Recent advances on thermoelectric materials, Front. Phys. China 3 (3) (2008) 269–279, https://doi.org/10.1007/s11467-008-0028-9.

[27] C. O'Dwyer, R. Chen, J.-H. He, J. Lee, K.M. Razeeb, Scientific and technical challenges in thermal transport and thermoelectric materials and devices, ECS Journal of Solid State Science and Technology 6 (3) (2017) N3058–N3064, https://doi.org/10.1149/2.0091703jss.

[28] P.A. Finn, C. Asker, K. Wan, E. Bilotti, O. Fenwick, C.B. Nielsen, Thermoelectric materials: current status and future challenges, Frontiers in Electronic Materials 1 (2021) 1–13, https://doi.org/10.3389/femat.2021.677845. August.

[29] H. Alghamdi, et al., From sunlight to power: enhancing 4E performance with two-stage segmented thermoelectric generators in concentrated solar applications, J. Clean. Prod. 429 (2023), https://doi.org/10.1016/j.jclepro.2023.139314. September.

[30] M. Mizoshiri, M. Mikami, K. Ozaki, K. Kobayashi, Thin-film thermoelectric modules for power generation using focused solar light, J. Electron. Mater. 41 (6) (2012) 1713–1719, https://doi.org/10.1007/s11664-012-2047-0.

[31] G. Neeli, D.K. Behara, M.K. Kumar, State of the art review on thermoelectric materials, International Journal of Science and Research (IJSR) 14 (10) (2013) 2319–7064, https://doi.org/10.21275/ART20162476.

[32] M.R. Shankar, A.N. Prabhu, A review on structural characteristics and thermoelectric properties of mid-temperature range Chalcogenide-based thermoelectric materials, J Mater Sci 58 (2023) 16591–16633, https://doi.org/10.1007/s10853-023-09028-8.

[33] R. Singh, et al., Advancements in thermoelectric materials for efficient waste heat recovery and renewable energy generation, Hybrid Advances 5 (2024) 100176, https://doi.org/10.1016/j.hybadv.2024.100176. March.

[34] H. Alghamdi, et al., Bayesian neural networks for solar power forecasts in advanced thermoelectric systems, Case Stud. Therm. Eng. 61 (2024) 104940, https://doi.org/10.1016/j.csite.2024.104940. April.

[35] Y. Liu, et al., Design and experimental study of a compact thermoelectric device driven by solar heating and radiative cooling, Next Energy 4 (2024) 100146, https://doi.org/10.1016/j.nxener.2024.100146. February.

[36] M. Hamid, et al., A review on thermoelectric renewable energy : principle parameters that affect their performance, Renew. Sustain. Energy Rev. 30 (2014) 337–355, https://doi.org/10.1016/j.rser.2013.10.027.

[37] X. Zhang, L.D. Zhao, Thermoelectric materials: energy conversion between heat and electricity, Journal of Materiomics 1 (2) (2015) 92–105, https://doi.org/10.1016/j.jmat.2015.01.001.

[38] P. Huen, W.A. Daoud, Advances in hybrid solar photovoltaic and thermoelectric generators, Renew. Sustain. Energy Rev. 72 (2017) 1295–1302, https://doi.org/10.1016/j.rser.2016.10.042. October 2016.

[39] L. Liu, J. Hong, Y. Zhang, R. Li, Y. Liao, J. Huang, Thermal concentration on thermoelectric thin film for efficient solar energy harvesting, Coatings 12 (5) (2022), https://doi.org/10.3390/coatings12050630.

[40] L. Xia, G. Wei, G. Wang, L. Cui, X. Du, Research on combined solar fiber lighting and photovoltaic power generation system based on the spectral splitting technology, Appl. Energy 333 (January 2023), https://doi.org/10.1016/j.apenergy.2022.120616.

[41] A. Weidenkaff, Thermoelectricity for future sustainable energy technologies, EPJ Web Conf. 148 (2017) 1–11, https://doi.org/10.1051/epjconf/201714800010.

[42] E. Elsarrag, H. Pernau, J. Heuer, N. Roshan, Y. Alhorr, K. Bartholomé, Spectrum splitting for efficient utilization of solar radiation: a novel photovoltaic–thermoelectric power generation system, Renewables: Wind, Water, and Solar 2 (1) (2015), https://doi.org/10.1186/s40807-015-0016-y.

[43] C. Shen, G. Lv, K. Zheng, C. Ruan, C. Zhang, Y. Dong, Modeling and investigating the detailed characteristics of solar lighting/heating system based on spectrum split of nanofluids, Energy and Built Environment 3 (1) (2022) 30–39, https://doi.org/10.1016/j.enbenv.2020.10.003.

