Journal of Information Systems Engineering and Management
2025, 10(32s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Advancement in Thermoelectric Generators: A Sustainable Approach to Power Generation and Waste Heat Recovery

Chandra Shekhar Choudhary [1], Avithi Desappan Dhass, [2], Ram Krishna [3*], Dhiren Patel [4]
[1, 3] Department of Metallurgical and Materials Engineering, National Institute of Technology Jamshedpur, Jamshedpur, Jharkhand, India
[2, 4] Mechanical Engineering Department, IITE, Indus University, Ahmedabad-382115, India
**Corresponding Author Email: krishna.met@nitjsr.ac.in*

ARTICLE INFO

Received: 31 Dec 2024

Revised: 20 Feb 2025

Accepted: 28 Feb 2025

ABSTRACT

Thermoelectric Generators (TEGs) directly convert thermal energy into electrical energy, rendering them a promising sustainable energy source. Using thermoelectric materials, TEGs convert energy efficiently and environmentally, making them appropriate for many applications. TEG uses waste heat to generate power without moving components or intermediate processes, lowering maintenance and operational expenses. The figure of merit, which measures thermoelectric conversion efficiency, has improved dramatically in recent years due to thermoelectric material system advances. These advances allow TEGs to provide microwatts for small devices and several watts for industrial applications. For widespread use and expansion, wearable Internet of Things devices need tiny, inexpensive, and continuous power sources. Large-scale industrial systems can improve sustainability by efficiently recovering waste heat and transforming it into electricity. This study examines materials and designs for small electronics, high-level industrial applications, waste heat recovery systems, and renewable energy solutions. TEGs will help achieve energy efficiency and sustainability across sectors by blending modern thermoelectric materials with novel engineering.

Keywords: TEGs, Figure of Merit, Modern materials, Performance analysis, Sustainable Energy.

INTRODUCTION

Sustainable energy solutions are needed due to rising global energy consumption, fossil resource finiteness, and environmental effect [1]. Thermoelectric generators, which directly transform heat energy into electricity without intermediate processes or moving parts, are promising [2]. Thermoelectricity relies on the Seebeck phenomenon, which creates an electric potential difference when a temperature gradient is applied.

TEGs have various advantages over conventional power plants. As they do not use combustion or mechanical components, they are environmentally benign and reduce maintenance and operational costs. TEGs can also be tiny, position-independent, and used in an array of applications, from small electronics to big industrial waste heat recovery systems [3].

By providing reliable, efficient, and environmentally friendly power generation, TEGs could revolutionise the energy landscape. Their capacity to use waste heat from traditional energy sources makes them a promising energy efficiency choice. Thermal energy can be transformed into electrical energy from industrial processes, automotive exhaust, and body heat [4].

Recent advances in thermoelectric materials, notably nanostructured ones, have considerably improved TEG conversion efficiency. These materials have improved thermoelectric properties, including a greater figure of merit, which affects thermoelectric device efficiency. Advanced engineering and materials allow TEGs to be employed in wearable electronics and industrial waste heat recovery systems [5][6][7][8].

Solid-state energy conversion, without moving parts or fluids, is reliable, maintainable, and long-lasting. Historically, TEG efficiency was limited by thermoelectric materials' figure of merit [9][10][3]. Latest materials science advances, such as nanostructured materials and innovative compositions, have improved ZT values, reviving TEG technology. This revival has enabled several uses, from powering wearable IoT gadgets to recovering waste heat in industry [10][11].

This study reviews thermoelectric generator technology, highlighting recent material, design, and application advances that demonstrate its growing importance as a sustainable power source. TEG technology can improve energy sustainability across sectors, it says. This breakthrough technology is covered in detail in the article, including its necessity, electrical conductivity, energy conversion efficiency, performance evaluation, and future possibilities.

1.1 Thermoelectric Materials and Efficiency Enhancement

TEG performance is mostly dependent on thermoelectric material quality. A material's Seebeck coefficient, thermal conductivity, and electrical conductivity make up dimensionless ZT. High-quality thermoelectric materials have improved conversion efficiency in recent decades. This field has advanced with nanostructured materials, which reduce thermal conductivity while keeping electrical qualities [12][13][10].

Nanostructures like quantum dots, superlattices, and hierarchical structures can disrupt phonons, the major heat carriers, while maintaining or improving electron transport, which is responsible for electrical conductivity. This method has produced innovative thermoelectric materials that outperform bulk materials [14][15][16]. In addition to nanostructuring, novel material compositions and doping methods have improved thermoelectric performance [15] [17][18]. Doping existing materials, such as SnSe with Ge, has improved Seebeck coefficient and thermoelectric performance [19]

1.2 Thermoelectric Generator Design and Applications

Design improves TEG performance and application. There are p- and n-type thermoelectric couplings in TEGs. They efficiently convert heat into electricity by connecting electrically in series and thermally in parallel [20].

The design of TEGs must address heat source characteristics, thermal management, electrical configurations, and target application integration. Modern TEG design improves thermal interfaces, heat transport, and electrical connectivity to maximise energy conversion efficiency [21]. Thermoelectric generators are used in anything from energy harvesting for wearable devices to industrial waste heat recovery systems [13][22].

TEG designs that can be customised are compact and high-performance thanks to advanced engineering. Nanostructured materials in TEG modules have made lightweight, flexible, high-power-density devices for wearable electronics and small-scale power generation [2]. These systems transform massive volumes of heat energy from industrial processes into clean, reliable electricity. Thermoelectric generators can boost industrial energy efficiency by harvesting waste heat, improving sustainability and cost savings [23]. Thermoelectric generators power car systems by converting engine exhaust and coolant heat [24]. TEGs are also used in remote and off-grid power generation, especially in spacecraft, satellites, and remote sensing stations.

1.3 Challenges and Future Prospects as Research Gap

Despite promising thermoelectric technology advances, numerous significant constraints prevent its mainstream use and transformational potential [25]. Although nanostructured materials and unique generator designs have greatly improved thermoelectric generator efficiency and performance, unresolved challenges still demand further research and innovation [26][27].

The low conversion efficiency of TEGs compared to other power generation technologies is a major issue. Improved thermoelectric materials have raised the figure of merit (ZT), but more optimisation is needed to compete with normal energy conversion methods. Scalable and cost-effective thermoelectric material and device manufacturing is difficult. Successfully commercialising TEG technology requires large-scale, low-cost, and environmentally friendly production processes [28].

In addition, engineering thermoelectric generator integration into complex systems like industrial processes and transportation applications is difficult. Systems that improve TEG efficiency and performance require considerable analysis and system-level optimisation research [2].

While ongoing research in materials science, device engineering, and system integration shows potential, there is a need for continued innovation to improve efficiency, cost-effectiveness, and the range of applications for thermoelectric generators [27] [2] [29] [30]. Identifying practical solutions to these challenges will pave the way for the broader adoption of TEGs and their contribution to a sustainable, energy-efficient future [29] [27] [2] [30]. These gaps in knowledge and technology represent opportunities for future research to address the barriers to thermoelectric technology's scalability and efficiency, ultimately unlocking its full potential as a sustainable power generation solution.

LITERATURE REVIEW

The energy was employed a lot in mechanized manufacturing. Energy demand has increased due to technology. Global warming and environmental problems have become major concerns with increased energy consumption. As energy consumption surged during this period, the unsustainable nature of fossil fuels became increasingly evident. Many innovative alternative energy technologies have been developed to address this challenge and the depletion of fossil resources. Thermal power generation and waste heat recovery are sustainable with thermoelectric technology [2][31]. Nanostructuring reduces heat conductivity while keeping electrical characteristics, improving thermoelectric performance [12] [2].

Integrated nanostructured materials into compact and flexible modules have expanded the applications of thermoelectric generators. Thermal generators are used in industrial waste heat recovery, automotive, and remote power generating [27] [12] [2]. However, significant thermoelectric technology adoption is still difficult. Thermoelectric generators must improve their conversion efficiency to compete with other power generation methods [12][27][29][2]. For thermoelectric device commercialisation, manufacturing procedures must be scalable and cost-effective. Advanced thermoelectric technology is expected from materials science, device engineering, and system integration research.

Historically, the coupling of two dissimilar metals under a temperature differential was observed to create a magnetic field. Thermoelectric devices were widely used in cooling heat pumps. Though thermoelectric cells could be employed in small-scale designs where cooling was prioritized over system efficiency, this technology became less prominent by the mid-20th century as semiconductors with lower band gaps outperformed the two-metal approach. However, renewed interest in thermoelectric power generation emerged around this time, as established thermoelectric materials were found to have relatively low figures of merit, limiting their power output efficiency compared to combustion heat engines[32][33].

The integration of these advanced thermoelectric materials into compact and flexible generator modules has expanded the potential applications of thermoelectric technology. Automotive, industrial waste heat recovery, and distant power generation have used thermoelectric generators successfully [27]. However, some key challenges remain to be addressed for the widespread adoption of thermoelectric generators.

Many thermoelectric materials were evaluated but failed to exceed a figure of merit of 1. This lowered research interest in thermoelectrics, casting doubt on their fossil fuel replacement potential. Researchers' interest in thermoelectrics returned in the 1990s as they sought a competitive figure of merit with conventional heat engines using new methods and materials. Bismuth chalcogenides like Bi_2Te_3 and Bi_2Se_3 are excellent thermoelectric materials with 0.8–1.0 figure of merit. Thorium-doped lead telluride has a 1.5 figure of merit at 773 K. Similar to bismuth chalcogenide, magnesium compounds are thermoelectric. Skutterudites and clathrates also show promise with 1.0 as the figure of merit value. Developing high-performance thermoelectric materials with better merits has made thermoelectric generator technology more feasible and competitive [9][29].

