Design of a Solar System for Converting Concentrated Thermal Energy into Electricity Using Thermoelectric Materials: A Theoretical and Experimental Study

Marwa Bakour[1], Fatima Battour[2] , Zakariya Zallam[3]‡
[1]Department of Physics, Faculty of Science, Aleppo University, Aleppo, Syria
[1]marwabakour@alepuniv.edu.sy
[2]Department of Physics, Faculty of Science, Aleppo University, Aleppo, Syria
[3]Department of Physics, Faculty of Science, Aleppo University, Aleppo, Syria
++abohosni.zallam@gmail.com

Abstract: This research presents the design, fabrication, and experimental evaluation of a solar-thermal energy conversion system developed at Aleppo university, Aleppo, Syria. The system aims to address the growing energy crisis in the region, where electricity shortages and high energy costs pose significant challenges to daily life and industrial development. The proposed system utilizes a parabolic dish to concentrate solar radiation onto a thermal chamber located at the focal point. Within this chamber, thermoelectric materials based on bismuth telluride (Bi_2Te_3) are strategically positioned to convert the absorbed heat into electrical energy through the Seebeck effect. This effect describes the generation of a voltage across a thermoelectric material when a temperature gradient is applied between its two ends. In this setup, the hot side of the module is exposed to intense solar heat, while the cold side is thermally insulated or cooled, creating a substantial temperature differential. This gradient drives charge carriers through the material, resulting in a measurable and usable electric current. The system was meticulously engineered to enhance thermal conductivity, reduce heat losses, and ensure efficient energy transfer to the thermoelectric elements. A series of experimental tests were conducted under varying solar irradiance conditions to assess voltage output, current stability, and overall conversion efficiency. The results demonstrated consistent and reliable power generation, with relatively high efficiency compared to conventional passive systems. This project offers a practical and scalable solution for decentralized electricity generation using clean energy sources. It highlights the potential of integrating solar concentration technologies with thermoelectric materials to meet local energy demands, particularly in regions that suffer from limited access to affordable electricity.

Keywords: Solar Energy, Electrical Energy, Seebeck Effect, Thermoelectric Materials, Bismuth Telluride, Parabolic Dish, Energy Harvesting

INTRODUCTION

The global demand for sustainable and clean energy sources has intensified in recent decades, driven by escalating environmental concerns and the depletion of fossil fuel reserves. Among the various renewable energy technologies, solar energy stands out due to its abundance, accessibility, and potential to meet long-term energy needs. While photovoltaic systems have dominated the solar energy landscape, alternative approaches such as solar thermal conversion offer promising avenues for efficient energy harvesting, particularly in regions with high solar irradiance [1][2]. climates—such as Syria and other parts of the Middle East—possess significant untapped solar potential. However, the integration of advanced solar thermal technologies into practical energy systems remains limited, often due to cost, complexity, or lack of localized research. This gap highlights the need for innovative, scalable solutions that can harness concentrated solar energy and convert it into usable electricity with minimal infrastructure [3] [4]. Thermoelectric materials, which convert heat directly into electricity via the Seebeck effect, present a compelling solution for such applications. Despite their theoretical promise, practical implementations of thermoelectric solar systems are still in early stages, with limited experimental validation and optimization in real-world conditions [5[[6]. This research aims to bridge that gap by designing and evaluating a solar concentrator system that utilizes.

thermoelectric materials to convert focused thermal energy into electrical power [7]. The study combines theoretical modeling with experimental testing to assess system performance, identify key design parameters, and explore the feasibility of deploying such systems in solar-rich environments. The remainder of this paper is organized as follows: Section 2 reviews relevant literature, Section 3 outlines the theoretical framework, Section 4 details the system design, Section 5 presents the experimental methodology, Section 6 discusses results and analysis, and Section 7 concludes with findings and future recommendations