[44] K. Tyagi, B. Gahtori, S. Kumar, S.R. Dhakate, Advances in solar thermoelectric and photovoltaic-thermoelectric hybrid systems for power generation, Sol. Energy 254 (2023) 195–212, https://doi.org/10.1016/j.solener.2023.02.051. February.

[45] J. Zhang, H. Zhai, Z. Wu, Y. Wang, H. Xie, M. Zhang, Enhanced performance of photovoltaic–thermoelectric coupling devices with thermal interface materials, Energy Rep. 6 (2020) 116–122, https://doi.org/10.1016/j.egyr.2019.12.001.

[46] C. Chen, et al., Recent advances in solar energy full spectrum conversion and utilization, ES Energy and Environment 11 (2021) 3–18, https://doi.org/10.30919/esee8c416.

[47] J.T. Jarman, E.E. Khalil, E. Khalaf, Energy analyses of thermoelectric renewable energy sources, Open J. Energy Effic. 2 (4) (2013) 143–153, https://doi.org/10.4236/ojee.2013.24019.

[48] T.M. Tritt, X. Tang, Q. Zhang, W. Xie, Solar thermoelectrics: direct solar thermal energy conversion, Fundamentals of Materials for Energy and Environmental

Sustainability 33 (2011) 289–294, https://doi.org/10.1017/CBO9780511718786.026. APRIL.

[49] X. Zhang, L.D. Zhao, Thermoelectric materials: energy conversion between heat and electricity, Journal of Materiomics 1 (2) (2015) 92–105, https://doi.org/10.1016/j.jmat.2015.01.001.

[50] Solar Radiation Standards" https://www.johnsonwindowfilms.com/dealer/articles/RB_SRstandards.html (Accessed on 20th October, 2024).

[51] W. Jing, et al., Enhancing thermoelectric generation: integrating passive radiative cooling and concentrated solar heating with consideration of parasitic heat conduction, Case Stud. Therm. Eng. 62 (2024) 105232, https://doi.org/10.1016/j.csite.2024.105232. July.

[52] M. Lyu, J. Lin, Y. Wang, J. Krupczak, D. Shi, Synergistic photothermal-thermoelectric-photovoltaic energy generation via a transparent spectral modulating solar module, Sol. Energy 258 (2023) 220–231, https://doi.org/10.1016/j.solener.2023.05.001. January.

[53] Y.A. Alamri, Enhancing solar thermoelectric power generation with supercritical CO_2 cooling: hydraulic, thermal, and exergy analysis, Therm. Sci. Eng. Prog. 54 (2024) 102833, https://doi.org/10.1016/j.tsep.2024.102833. May.

[54] Y. Long, E. Yin, Q. Li, S. Yang, Experimental study on a solar thermoelectric power generation system under non-uniform irradiation, Appl. Therm. Eng. 256 (2024) 124101, https://doi.org/10.1016/j.applthermaleng.2024.124101. April.

[55] H. Zhu, Z. Luo, Q. Cheng, L. Lu, Highly efficient spectrum-splitting solar energy utilization based on near- and far-field thermophotovoltaics, Energy 309 (2024), https://doi.org/10.1016/j.energy.2024.133137. February.

[56] S. Lv, et al., Comparative analysis of photovoltaic thermoelectric systems using different photovoltaic cells, Appl. Therm. Eng. 235 (2023) 121356, https://doi.org/10.1016/j.applthermaleng.2023.121356. August.

[57] S.J. Cobb, et al., A photoelectrochemical-thermoelectric device for semi-artificial CO_2 fixation employing full solar spectrum utilization, Device (2024), https://doi.org/10.1016/j.device.2024.100505.

[58] G. Huang, K. Wang, C.N. Markides, Efficiency limits of concentrating spectral-splitting hybrid photovoltaic-thermal (PV-T) solar collectors and systems, Light Sci. Appl. 10 (1) (2021) 1–14, https://doi.org/10.1038/s41377-021-00465-1.

[59] G. Tan, M. Ohta, M.G. Kanatzidis, Thermoelectric power generation: from new materials to devices, Phil. Trans. Math. Phys. Eng. Sci. 377 (2152) (2019), https://doi.org/10.1098/rsta.2018.0450.

[60] S. Kumari, A. Bhende, A. Pandit, S. Rayalu, Efficiency enhancement of photovoltaic panel by heat harvesting techniques, Energy for Sustainable Development 73 (2023) 303–314, https://doi.org/10.1016/j.esd.2023.02.007. March.