Researchers are studying the thermoelectric characteristics of skutterudite, a nickel-iron cobalt arsenide mineral. These materials enable multistage thermoelectric devices with figures of merit larger than 1. Oxide thermoelectrics can be used at 1000 K. Oxide thermoelectric materials include strontium titanate and oxide. At 1000 K, oxide thermoelectric materials have a lower merit of 0.34. Good high-temperature thermoelectric materials are half Heusler alloys, notably n-types [34][35][36].

Bismuth chalcogenide nanostructuring raised the p-type material's GMR to 2.4. The figure of merit of lead selenide and telluride quantum dot superlattices has risen to 1.5, surpassing bulk thermoelectric materials. Novel materials and nanostructured thermoelectrics research have expanded small-to-medium thermal power generating thermoelectric device options. Due to space oxygen shortages, radioisotope thermoelectric power systems are only for spacecraft. Using renewable or sustainable energy heat sources, non-isotope thermoelectric devices have been extensively studied for small to medium-scale power generation. Then, this study evaluates non-isotope thermoelectric power generating methods that could become mainstream in small to medium-sized stand-alone or grid-integrated systems (Figure 1).[6][37]

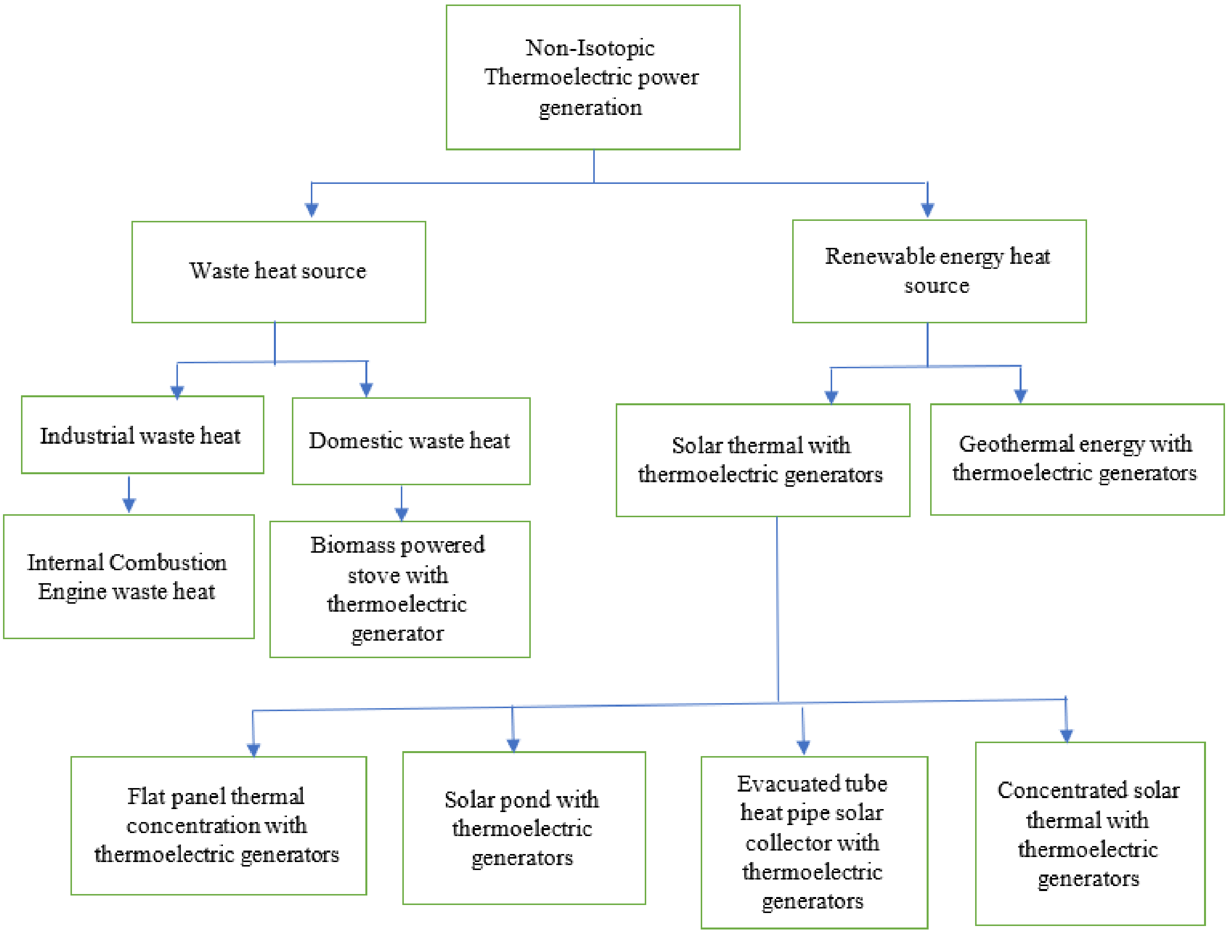


Figure 1. Classification of small-to-medium power production non-isotopic thermal sources and technologies [38] (Date A.,et al., (2014) ; Adopted from *Renewable and Sustainable Energy Reviews Journal*).

Though thermoelectric generators have made significant technological progress, improving their conversion efficiency remains a key challenge.

Thermoelectric generator (TEG) systems for waste heat recovery have gained popularity recently due to their unique benefits: Thermoelectric generators convert thermal energy into electricity without turbines, saving maintenance and replacement expenses. In small contexts, TEGs can produce kilowatts or microgeneration without economies of scale. Without sound pollution, TEGs are environmentally friendly. In contrast, thermoelectric generators require a consistent heat source and have low energy conversion efficiency.

Research in advanced materials and gadget design tries to overcome these limits. Some promising methods include:

- Exploring novel thermoelectric materials with higher figures of merit, like skutterudites, half-Heusler alloys, and chalcogenides [39][22][13] [22] [12] [39] [13]
- Developing nanostructured thermoelectric materials to reduce thermal conductivity and enhance electrical properties
- By integrating thermoelectric generators into combined heat and power systems, waste heat can be captured more efficiently [40][13][22][39] [13] [22]

Thermoelectric generators can generate power and recover waste heat sustainably by improving technology. Making materials more thermoelectric through nanostructuring and doping Thermoelectric module operation depends on N- and p-type materials. Effective implementation requires equal Figures of Merit for n- and p-type legs, but stiff materials make next-generation TEG models difficult. Flexible contacts could help. Materials research and nanotechnology have increased dimensionless worth in recent decades [41].

Thus, methodology advancement masks TE component output reduction. However, well-designed solutions can improve performance and save money or the environment. Manufacturers could mass-produce combined heat and power systems with new low-cost materials and TE module production[3] (Jouhara et al., (2021)). Figure 2(a) shows a thermoelectric power generation (TEG) system as a heat engine that employs electrons. An automotive waste heat recovery 400-module thermoelectric generator (TEG) system with 28 half-Heusler-based thermoelectric uncouplers is shown in Figure 2(b). Power from diesel engine exhaust waste heat was 1 kW. System efficiency is affected by TEG component integration with heat source and heat sink heat dissipation (air or water cooling).

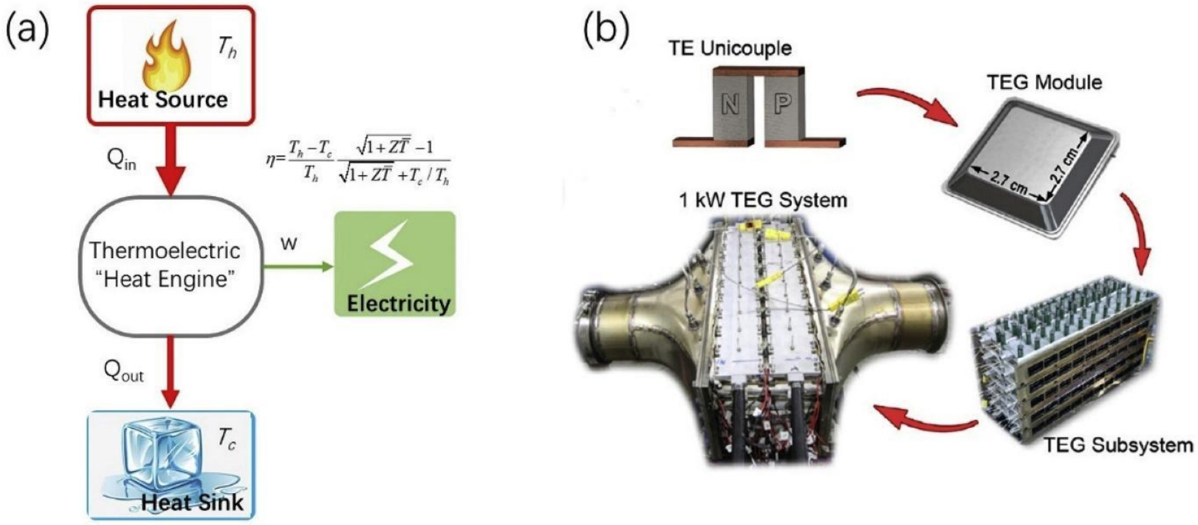


Figure 2. Thermoelectric power generating. (a) The thermodynamic operating theory, (b) functional thermoelectric generator for automotive waste heat recovery[42] (Liu, W, Bai, S (2019): Adopted from *Journal of Materiomics Journal*).

Minimise TEG conversion phonon thermal energy loss. Nanograins, nanoinclusions, and nanoparticles improve ZT and lower lattice thermal conductivity phonon mean free path. In summary, recent advancements in thermoelectric generators enable promising pathways for sustainable power generation and waste heat recovery. Continued progress in materials engineering, module design, and system integration will drive further improvements in energy conversion efficiency and expanduniquely benefits [43] [44] [3] [10].