2- Literature Review

Recent advancements in solar energy research have explored the integration of thermoelectric generators (TEGs) with solar concentrator systems as a promising alternative to conventional photovoltaic technologies. One notable study by Munir et al. investigated the use of fixed-focus Scheffler dishes combined with TEGs, demonstrating the feasibility of medium-temperature applications and highlighting the scalability of hybrid systems for decentralized energy production While the design proved effective in capturing solar heat, the study lacked detailed optimization of the thermoelectric module arrangement and did not address long-term thermal stability [8]. Another significant contribution by Ravi and Reddy focused on enhancing power generation efficiency by integrating TEGs with parabolic dish concentrators (PDCs) under high-temperature conditions. Their findings confirmed the potential of such systems to deliver stable electrical output, especially when solar tracking mechanisms are employed. However, the complexity of the tracking system and the cost of implementation were identified as limiting factors for widespread adoption [9]. In another study intravised and colleagues developed a hybrid solar energy system that integrates thermoelectric generators (TEGs) with a solar tracking parabolic dish concentrator. Their experimental setup compared a stationary dish with a multifaceted tracking system. The results demonstrated that solar tracking significantly enhances thermal concentration and electrical output. The study also explored the use of hybrid nanofluids to improve heat transfer efficiency. This work highlights the potential of combining passive thermoelectric conversion with active solar tracking to optimize renewable energy systems in high-irradiance regions [10]. Mouaici et al, investigates the performance boundaries of hybrid photovoltaic-thermoelectric systems using parabolic solar concentrators and ternary nanofluids ($Cu–Al_2O_3–$MWCNT/water). Simulations conducted under Algerian meteorological conditions revealed that using a 2% volume fraction of nanoparticles enhanced thermal output by 14.5%, electrical yield by 11.2%, and thermoelectric production by 22.6%. The authors developed predictive models to optimize system design based on concentration ratio and fluid flow rate [11]. Ahmed et al. (2022) investigated the integration of a concentrator photovoltaic (CPV) cell with a thermoelectric generator (TEG) to enhance energy conversion efficiency and utilize waste heat. Their study demonstrated that the hybrid CPV/TEG system could operate under solar concentration levels up to 37.6 suns, compared to 18.25 suns for the uncooled system. This integration led to an increase in electrical power output from 0.7 to 1.433 W/cm². The findings highlight the potential of TEGs not only as passive cooling devices but also as contributors to additional power generation, supporting the development of more efficient thermoelectric systems [12]. Abbas, W. N., Aljibory, M. W., & Hashim, H. T. (2023) conducted an experimental investigation on a hybrid photovoltaic–thermoelectric generator (PV–TEG) system. Their research aimed to optimize the performance of a PV–TEG setup under controlled indoor conditions. The results revealed that the hybrid system, consisting of 50 TEG units, achieved a 31.66% and 16.5% increase in electrical power output compared to traditional PV-only and PV/T systems, respectively. The electrical output reached 20.21 W with an efficiency of 5.83%, demonstrating the potential of TEGs to significantly enhance solar energy harvesting by utilizing waste heat [13]

3- Theoretical Framework

Seebeck Effect and Thermoelectric Conversion:

The foundation of thermoelectric energy conversion lies in the Seebeck effect, discovered by Thomas Johann Seebeck in 1821. When a temperature gradient is applied across a thermoelectric material, charge carriers (electrons or holes) migrate from the hot side to the cold side, generating a voltage difference. This phenomenon enables the direct conversion of thermal energy into electrical energy without moving parts, making it ideal for solar-thermal applications [14]. Recent studies have explored enhanced Seebeck coefficients in organic semiconductors, achieving values exceeding 0.1 V/K near room temperature, which opens new possibilities for flexible and lightweight thermoelectric generators [15]. To evaluate the performance of thermoelectric systems, several key equations are used:

$V = S \cdot \Delta T$ (1)

V: Generated voltage

S: Seebeck coefficient (V/K)

ΔT: Temperature difference across the material.