[61] S.K. Bhukesh, A. Kumar, S.K. Gaware, Bismuth telluride (Bi2Te3) thermoelectric material as a transducer for solar energy application, Mater. Today: Proc. 26 (2019) 3131–3137, https://doi.org/10.1016/j.matpr.2020.02.646.

[62] S.K.G. Sanjeev Kumar Bhukesh, Anil Kumar, Performance evaluation of bismuth telluride semiconductor based parabolic dish concentrated solar thermoelectric generator in realistic meteorological conditions of Central India, Semicond. Optoelectron. 42 (1) (2023) 645–673.

[63] Zhenglong Tang, Lipeng Hu, Tiejun Zhu, Xiaohua Liu, A Xinbing Zhao, "High performance n-type bismuth telluride based alloys for midtemperature power generation,", J. Mater. Chem. C (2013) https://doi.org/10.1039/x0xx00000x.

[64] Y. Sun, Y. Liu, R. Li, Y. Li, S. Bai, Strategies to improve the thermoelectric figure of merit in thermoelectric functional materials, Front. Chem. 10 (2022) 1–22, https://doi.org/10.3389/fchem.2022.865281. May.

[65] O. Caballero-Calero, J.R. Ares, M. Martín-González, Environmentally friendly thermoelectric materials: high performance from inorganic components with low toxicity and abundance in the earth, Advanced Sustainable Systems 5 (11) (2021), https://doi.org/10.1002/adsu.202100095.

[66] R. Manghwar, J. Selvaraj, N. Abd Rahim, L. Kumar, H. Khoharo, Global advancements of solar thermoelectric generators application, limitations, and prospects: a comprehensive review, Appl. Therm. Eng. 257 (PA) (2024) 124231, https://doi.org/10.1016/j.applthermaleng.2024.124231.

[67] A.S. Mafe, O.E. Shogo, B.W. Bello, A.A. Musari, Systematic study of stable palladium and nickel based half-Heusler compounds for thermoelectric generators, Solid State Sci. 149 (2024) 107451, https://doi.org/10.1016/j.solidstatesciences.2024.107451. December 2023.

[68] D.A.R. Barkhouse, O. Gunawan, T. Gokmen, T.K. Todorov, D.B. Mitzi, Yield predictions for photovoltaic power plants: empirical validation, recent advances and remaining uncertainties, Prog. Photovoltaics Res. Appl. 20 (1) (2015) 6–11, https://doi.org/10.1002/pip.

[69] M.Y. Zulakmal, A. Fudholi, N.S. Rukman, S. Mat, H.Y. Chan, K. Sopian, Solar photovoltaic/thermal-thermoelectric generator performance review, IOP Conf. Ser. Earth Environ. Sci. 268 (1) (2019), https://doi.org/10.1088/1755-1315/268/1/012120.

[70] N. Syakirah, et al., Analytical and experimental study of hybrid photovoltaic – thermal – thermoelectric systems in sustainable energy generation, Case Stud. Therm. Eng. 51 (June) (2023), https://doi.org/10.1016/j.csite.2023.103522.

[71] A. Acır, O. Kaan Çinici, Experimental investigation of a thermal energy storage unit integrated with thermoelectric generators under solar radiation, Sol. Energy 265 (2023), https://doi.org/10.1016/j.solener.2023.112028. January.

[72] E. Manay, S. Bayram, Desalination performance evaluation of a solar still enhanced by thermoelectric modules, Sol. Energy 268 (2024) 112325, https://doi.org/10.1016/j.solener.2024.112325.

[73] N. Rahbar, A. Gharaiian, S. Rashidi, Exergy and economic analysis for a double slope solar still equipped by thermoelectric heating modules - an experimental investigation, Desalination 420 (2017) 106–113, https://doi.org/10.1016/j.desal.2017.07.005. May.

[74] J.A. Esfahani, N. Rahbar, M. Lavvaf, Utilization of thermoelectric cooling in a portable active solar still - an experimental study on winter days, Desalination 269 (1–3) (2011) 198–205, https://doi.org/10.1016/j.desal.2010.10.062.

[75] M. Feng, S. Lv, J. Deng, Y. Guo, Y. Wu, G. Shi, An overview of environmental energy harvesting by thermoelectric generators, Renew. Sustain. Energy Rev. 187 (2023), https://doi.org/10.1016/j.rser.2023.113723. September.

[76] M. Alnajideen, G. Min, Hybrid photovoltaic-thermoelectric system using a novel spectral splitting solar concentrator, Energy Convers. Manag. 251 (2022) 114981, https://doi.org/10.1016/j.enconman.2021.114981.

[77] H. Pan, S. Wang, Y. Zhao, Y. Lu, Full-spectrum solar water decomposition for hydrogen production via a concentrating photovoltaic-thermal power generator-solid oxide electrolysis cell system, Energy Convers. Manag. 322 (2024) 119158, https://doi.org/10.1016/j.enconman.2024.119158. April.