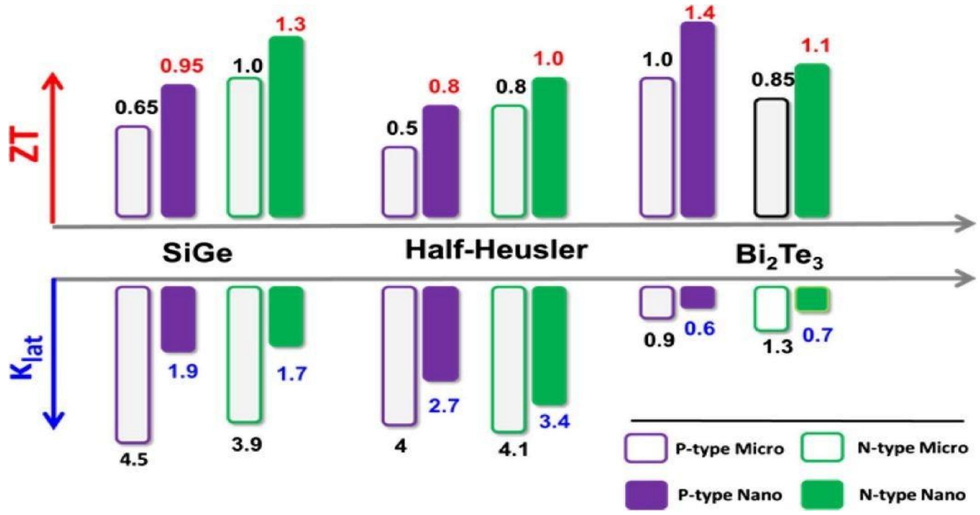


Figure 3. Nanotechnology method involving to improve ZT and lattice thermal conductivity (Liu et al., (2015): Adopted from *Acta Materialia Journal*)[45].

Figure 3 compares the ZTs of ball milled and hot pressed thermoelectric materials (SiGe, half-Heusler alloys, Bi2Te3). This powder metallurgy technique produces a nanocomposite with a broad grain size distribution from hundreds to several nanometers, compositional nanoinclusions, and secondary-phase nanoparticles at grain boundaries. Smaller particle size increases total grain boundaries, which inhibits phonon propagation most. All three material systems for p- and n-type materials show a 30–40% increase in ZT due to lower lattice thermal conductivity. Optimization of carrier mobility requires a THP/Tm ratio of 0.8–0.9. Many materials struggle to decrease grainification without compromising carrier mobility. Heat conductivity decreases as nanoinclusions melt and quench.[46][47]

In summary, thermoelectric materials research has progressed. Materials science, nanostructuring, and integration have made thermoelectric generators more feasible and competitive for waste heat recovery and power generation [48] [2] [13] [19]. Recent research demonstrated that melting, quenching, ball milling, and hot pressing lower PbTe with SrTe thermal conductivity to 0.5, raising ZT above 2.0[49]. These materials have low lattice thermal conductivity and little room for development (Figure. 4). Lead-free chalcogenides, like SnSe, show great promise, with zT greater than 2.5 nearing the theoretical limit [19] [48].

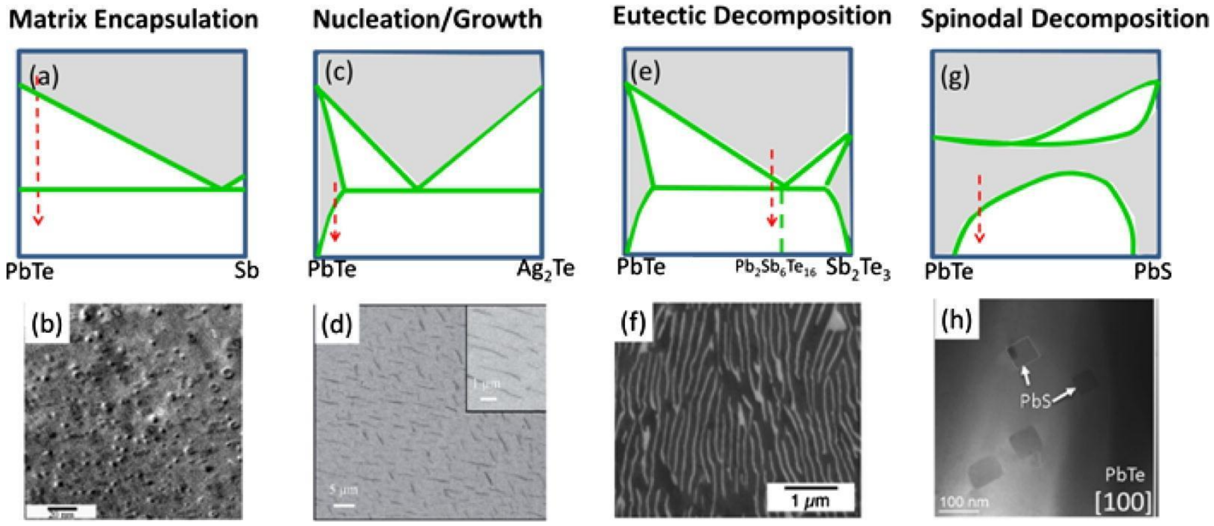


Figure 4. Making nanostructures by melting/casting includes: (a) matrix encapsulation, (b) nucleation and growth, (c) eutectic decomposition, and (d) spinodal decomposition (Liu et al., (2015) : Adopted from *Acta Materialia Journal*)[50].

In today's world, where energy powers almost every aspect of our lives, finding reliable and efficient ways to generate and utilize energy is more important than ever. One exciting possibility lies in harnessing waste heat—energy that would otherwise go unused. TEGs are stepping into the spotlight as a promising technology for this purpose thanks to their unique and practical advantages[51].

TEGs work by taking advantage of a simple but powerful phenomenon called the Seebeck effect. Since TEGs have no moving components or liquids, they are reliable and low-maintenance. Their simplicity and efficiency make them appealing for many power generation applications [51][52].

Despite this, TEGs confront obstacles. Efficiency and power production of these materials are important challenges. To become sustainable energy game-changers, they must overcome this challenge. Their many benefits make thermoelectric generators a good power source:

1 Lack of Moving Parts and Fluids: TEGs contain no moving parts or fluids, reducing maintenance and operational costs. This simplicity improves reliability and durability [11].

2 Longevity with Constant Heat Sources: With reliable heat sources like industrial waste heat or specific combustion systems, TEGs can operate for long periods. This ensures reliable power generation throughout the system's lifespan [53].

3 Silent Operation: TEGs are ideal for remote or residential applications that require noise-free operation [3].

4 Versatility and Portability: TEGs are tiny and self-contained, making them suitable for use in remote off-grid sites and embedded systems with limited space and weight [2].

Due to their longevity, TEGs powered most space probes for years without these features. However, its inefficiency and high cost have hampered uptake [9][54] (Champier D (2017)).

METHODOLOGY

This comprehensive overview examines thermoelectric generator technological advances and limitations. The review covers peer-reviewed scientific, technical, and industry literature. Recent thermoelectric materials, device design, and system integration advances and their potential impact on energy sustainability are highlighted [22][32].

The analysis focuses on several key aspects of TEG technology:

3.1 Material Advancements: Nanostructured thermoelectric materials, new compositions, and figure of merit enhancement are included in the review. This includes assessing these materials' thermal stability, mechanical strength, and electrical contact qualities, especially at high temperatures [28].

3.2 Device Design and Optimization: The study examines in-plane and out-of-plane TEG topologies and their appropriateness for diverse applications. Design characteristics like fill factor, thermoelectric leg height, and device area affect performance metrics including output voltage, power density, and conversion efficiency [55].

3.3 System Integration and Applications: Wearable IoT devices, industrial waste heat recovery systems, and renewable energy systems are reviewed for TEG integration. This analyses system-level integration difficulties and opportunities such temperature management, power conditioning, and cost optimisation [56].

3.4 Performance Evaluation: The study analyses TEGs based on ZT, power density, conversion efficiency, and cost-effectiveness. This compares TEG technologies and their appropriateness for particular applications [57].

3.5 Future Aspects: Material development, device design, system integration, and cost reduction techniques are identified as TEG technology research priorities in the evaluation. This includes assessing TEGs' ability to promote sustainable energy [57].

The technique used in this offers a thorough and organised way to examine the present level of TEG technology, find important obstacles and possibilities, and describe where the field could go from here in terms of research.

RESULTS AND DISCUSSION

4.1 Thermoelectric Materials: Low Power Generation

Bismuth tellurides and selenides are thermoelectric materials when the ZT value is high at 100-250 °C. Thus, these materials are ubiquitous in thermoelectric generators. Thermoelectric elements in Bi_2Te_3 thermoelectric generators are usually connected using stripes of copper or silver. An important finding from a recent study is that self-assembled 3-mercaptopropyl-trimethoxysilane can improve the connections between the Bi_2Te_3 thermoelectric elements by covalently linking the Ni layer to their ends [58][59][60].

The contact resistance (q_c) of p- and n-type thermoelements was 1 $\mu\Omega$ cm² after adjustment. Ni powder vacuum hot pressing at p-type Bi_2Te_3 terminals reduces q_c [61][62]. Organic material-based low-temperature TEGs are being developed alongside bismuth tellurides and selenides. The statistics show that these devices extract little current due to the organic components' high resistivity[63][64][57].