Thermoelectric Figure of Merit (ZT)

To evaluate the efficiency of thermoelectric materials, the dimensionless figure of merit ZT is used. It combines electrical and thermal properties to quantify how effectively a material converts heat into electricity. This coefficient can be expressed by the following equation:

$$ZT=S^2\cdot\sigma\cdot T/\kappa$$

Where:

S: Seebeck coefficient (V/K)

σ: Electrical conductivity (S/m)

T: Absolute temperature (K)

κ: Thermal conductivity (W/m·K)

A higher ZT value indicates better thermoelectric performance. Ideal materials exhibit a high Seebeck coefficient, high electrical conductivity, and low thermal conductivity [16].

Properties of Selected Thermoelectric Materials

Bismuth Telluride (Bi_2Te_3):

Bismuth telluride has the following unique properties: Seebeck coefficient: ~200 μV/K, Thermal conductivity: ~1.5 W/m·K, Optimal operating range: 300–500 K, Widely used in commercial thermoelectric devices for low to moderate temperature applications

Lead Telluride (PbTe):

While lead telluride has the following properties: Seebeck coefficient: ~150–250 μV/K, Thermal conductivity: ~2 W/m·K, Effective in medium to high temperature ranges (500–800 K), Commonly used in industrial waste heat recovery and space power systems

Doped Graphene:

Seebeck coefficient: Tunable via chemical doping, Electrical conductivity: Extremely high, Thermal conductivity: Naturally high, but can be reduced through nanostructuring, Promising candidate in advanced research for enhancing ZT through nanoscale engineering

This theoretical foundation supports the design and implementation of the proposed solar-thermoelectric system, which aims to convert concentrated solar heat into electrical energy using high-performance thermoelectric materials [17].

4. System Design

Geometric Description of the Parabolic Solar Reflector

The solar concentrator used in this system is a parabolic dish reflector, designed to focus incident solar radiation onto a single focal point. The parabolic geometry ensures that all parallel rays of sunlight are reflected toward the focus, maximizing thermal concentration. Important parameters in a parabolic dish:

Diameter of the dish: Typically ranges from 1 to 2 meters for small-scale applications.

Focal length (f): Determined by the equation of a parabola:

$$y^2=4f(x)$$

where f is the distance from the vertex to the focus.

Reflective surface: Made of polished aluminum coated glass to ensure high reflectivity (>90%). This design allows for efficient solar energy collection, especially when combined with a solar tracking mechanism to maintain alignment with the sun throughout the day. The figure (1) shows the parabolic dish used in the system.

The figure (1): parabolic dish

Thermal Chamber Design

At the focal point of the parabolic dish, a thermal chamber is placed to absorb concentrated solar heat. This chamber is constructed using high-temperature resistant materials such as Aluminum. The thermal chamber is designed according to the following specifications: Insulated walls: To minimize heat loss and maintain a high temperature gradient. Internal heat absorber: A blackbody-coated surface to enhance thermal absorption. Temperature range: Designed to operate between 100°C and 400°C depending on the material used. The figure (2) shows the geometric design using the computer simulation program Solid Program for the thermal chamber

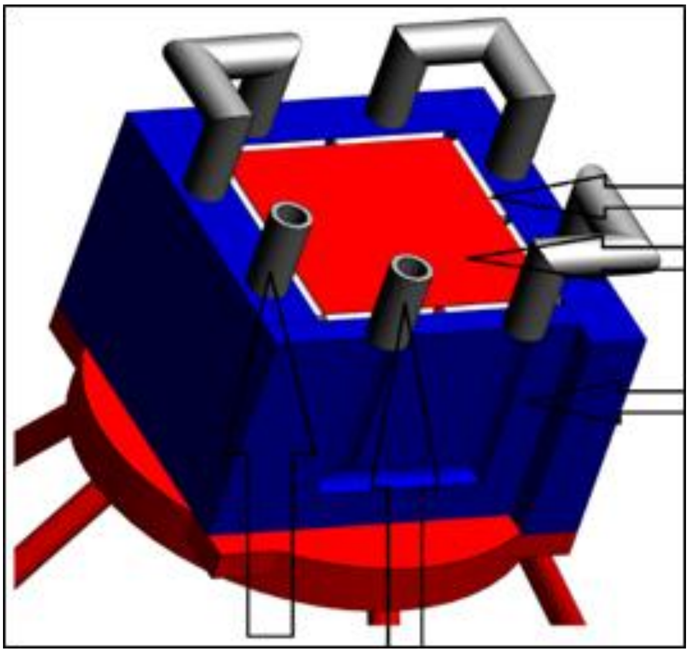


Figure (2): The thermal chamber

While the figure (3) shows the thermal chamber after manufacturing.