[78] K. Guo, et al., Hydrogen production and solar energy storage with thermo-electrochemically enhanced steam methane reforming, Sci. Bull. 69 (8) (2024) 1109–1121, https://doi.org/10.1016/j.scib.2024.01.028.

[79] B.L. Bai, S. Du, M.J. Li, Solar-driven photovoltaic-steam-thermoelectric-steam cogeneration system by the interfacial cooling design, Energy Convers. Manag. 302 (2024), https://doi.org/10.1016/j.enconman.2024.118147. January.

[80] A. Patyk, Thermoelectrics: impacts on the environment and sustainability, J. Electron. Mater. 39 (9) (2010) 2023–2028, https://doi.org/10.1007/s11664-009-1013-y.

[81] M. Kavosh, F. Jamali-Sheini, R. Yousefi, M. Cheraghizade, Enhanced performance of visible-range nanostructured CuS photodetectors by Zn concentrations, Solid State Sci. 143 (2023) 107272, https://doi.org/10.1016/j.solidstatesciences.2023.107272. June.

[82] Oleg Sherbakov, Study shows how adding impurities to thermoelectric materials impacts their mechanical properties, retrieved 24 August 2024 from, https://phys.org/news/2024-01-adding-impurities-thermoelectric-materialsimpacts.html, 2024.

[83] J.I. Ghojel, Thermal and environmental assessment of a conceptual waste heat recovery system for automotive application, in: Proceedings ICED 05, the 15th International Conference on Engineering Design, DS 35, 2005.

[84] H.E. Rebellon, O.F.P. Henao, E.I. Gutierrez-Velasquez, A.A. Amell, H.A. Colorado, Thermoelectric modules: applications and opportunities in building environments for sustainable energy generation: from biomass, municipal waste, and other sources, Engineered Science (2024) 1–46, https://doi.org/10.30919/es1164.

[85] R.K. Iyer, S. Pilla, Environmental profile of thermoelectrics for applications with continuous waste heat generation via life cycle assessment, Sci. Total Environ. 752 (2021) 141674, https://doi.org/10.1016/j.scitotenv.2020.141674.

[86] Z. Soleimani, S. Zoras, B. Ceranic, S. Shahzad, Y. Cui, The cradle to gate life-cycle assessment of thermoelectric materials: a comparison of inorganic, organic and hybrid types, Sustain. Energy Technol. Assessments 44 (2021) 101073, https://doi.org/10.1016/j.seta.2021.101073.

[87] S.K. Bhukesh, S.K. Gawre, A. Kumar, Review on advancement in solar and waste heat based thermoelectric generator, Energy Sources, Part A Recovery, Util. Environ. Eff. 45 (2) (2023) 4982–5002, https://doi.org/10.1080/15567036.2023.2206370.

[88] J. Dong, et al., Challenges and opportunities in low-dimensional thermoelectric nanomaterials, Mater. Today 66 (2023) 137–157, https://doi.org/10.1016/j.mattod.2023.04.021. June.

[89] Z. Han, et al., Room-temperature thermoelectric materials: challenges and a new paradigm, Journal of Materiomics 8 (2) (2022) 427–436, https://doi.org/10.1016/j.jmat.2021.07.004.

[90] C. Artini, et al., Roadmap on thermoelectricity, Nanotechnology 34 (29) (2023), https://doi.org/10.1088/1361-6528/acca88.

[91] C. Wan, Y. Wang, N. Wang, W. Norimatsu, M. Kusunoki, K. Koumoto, Development of novel thermoelectric materials by reduction of lattice thermal conductivity, Sci. Technol. Adv. Mater. 11 (4) (2010), https://doi.org/10.1088/1468-6996/11/4/044306.

[92] C. Fiedler, T. Kleinhanns, M. Garcia, S. Lee, M. Calcabrini, M. Ibáñez, Solution-processed inorganic thermoelectric materials: opportunities and challenges, Chem. Mater. 34 (19) (2022) 8471–8489, https://doi.org/10.1021/acs.chemmater.2c01967.

[93] Z. Liu, Challenges for thermoelectric power generation: from a material perspective, Materials Lab 1 (February) (2022) 1–12, https://doi.org/10.54227/mlab.20220003.

[94] J.J. Gutiérrez Moreno, J. Cao, M. Fronzi, M.H.N. Assadi, A review of recent progress in thermoelectric materials through computational methods, Materials for Renewable and Sustainable Energy 9 (3) (2020) 1–22, https://doi.org/10.1007/s40243-020-00175-5.