4.2 Electrical Conductivity and Thermal Stability

Enhancing electrical conductivity of thermoelectric materials while preserving low thermal conductivity is a key challenge. Interfacial engineering has proven effective, such as doping with scandium in Mg2Si[65]. Scandium doping improves electrical conductivity by 30% without increasing thermal conductivity. To maintain thermal stability, materials like CoSb3 skutterudites and Zn4Sb3 Zintl phases are being investigated[66][67][68].

Electrochemical or chemical doping is a common process for polymers. The term "doping" can be misleading in this context, as it refers to the formation of ionic complexes through redox reactions between polymeric cations or anions and reduced or oxidized chemicals. Polymers with π-bonded unsaturated bonds are ideal for these reactions, as their π-electrons can be easily delocalized without compromising the integrity of the sigma bonds[69][70].

Doping in this manner increases the electrical conductivity of organic thermoelectric materials like polypyrrole, polyaniline, and polythiophene by several orders of magnitude, from being insulators to semiconductors[71].

Bipolarons are thermodynamically more stable than two independent polarons, so higher doping levels increase their formation. The schematic in Figure 5 illustrates how the doping levels in conducting polymers create polarons, bipolarons, and bipolaron bands. Low doping concentrations yield spin ½ polarons, which recombine to become spinless bipolarons as further doping increases. Bipolaron levels combine into continuous bands as doping increases. Bipolaron bands/states at the conduction and valence bands increase the band gap, as shown in Figure 5a [72]. Doping improves organic materials' thermoelectric performance by increasing electrical conductivity. Although polythiophenes and polyparaphenylene behave similarly, doped polypyrrole has characterised the bipolaron model and band gap widening (Figure 5 b)[73].

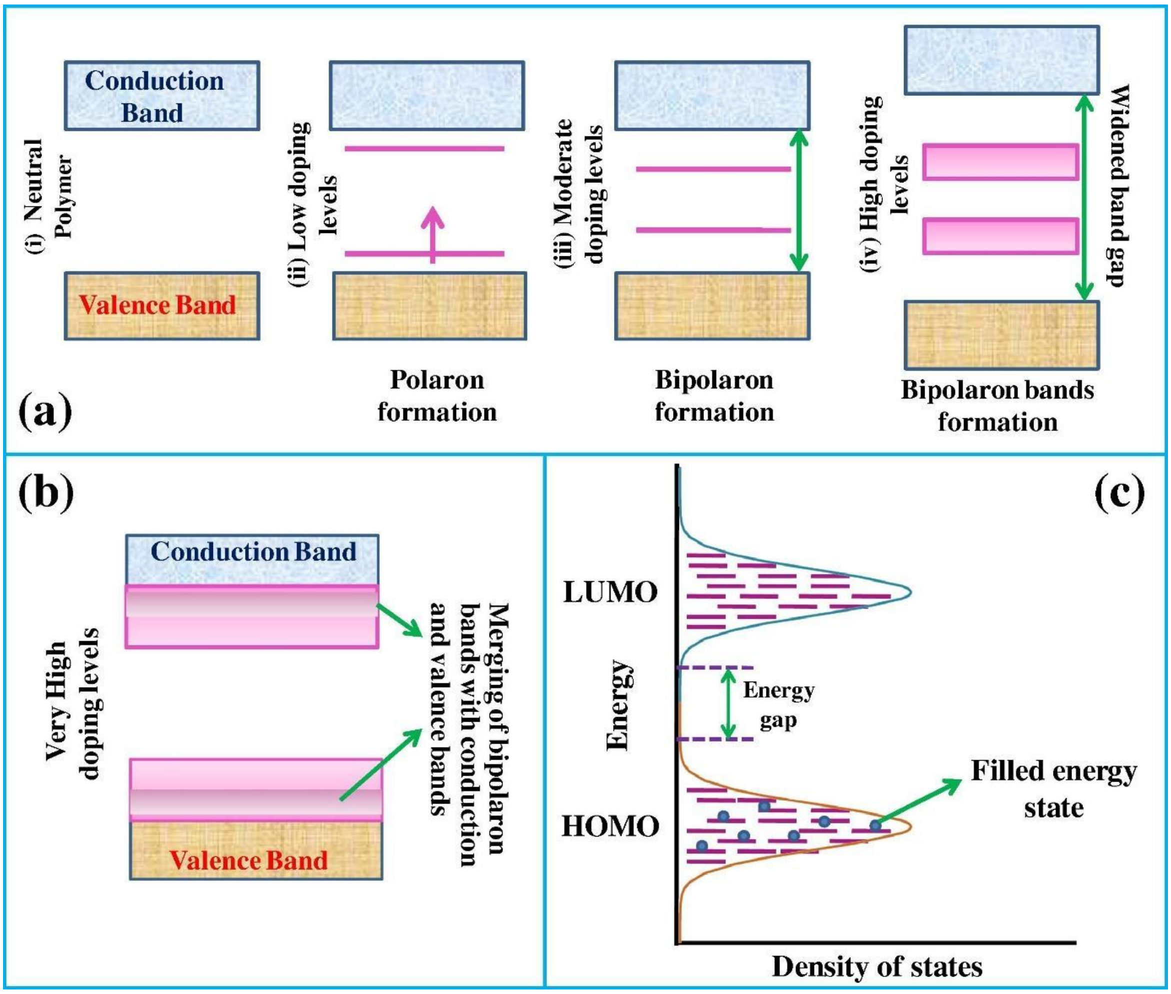


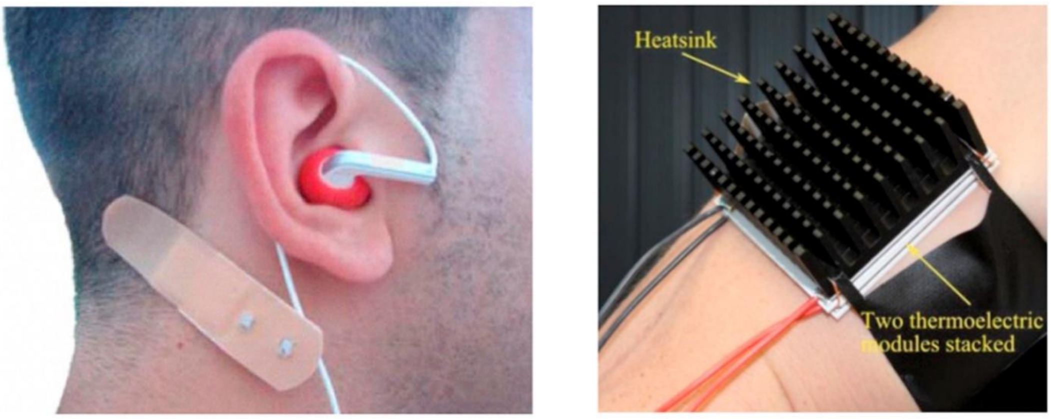
Figure 5. Schematic illustrating (a) Doping in conducting polymers creates polarons, bipolarons, and bipolaron bands; (b) at high doping levels (c) Conducting polymers' HOMO and LUMO orbitals[5]. (Siddique et al., (2017): Adopted from *Renewable and Sustainable Energy Reviews Journal*).

Polyacetylene, a conjugated polymer with a degenerate ground state, exhibits a distinct conduction mechanism. Along with polarons, solitons also carry charges. With the nearby electron, the soliton can travel the chain unobstructed. Doping generates larger solitons compared to bond alteration defects in conduction systems.

The degeneracy of charge carrier polymers allows doping to weakly bond and separate the charges that form bipolarons. In a pure trans-polyacetylene neutral soliton, there is an unpaired electron and an odd number of conjugated carbons. Adding unpaired electrons creates negatively charged solitons, while removing them leads to positively charged solitons[74][75].

Thermoelectric generators are increasingly being used to power biomedical devices by harnessing body heat. Compared to motion energy harvesters, TEGs offer higher power densities, typically around 10 μW/cm³ during activities like ambulation and jogging[5][76]. Studies have explored the use of implantable medical devices powered by thermoelectric generators. These investigations examined environmental and physical factors affecting a patient's thermal conditions, finding that power harvesting is most effective near the skin. Furthermore, research has proposed utilizing a TEG to power a hearing aid[77][78][11][79][80].

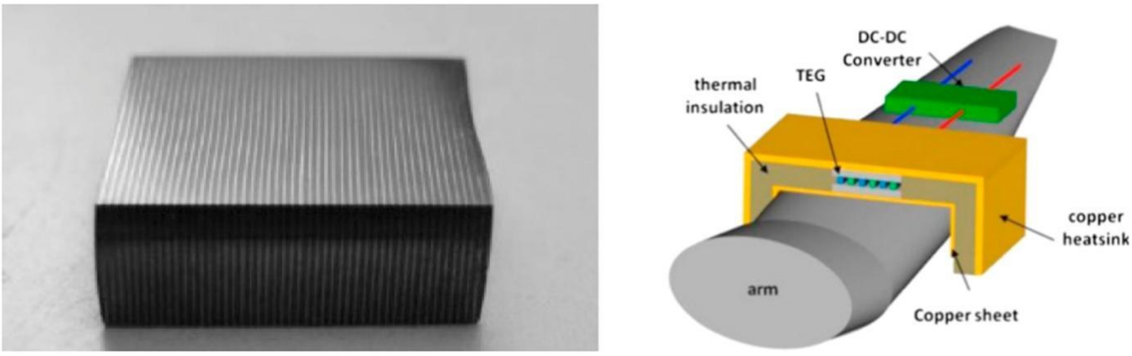
A power management circuit and battery provided backup power. At low body temperatures, resonance and voltage configuration methods were used to increase the efficiency of TEG power harvesting. When thermal coupling was low, a unique parameter ZE, dependent on material parameters, boosted the power output of the TEG. The addition of a heat sink, as depicted in Figure 6, further enhanced TEG performance[52].



(a) (b)

Figure 6. A hearing aid utilizing a thermoelectric generator (TEG). (b) To harvest hand energy, the fin was attached to the cold module (two TEG modules in sequence)[5] (Siddique et al., (2017): Adopted from *Renewable and Sustainable Energy Reviews Journal*).

To test bismuth telluride, their prototype generator used $Ni_{0.9}Mo_{0.1}$ for the n-type and $La_{0.035}Sr_{0.965}TiO_3$ for the p-type. Between the n- and p-type components was $Y_{0.03}Zr_{0.97}O_2$ insulation. It was a multilayer co-fired ceramic generator. In Figure 7(a), the prototype activated the radio transmitter with 100 µW at a temperature differential of 10 °C. Figure 7(b) shows 4.18 V from TEG heat sinks below 5 mm (Siddique et al., (2017)).



(a) (b)

Figure 7. A monolithic thermoelectric generator (TEG) using MLCC technology. A thermoelectric generator-integrated DC-DC converter. A heat spreader managed thermal energy in the TEG[5] (Siddique et al., (2017) Adopted from *Renewable and Sustainable Energy Reviews Journal*).

The ideal fill factor for f-TEG power density in wearables is often below 3%. However, the story becomes more complex when considering the role of the Power Management Integrated Circuit. All energy harvesters, including thermoelectric devices, require a PMIC to condition the generated power and drive electronic devices. The conventional PMIC power transfer efficiency curve versus input voltage is shown in Figure 8a[78].

For high-impedance thermoelectric generators with a fixed hot-side temperature, the optimal load voltage is often high, over 3V, to maximize the power transfer efficiency[81].

Statistical data indicates that when the TEG output voltage, which is the PMIC input voltage, is around 100 mV, only 30% of the generated power is usable. In wearable applications with small temperature differentials, both the output voltage and power of a thermoelectric generator are equally crucial. This can lead the PMIC to waste a significant portion of the produced power due to its inefficiency at low input voltage. Integrating the PMIC into the same package as the f-TEG is a potential solution, as shown in Figure 7 [11][82][83].

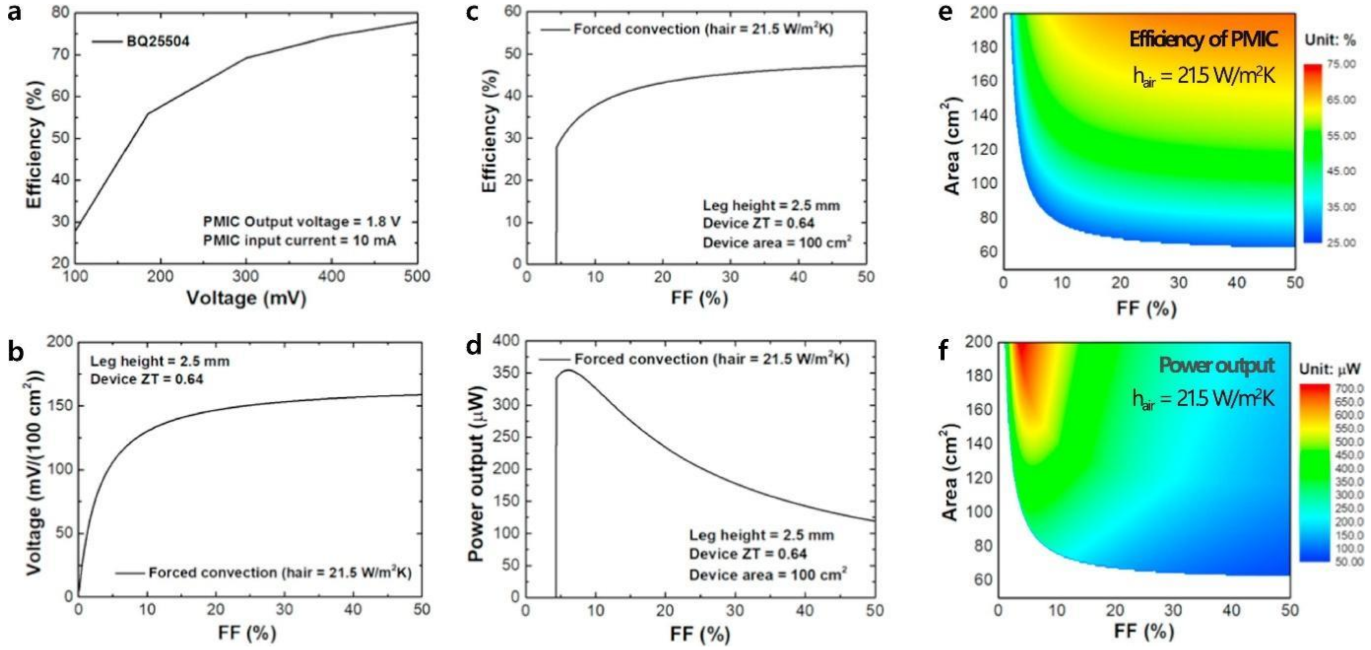


Figure 8. (a) Typical commercial PMIC power transfer efficiency curve. (b) Fill factor vs. output voltage. In this case, the device area is 100cm2. (c, d) Effect of fill factor on energy harvesting system PMIC efficiency and output power. (e, f) Contour plot of PMIC efficiency and system output power vs. fill factor and device area[84] (Kim C et al., (2018): Adopted from *Applied Energy Journal*).

As a function of fill factor, Figures 8a and 8b determine power management integrated circuit efficiency. For a 100 cm^2 flexible thermoelectric generator (f-TEG) with 2.5 mm leg height and forced convection, a fill factor below 10% is associated with rapid output voltage growth before plateauing (Figure 8b). Efficient f-TEG conversion is 47.2% at 50% fill factor, while PMIC is useless below 4.4% [85][86][87][88][89].

The PMIC efficiency for a wearable f-TEG under forced convection was determined based on the fill factor. The results show that device area and fill factor boost PMIC efficiency. A 200 cm^2 device area yields a maximum PMIC efficiency of 71.2% with a 50% fill factor. Using the data in Figure 8e, we can reevaluate the output power in Figure 8f. Based on device area, the ideal fill factor ranges from 3.8% to 39.0%, while without the PMIC it is 2% to 5%[90][91][92][88][93]. Finally, thermoelectric generators are a promising sustainable power generating and waste heat recovery technology with energy efficiency, low maintenance, and extended lifespans.

4.3 Thermoelectric Materials: High Power Generation

Nanostructuring has enhanced the material value of thermoelectric generators, making them attractive. ZT advancements have improved nanostructured materials for waste heat recovery, but they still lack thermal stability, mechanical strength at high temperatures, and dependable electrical contacts with low contact resistances [94].

There are two main ways to adapt thermoelectric generators. The initial method uses adaptable thermoelectric (TE) materials and substrates to create thermoelectric generators (TEGs) with in-plane configurations using thermoelectric films like conjugated organic polymers like P3HT and PDOT:PSS, very pliable semiconductors, and thin-layered Bi_2Te_3-based materials. At ambient temperature, these TEGs have a power density of just nW/cm^2. Used TEGs age and lose reliability, making it hard to power wearable electronics and restricting their uses.

The efficiency of f-TEG power output was tested at ΔT values between 10 and 50 K (Figure 9). The f-TEG generates power and is flexible. The power generation test equipment maintains 0.156 MPa pressure and intimate contact with the f-TEG with a spring knob (Figure 9a). The f-TEG was between two thermally conductive surfaces with fine regulation (Figure 9b). Figure 9c shows output voltage and power as current functions at different ΔT in a flat setup. With an open-circuit voltage of 236 mV at ΔT = 50 K, the f-TEG generates over 4.19 mW of power 6.5 mm-bent f-TEG output shown in Figure 9d. The open-circuit voltage was 189 mV at ΔT = 50 K, a 15% decrease from Voc under flat circumstances. Bent blocks and f-TEG have stronger contact thermal resistance than flat. Bent f-TEGs output over 2.2 mW. Figure 9e displays the f-TEG's power density (3.4 mW/cm²) and power per unit weight (21.0 mW/g) at ΔT = 50 K in flat [95][96][97].

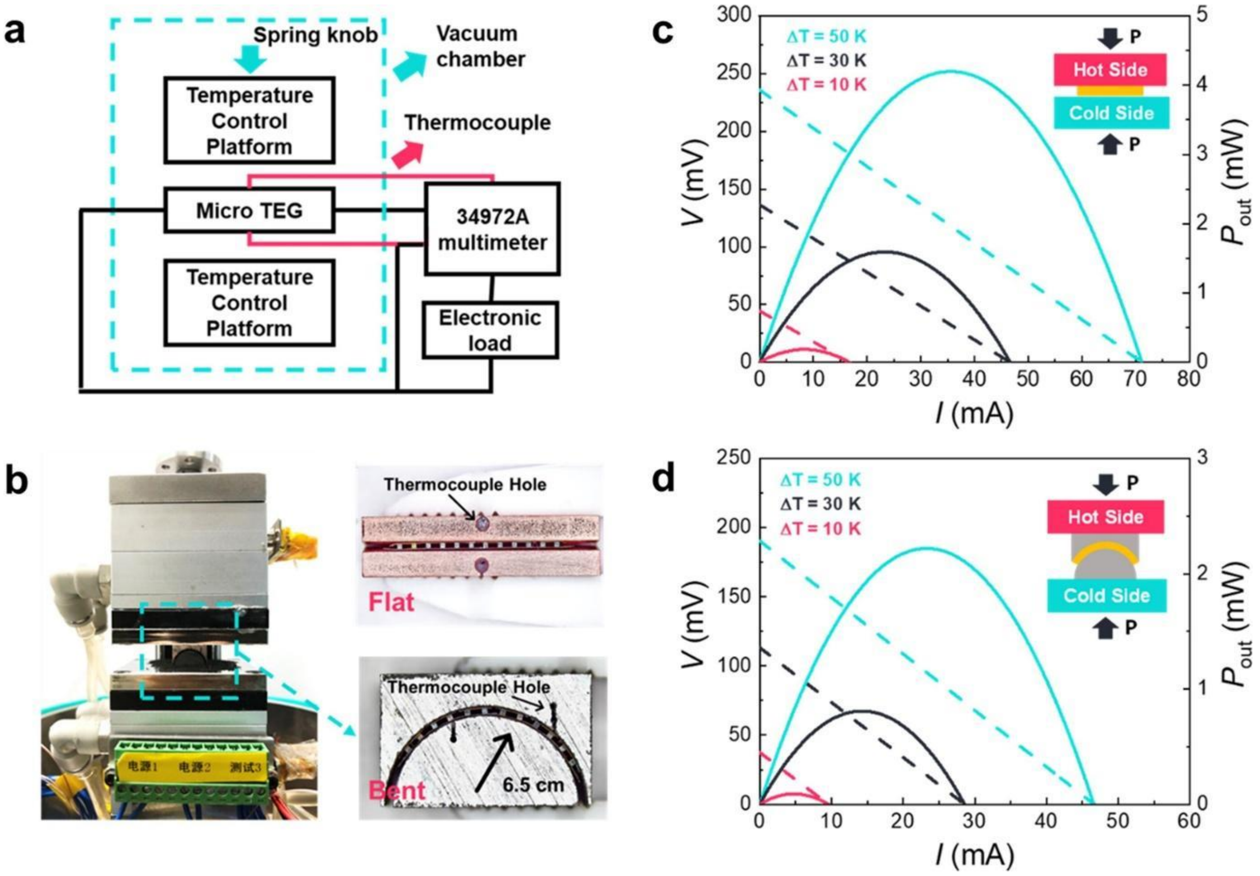


Figure 9. A custom-built testing rig examined f-TEG power generation: (a) Testing apparatus diagram (b) Testing equipment and test mold images (c) A flat configuration's output voltage and power throughout temperature differentials (d) Power and output voltage in a bent shape at different temperatures[98] (You H., et al., (2022) Adopted from *Applied Thermal Engineering Journal*).

The flexible f-TEG devices demonstrated power densities over 1 W/cm² with 50 K temperature difference, which is suitable for powering many wearable electronics.

In conclusion, thermoelectric generators have shown significant progress in materials, design, and manufacturing, enabling enhanced performance, efficiency, and sustainability.

CONCLUSION

Integration of thermoelectric generator modules remains a significant challenge, as they are often expensive, limiting their broader adoption and use. Thus, this field necessitates the development of more reliable and versatile material preparation methods to facilitate the expansion of TEG applications. Additionally, this hybrid system requires in-depth cost optimization analyses to be successfully commercialized. Current research on cost analysis and system performance is lacking, underscoring the urgent need for further study in this area. Specifically, a systematic design framework for the hybrid TEG-PCM (phase change material) system is missing from the existing literature, which would be useful for understanding the technology's prospective future uses.

A notable property of thermoelectric generators is its capacity to produce electric current across a wide range of temperatures, even from very small temperature differences. Because to this quality, they may still find static, eco-friendly solutions to problems related to power generation and waste heat recovery, even in the most challenging of environments. The intrinsic inefficiency of TEGs has prevented their broad adoption and expansion unless they can surpass other technologies in particular areas. There has been a wide range of viewpoints and experiences with thermoelectricity in both academic and industrial settings, with some uses being fruitful and others failing miserably.

The present status of thermoelectric generators, their ability to convert energy across a wide range of temperature differentials, and the promising future advancements are summarised in this review paper in a simple yet incisive manner. Thermoelectricity is a promising technology, but there are still a lot of obstacles to overcome before it can be used in many commercial contexts. One of these is improving the figure of merit (zT). The field of thermoelectricity has a promising future ahead of it, thanks to a mix of extensive and targeted research activities.

REFERENCES

[1] A. Sh. M. Al-Obaidi and T. NguyenHuynh, “Renewable vs. conventional energy: which wins the race to sustainable development?,” Dec. 03, 2018, IOP Publishing. doi: 10.1088/1757-899x/434/1/012310.

[2] N. Neophytou et al., “Hierarchically nanostructured thermoelectric materials: challenges and opportunities for improved power factors,” Nov. 01, 2020, Springer Science+Business Media. doi: 10.1140/epjb/e2020-10455-0.

[3] H. Jouhara et al., “Thermoelectric generator (TEG) technologies and applications,” Jan. 10, 2021, Elsevier BV. doi: 10.1016/j.ijft.2021.100063.

[4] N. Putra, R. A. Koestoer, M. Adhitya, A. Roekettino, and B. P. Trianto, “POTENSI PEMBANGKIT DAYA TERMOELEKTRIK UNTUK KENDARAAN HIBRID,” Oct. 14, 2010. doi: 10.7454/mst.v13i2.466.

[5] A. R. M. Siddique, S. Mahmud, and B. V. Heyst, “A review of the state of the science on wearable thermoelectric power generators (TEGs) and their existing challenges,” Renewable and Sustainable Energy Reviews, vol. 73. Elsevier BV, p. 730, Feb. 04, 2017. doi: 10.1016/j.rser.2017.01.177.

[6] O. L. Ayodele and M. T. Kahn, “Underutilise waste heat as potential to generate environmental friendly energy,” Aug. 01, 2014. doi: 10.1109/icue.2014.6904208.

[7] R. Freer and A. V. Powell, “Realising the potential of thermoelectric technology: a Roadmap,” Nov. 28, 2019, Royal Society of Chemistry. doi: 10.1039/c9tc05710b.

[8] Q. Jiang, J. Yang, P. Hing, and H. Ye, “Recent advances, design guidelines, and prospects of flexible organic/inorganic thermoelectric composites,” Jan. 01, 2020, Royal Society of Chemistry. doi: 10.1039/d0ma00278j.

[9] J. He and T. M. Tritt, “Advances in thermoelectric materials research: Looking back and moving forward,” Science, vol. 357, no. 6358. American Association for the Advancement of Science, Sep. 29, 2017. doi: 10.1126/science.aak9997.

[10] M. He, E. Wang, T. Liu, F. Zhang, and C. Zhao, “Development and application of thermoelectric power generation for waste heat recovery,” Jan. 01, 2018. doi: 10.2991/iceep-18.2018.106.

[11] N. Jaziri, A. Boughamoura, J. Müller, B. Mezghani, F. Tounsi, and M. Ismail, “A comprehensive review of Thermoelectric Generators: Technologies and common applications,” Energy Reports, vol. 6. Elsevier BV, p. 264, Dec. 23, 2019. doi: 10.1016/j.egyr.2019.12.011.

[12] M. Martín-González, O. Caballero-Calero, and P. Díaz-Chao, “Nanoengineering thermoelectrics for 21st century: Energy harvesting and other trends in the field,” Apr. 17, 2013, Elsevier BV. doi: 10.1016/j.rser.2013.03.008.

[13] J. Zheng, “Recent advances on thermoelectric materials,” Jul. 07, 2008, Springer Science+Business Media. doi: 10.1007/s11467-008-0028-9.

[14] L. Yang, Z. Chen, and J. Zou, “High-Performance Thermoelectric Materials for Solar Energy Application,” in Elsevier eBooks, Elsevier BV, 2018, p. 3. doi: 10.1016/b978-0-12-813794-9.00001-6.

[15] R. Tian, C. Wan, N. Hayashi, T. Aoai, and K. Koumoto, “Wearable and flexible thermoelectrics for energy harvesting,” Mar. 01, 2018, Springer Nature. doi: 10.1557/mrs.2018.8.

[16] “Thermoelectric Properties of Materials.” Feb. 2023. Accessed: Dec. 31, 2024. [Online]. Available: http://thermoelectrics.matsci.northwestern.edu/thermoelectrics/index.html

[17] J. R. Sootsman, D. Y. Chung, and M. G. Kanatzidis, “New and Old Concepts in Thermoelectric Materials,” Oct. 28, 2009, Wiley. doi: 10.1002/anie.200900598.

[18] J. Wei et al., “Review of current high-ZT thermoelectric materials,” Jun. 22, 2020, Springer Science+Business Media. doi: 10.1007/s10853-020-04949-0.

[19] M. Gharsallah et al., “Giant Seebeck effect in Ge-doped SnSe,” Jun. 02, 2016, Nature Portfolio. doi: 10.1038/srep26774.

[20] Y. Ismail and A. Alaskalany, “Thermoelectric Devices: Cooling and Power Generation,” Jan. 01, 2014, Cornell University. doi: 10.48550/arxiv.1403.3836.

[21] K. M. Saqr, M. K. Mansour, and M. Musa, “Thermal design of automobile exhaust based thermoelectric generators: Objectives and challenges,” Apr. 01, 2008, Springer Science+Business Media. doi: 10.1007/s12239-008-0020-y.

[22] I. Šumiga and Ž. Kondić, “Application of Thermoelectric Modules as Renewable Energy Sources,” Sep. 25, 2018, Croatian Dairy Union. doi: 10.31803/tg-20180301181527.

[23] S. O. Oyedepo and B. A. FAKEYE, “WASTE HEAT RECOVERY TECHNOLOGIES: PATHWAY TO SUSTAINABLE ENERGY DEVELOPMENT,” Dec. 30, 2020, Yıldız Technical University. doi: 10.18186/thermal.850796.

[24] D. M. Rowe, “Thermoelectric harvesting of low temperature natural/waste heat,” Jan. 01, 2012, American Institute of Physics. doi: 10.1063/1.4731600.

[25] Q. Zhu et al., “Bottom-Up Engineering Strategies for High-Performance Thermoelectric Materials,” Nano-Micro Letters, vol. 13, no. 1. Springer Science+Business Media, May 03, 2021. doi: 10.1007/s40820-021-00637-z.

[26] P. A. Gilhooly-Finn, C. Asker, K. Wan, E. Bilotti, O. Fenwick, and C. B. Nielsen, “Thermoelectric Materials: Current Status and Future Challenges,” Jul. 20, 2021, Frontiers Media. doi: 10.3389/femat.2021.677845.

[27] F. F. Jaldurgam, Z. Ahmad, and F. Touati, “Synthesis and Performance of Large-Scale Cost-Effective Environment-Friendly Nanostructured Thermoelectric Materials,” Nanomaterials, vol. 11, no. 5. Multidisciplinary Digital Publishing Institute, p. 1091, Apr. 23, 2021. doi: 10.3390/nano11051091.

[28] S. Lv, Z. Qian, D. Hu, X. Li, and W. He, “A Comprehensive Review of Strategies and Approaches for Enhancing the Performance of Thermoelectric Module,” Energies, vol. 13, no. 12. Multidisciplinary Digital Publishing Institute, p. 3142, Jun. 17, 2020. doi: 10.3390/en13123142.

[29] M. Brignone and A. Ziggiotti, “Impact of novel thermoelectric materials on automotive applications,” Jan. 01, 2012, American Institute of Physics. doi: 10.1063/1.4731601.

[30] T. Kuroki et al., “Influence of Heat Collection Plate Structure on Thermoelectric Generation Unit Performance for Radiant Waste Heat Recovery in Continuous Casting Process,” Jan. 01, 2017, The Iron and Steel Institute of Japan. doi: 10.2355/isijinternational.isijint-2017-058.

[31] M. Diantoro, S. K. G. Tiana, U. Sa’adah, R. A. Sawitri, C. I. Yogihati, and S. Sunaryono, “Bismuth and thermal induced electrical conductivity of high temperature thermoelectric SrTi1-xBixO3 system,” Jan. 01, 2020, American Institute of Physics. doi: 10.1063/5.0000992.

[32] L. E. Bell, “Cooling, Heating, Generating Power, and Recovering Waste Heat with Thermoelectric Systems,” Sep. 12, 2008, American Association for the Advancement of Science. doi: 10.1126/science.1158899.

[33] G. D. Mahan, B. C. Sales, and J. Sharp, “Thermoelectric Materials: New Approaches to an Old Problem,” Mar. 01, 1997, AIP Publishing. doi: 10.1063/1.881752.

[34] N. V. Nong and N. Pryds, “Nanostructured oxide materials and modules for high-temperature power generation from waste heat,” Mar. 25, 2013, IOP Publishing. doi: 10.1088/2043-6262/4/2/023002.

[35] A. Polozine, S. V. Sirotinskaya, and L. Schaeffer, “History of development of thermoelectric materials for electric power generation and criteria of their quality,” Oct. 01, 2014, Associação Brasileira de Metalurgia e Materiais (ABM); Associação Brasileira de Cerâmica (ABC); Associação Brasileira de Polímer. doi: 10.1590/1516-1439.272214.

[36] Y. Ismail and A. Alaskalany, “Thermoelectric Devices: Cooling and Power Generation,” Jan. 01, 2014, Cornell University. doi: 10.48550/arXiv.1403.

[37] D. Champier, “Thermoelectric generators: A review of applications,” Energy Conversion and Management, vol. 140. Elsevier BV, p. 167, Mar. 07, 2017. doi: 10.1016/j.enconman.2017.02.070.

[38] A. Date, A. Date, C. Dixon, and A. Akbarzadeh, “Progress of thermoelectric power generation systems: Prospect for small to medium scale power generation,” Mar. 04, 2014, Elsevier BV. doi: 10.1016/j.rser.2014.01.081.

[39] Z. Chen, G. Han, L. Yang, L. Cheng, and J. Zou, “Nanostructured thermoelectric materials: Current research and future challenge,” Dec. 01, 2012, Elsevier BV. doi: 10.1016/j.pnsc.2012.11.011.

[40] P. M. Kumar et al., "The Design of a Thermoelectric Generator and Its Medical Applications," Apr. 26, 2019, Multidisciplinary Digital Publishing Institute. doi: 10.3390/designs3020022.

[41] O. Meroz and Y. Gelbstein, "Thermoelectric Bi2Te3−xSex alloys for efficient thermal to electrical energy conversion," Jan. 01, 2018, Royal Society of Chemistry. doi: 10.1039/c7cp06176e.

[42] W. Liu and S. Bai, "Thermoelectric interface materials: A perspective to the challenge of thermoelectric power generation module," Apr. 22, 2019, Elsevier BV. doi: 10.1016/j.jmat.2019.04.004.

[43] M. Tewolde, J. P. Longtin, L. Zuo, D. J. Hwang, and S. Sampath, "Fabrication of Thermoelectric Devices for Vehicle Exhaust Applications Using Thermal Spray and Laser Processing," Jul. 08, 2012. doi: 10.1115/ht2012-58600.

[44] L. Su and X. Yong, "Advances in Thermoelectric Energy Conversion Nanocomposites," in InTech eBooks, 2011. doi: 10.5772/14868.

[45] W. Liu, Q. Jie, H. S. Kim, and Z. Ren, "Current progress and future challenges in thermoelectric power generation: From materials to devices," Jan. 31, 2015, Elsevier BV. doi: 10.1016/j.actamat.2014.12.042.

[46] A. Kallel, G. Roux, T. Derycke, C. Martín, M. Marinova, and C. Cayron, "Microstructure and thermoelectric properties of bulk and porous n-type silicon-germanium alloy prepared by HUP," Jan. 01, 2012, American Institute of Physics. doi: 10.1063/1.4731583.

[47] G. Lee et al., "Material Optimization for a High Power Thermoelectric Generator in Wearable Applications," Sep. 30, 2017, Multidisciplinary Digital Publishing Institute. doi: 10.3390/app7101015.

[48] T. Kyratsi, A. Angelopoulos, and T. Fildisis, "Thermoelectric Materials and Applications on the Recovery of Waste Heat Energy," Jan. 01, 2010, American Institute of Physics. doi: 10.1063/1.3322538.

[49] Y. Pei et al., "Integrating Band Structure Engineering with All-Scale Hierarchical Structuring for High Thermoelectric Performance in PbTe System," Oct. 12, 2016, Wiley. doi: 10.1002/aenm.201601450.

[50] "Synthesis and Characterization of ZnO and Mn-Doped ZnO Nanoparticles," Nov. 05, 2015. doi: 10.21275/v4i11.nov151529.

[51] N. Sugiartha and P. S. Negara, "Technical Feasibility Evaluation on The Use of A Peltier Thermoelectric Module to Recover Automobile Exhaust Heat," Jan. 01, 2018, IOP Publishing. doi: 10.1088/1742-6596/953/1/012090.

[52] D. Narducci, "Thermoelectric harvesters and the internet of things: technological and economic drivers," Mar. 04, 2019, IOP Publishing. doi: 10.1088/2515-7655/ab0c3a.

[53] O. H. Ando, N. H. Calderon, and S. S. de Souza, "Characterization of a Thermoelectric Generator (TEG) System for Waste Heat Recovery," Jun. 14, 2018, Multidisciplinary Digital Publishing Institute. doi: 10.3390/en11061555.

[54] D. B. Go et al., "Thermionic Energy Conversion in the Twenty-first Century: Advances and Opportunities for Space and Terrestrial Applications," Nov. 08, 2017, Frontiers Media. doi: 10.3389/fmech.2017.00013.

[55] I. Sil, S. Mukherjee, and K. Biswas, "Design Optimization of CMOS Thermoelectric Energy Harvester for High Thermoelectric Efficiency," May 01, 2018. doi: 10.1109/iementech.2018.8465264.

[56] S. Heinen and M. O'Malley, "Complementarities of Supply and Demand Sides in Integrated Energy Systems," Sep. 28, 2018, Institute of Electrical and Electronics Engineers. doi: 10.1109/tsg.2018.2871393.

[57] D. K. Aswal, R. Basu, and A. Singh, "Key issues in development of thermoelectric power generators: High figure-of-merit materials and their highly conducting interfaces with metallic interconnects," Feb. 16, 2016, Elsevier BV. doi: 10.1016/j.enconman.2016.01.065.

[58] K. H. Jong, T. Y. Lee, and Y. X. Gan, "Thermoelectric Power Generation by Harvesting the Waste Heat From a Car Engine," Jun. 28, 2015. doi: 10.1115/es2015-49225.

[59] F. J. DiSalvo, "Thermoelectric Cooling and Power Generation," Jul. 30, 1999, American Association for the Advancement of Science. doi: 10.1126/science.285.5428.703.

[60] S. Culp, S. J. Poon, N. Hickman, T. M. Tritt, and J. Blumm, "Effect of substitutions on the thermoelectric figure of merit of half-Heusler phases at 800 °C," Jan. 23, 2006, American Institute of Physics. doi: 10.1063/1.2168019.

[61] S. K. Tripathi, A. Kumari, R. Ridhi, and J. Kaur, "Synthesis and characterization of Bi-Te-Se thermoelectric materials," Jan. 01, 2015, American Institute of Physics. doi: 10.1063/1.4929230.

[62] A. Bohra et al., "Transition from n- to p-type conduction concomitant with enhancement of figure-of-merit in Pb doped bismuth telluride: Material to device development," Aug. 22, 2018, Elsevier BV. doi: 10.1016/j.matdes.2018.08.035.

[63] H. J. Goldsmid, “Bismuth Telluride and Its Alloys as Materials for Thermoelectric Generation,” Materials, vol. 7, no. 4. Multidisciplinary Digital Publishing Institute, p. 2577, Mar. 28, 2014. doi: 10.3390/ma7042577.

[64] A. Nozariasbmarz, B. Poudel, W. Li, H. B. Kang, H. Zhu, and S. Priya, “Bismuth Telluride Thermoelectrics with 8% Module Efficiency for Waste Heat Recovery Application,” Jul. 01, 2020, Cell Press. doi: 10.1016/j.isci.2020.101340.

[65] W. Luo, M. Yang, F. Chen, Q. Shen, H. Jiang, and L. Zhang, “Fabrication and thermoelectric properties of Mg2Si1−xSnx (0 ≤ x ≤ 1.0) solid solutions by solid state reaction and spark plasma sintering.” Nov. 2023. Accessed: Dec. 31, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0921510709000117

[66] J. Zhang, L. Song, S. H. Pedersen, H. Yin, L. T. Hung, and B. B. Iversen, “Discovery of high-performance low-cost n-type Mg3Sb2-based thermoelectric materials with multi-valley conduction bands,” Jan. 06, 2017, Nature Portfolio. doi: 10.1038/ncomms13901.

[67] J. Zhang, L. Song, A. Mamakhel, M. R. V. Jørgensen, and B. B. Iversen, “High-Performance Low-Cost n-Type Se-Doped Mg3Sb2-Based Zintl Compounds for Thermoelectric Application.” Nov. 2023. Accessed: Dec. 31, 2024. [Online]. Available: https://pubs.acs.org/doi/10.1021/acs.chemmater.7b01746

[68] A. Zevalkink, G. Pomrehn, Y. Takagiwa, J. G. Swallow, and G. J. Snyder, “Thermoelectric Properties and Electronic Structure of the Zintl-Phase Sr3AlSb3,” Sep. 23, 2013, Wiley. doi: 10.1002/cssc.201300518.

[69] J. Ma et al., “Conducting Polymers Based Composite Electrode Materials in Supercapacitor Application,” May 01, 2019, IOP Publishing. doi: 10.1088/1755-1315/267/4/042047.

[70] T. M. Swager and M. J. Marsella, “New designs for sensory materials: Conducting polymers displaying molecular recognition,” Jul. 01, 1995, Wiley. doi: 10.1002/masy.19950980172.

[71] L. Cowen, J. Atoyo, M. J. Carnie, D. Baran, and B. C. Schroeder, “Review—Organic Materials for Thermoelectric Energy Generation,” Jan. 01, 2017, Institute of Physics. doi: 10.1149/2.0121703jss.

[72] I. Petsagkourakis, K. Tybrandt, X. Crispin, I. Ohkubo, N. Satoh, and T. Mori, “Thermoelectric materials and applications for energy harvesting power generation,” Science and Technology of Advanced Materials, vol. 19, no. 1. Taylor & Francis, p. 836, Nov. 14, 2018. doi: 10.1080/14686996.2018.1530938.

[73] L. Hao, C. Dong, L. Zhang, K. Zhu, and D. Yu, “Polypyrrole Nanomaterials: Structure, Preparation and Application,” Polymers, vol. 14, no. 23. Multidisciplinary Digital Publishing Institute, p. 5139, Nov. 25, 2022. doi: 10.3390/polym14235139.

[74] N. Sai, Z. Q. Li, M. C. Martin, D. N. Basov, and M. D. Ventra, “Electronic excitations and metal-insulator transition in poly(3-hexylthiophene) organic field-effect transistors,” Jan. 05, 2007, American Physical Society. doi: 10.1103/physrevb.75.045307.

[75] D. S. Boudreaux, R. R. Chance, J. Brédas, and R. Silbey, “Solitons and polarons in polyacetylene: Self-consistent-field calculations of the effect of neutral and charged defects on molecular geometry,” Dec. 15, 1983, American Physical Society. doi: 10.1103/physrevb.28.6927.

[76] D. Enescu, “Thermoelectric Energy Harvesting: Basic Principles and Applications,” in IntechOpen eBooks, IntechOpen, 2019. doi: 10.5772/intechopen.83495.

[77] V. Leonov, “Thermoelectric energy harvesters for powering wearable sensors,” Oct. 01, 2012. doi: 10.1109/icsens.2012.6411414.

[78] E. A. Aydın and İ. Güler, “Recent Advances on Body-Heat Powered Medical Devices,” Apr. 01, 2011, Bentham Science Publishers. doi: 10.2174/1874764711104010033.

[79] V. Leonov, “Theoretical Performance Characteristics of Wearable Thermoelectric Generators,” Oct. 27, 2010, Trans Tech Publications. doi: 10.4028/www.scientific.net/ast.74.9.

[80] A. Lay-Ekuakille, G. Vendramin, and A. Trotta, “Design of an energy harvesting conditioning unit for hearing aids,” Aug. 01, 2008. doi: 10.1109/iembs.2008.4649660.

[81] J. Vincent and H. Lee, “Power Wearable Medical Device Components Via Thermoelectric Circuit Integration,” Oct. 01, 2019. doi: 10.1109/ghtc46095.2019.9033078.

[82] M. T. Dunham, M. T. Barako, S. LeBlanc, M. Asheghi, B. Chen, and K. E. Goodson, “Power density optimization for micro thermoelectric generators,” Nov. 19, 2015, Elsevier BV. doi: 10.1016/j.energy.2015.10.032.

[83] M. Abdelfattah, A. N. Mohieldin, A. Emira, A. K. Hussien, and E. Sánchez-Sinencio, “Ultra-low-voltage power management unit for thermal energy harvesting applications,” Jun. 01, 2012. doi: 10.1109/newcas.2012.6329036.

[84] C. S. Kim et al., “Structural design of a flexible thermoelectric power generator for wearable applications,” Feb. 12, 2018, Elsevier BV. doi: 10.1016/j.apenergy.2018.01.074.

[85] A. Nozariasbmarz et al., “Review of wearable thermoelectric energy harvesting: From body temperature to electronic systems,” Nov. 20, 2019, Elsevier BV. doi: 10.1016/j.apenergy.2019.114069.

[86] M. Cernaianu, C. Cirstea, and A. Gontean, “Thermoelectrical energy harvesting system: Modelling, simulation and implementation,” Nov. 01, 2012. doi: 10.1109/isetc.2012.6408047.

[87] S. M. Yang, J. Y. Wang, and M. D. Chen, “On the improved performance of thermoelectric generators with low dimensional polysilicon-germanium thermocouples by BiCMOS process,” Mar. 12, 2020, Elsevier BV. doi: 10.1016/j.sna.2020.111924.

[88] T. Tran-Dinh et al., “Low-Power PMIC with Two Hybrid Converters for TEG Application,” Dec. 08, 2020. doi: 10.1109/apccas50809.2020.9301651.

[89] Chang, C. L., & Lee, T. C. (2014, December). A compact multi-input thermoelectric energy harvesting system with 58.5% power conversion efficiency and 32.4-mW output power capability. In *2014 International Symposium on Integrated Circuits (ISIC)* (pp. 1-4). IEEE.

[90] P. A. M. Bezerra et al., “Electrical and Thermal Characterization of an Inductor-Based ANPC-Type Buck Converter in 14 nm CMOS Technology for Microprocessor Applications,” Jan. 01, 2020, Institute of Electrical and Electronics Engineers. doi: 10.1109/ojpel.2020.3025658.

[91] M. Zargham and P. G. Gulak, “High-efficiency CMOS rectifier for fully integrated mW wireless power transfer,” May 01, 2012. doi: 10.1109/iscas.2012.6271912.

[92] T. Tran-Dinh, H. Pham, T.-L. Vu, L. Pham-Nguyen, and S. Lee, “Three-Phase Boost-Converter Based PMIC for Thermal Electric Generator Application,” Nov. 01, 2019. doi: 10.1109/apccas47518.2019.8953129.

[93] Y. Jeyashree, A. V. Juliet, and A. A. Joseph, “Experimental analysis of thermoelectric generator using solar energy,” Oct. 01, 2014. doi: 10.1109/icsss.2014.7006197.

[94] Y. Zhang et al., “High-temperature and high-power-density nanostructured thermoelectric generator for automotive waste heat recovery,” Sep. 03, 2015, Elsevier BV. doi: 10.1016/j.enconman.2015.08.051.

[95] Y. Ekubaru et al., “Fabrication and Characterization of Ultra-Lightweight, Compact, and Flexible Thermoelectric Device Based on Highly Refined Chip Mounting,” Mar. 18, 2020, Wiley. doi: 10.1002/admt.201901128.

[96] Y. J. Kim et al., “Realization of High-Performance Screen-Printed Flexible Thermoelectric Generator by Improving Contact Characteristics,” Oct. 16, 2017, Wiley. doi: 10.1002/admi.201700870.

[97] Z. Yuan, K. Ziouche, Z. Bougrioua, P. Lejeune, T. Lasri, and D. Leclercq, “A planar micro thermoelectric generator with high thermal resistance,” Nov. 03, 2014, Elsevier BV. doi: 10.1016/j.sna.2014.10.026.

[98] H. You et al., “Flexible Bi2Te3-based thermoelectric generator with an ultra-high power density,” Nov. 17, 2021, Elsevier BV. doi: 10.1016/j.applthermaleng.2021.117818.