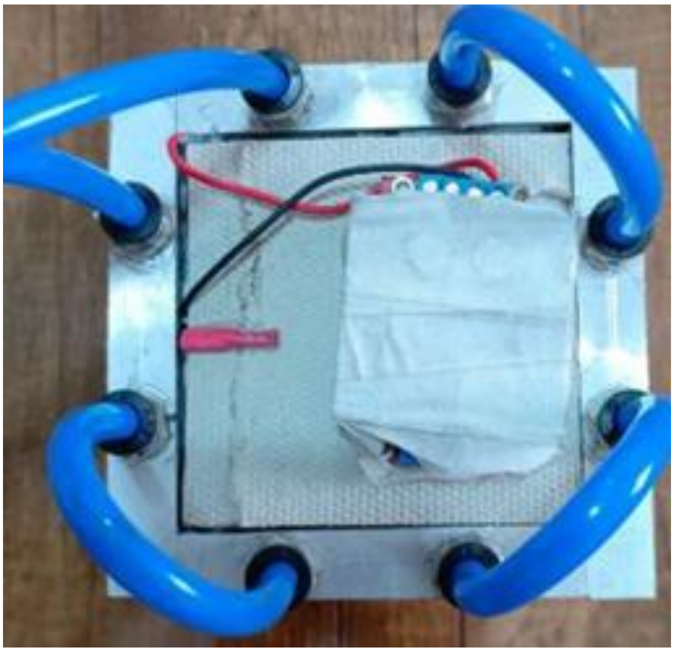


Figure (3): thermal chamber after manufacturing

Thermoelectric Material Distribution

Inside the thermal chamber, thermoelectric modules are strategically placed to maximize exposure to the temperature gradient. Hot side, In direct contact with the inner wall of the thermal chamber. While Cold side, Connected to a heat sink or ambient air to maintain a lower temperature. The thermoelectric materials were placed so that the inner surface of the thermal chamber was the hot end while the outer end of the thermal chamber was the cold end, and the thermoelectric materials were fixed between these two ends. Modules are arranged in alternating n-type and p-type legs, connected electrically in series and thermally in parallel, forming a complete thermoelectric generator (TEG). The figure (4) provides a detailed overview of the geometric structure of the thermoelectric material samples used in this project.

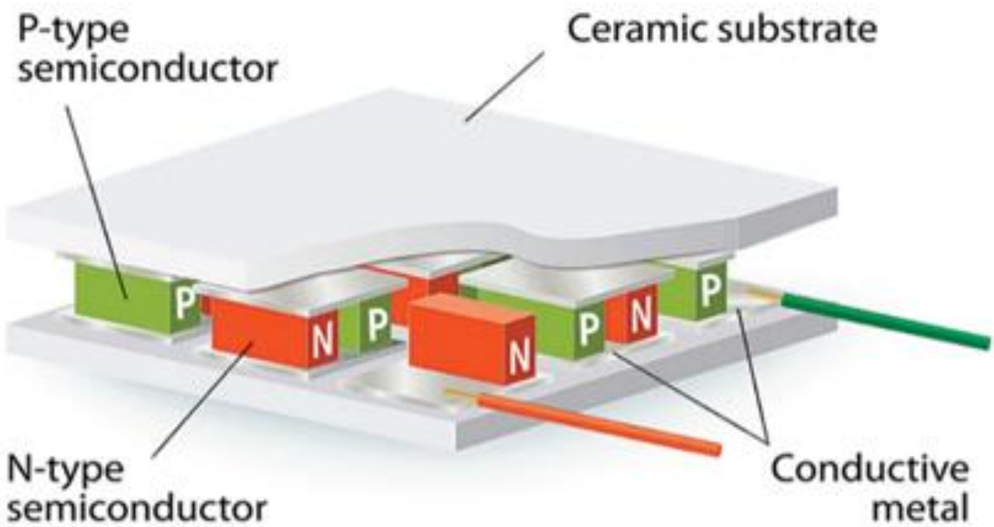


Figure (4): the geometric structure of the thermoelectric material

5. Methodology

Experimental Procedure

The experimental setup involves constructing a solar-thermoelectric conversion system composed of a parabolic dish reflector, a thermal chamber, and thermoelectric modules. The steps are as follows:

Assembly of the parabolic reflector using a polished aluminum surface with a calculated focal length to concentrate solar radiation.

Installation of the thermal chamber at the focal point, designed to absorb and retain heat efficiently.

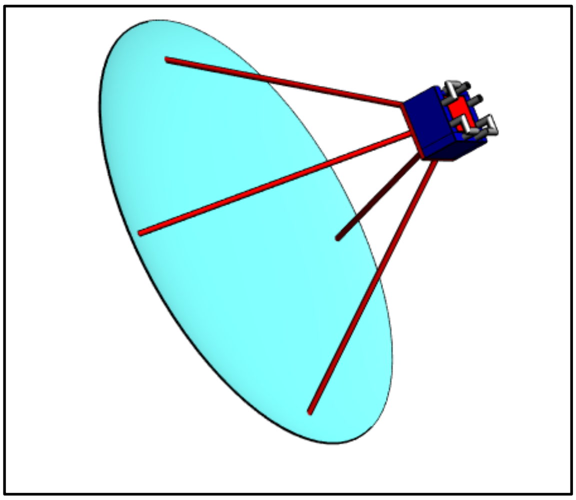
Placement of thermoelectric modules (Bi_2Te_3) inside the chamber, ensuring proper thermal contact and electrical connections.

Integration of heat sinks on the cold side of the modules to maintain a temperature gradient.

Connection to a data acquisition system to monitor voltage, current, and temperature in real time.

Operation under direct sunlight, with measurements taken at regular intervals throughout the day.

The figure (5) shows the thermoelectric system in its final form. The figure shows the thermoelectric system in its final form.



The figure (5): the thermoelectric system

6. Measurement and Results:

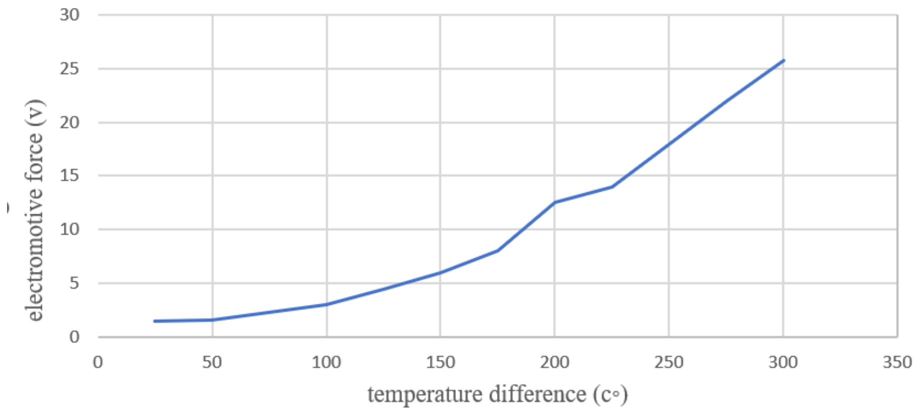
Data collection focuses on evaluating the electrical output and thermal performance of the system. The

following parameters are recorded:

Temperature difference (ΔT) across each thermoelectric module using thermocouples, Generated voltage (V) and current (I) using a multimeter, Solar irradiance (W/m^2) using a pyranometer and Ambient temperature and wind speed to account for environmental effects. Measurements are taken every 15 minutes during peak sunlight hours (10:00–14:00), and data is logged for later analysis. The electrical power output is calculated using:

$P = V \cdot I$

And the efficiency was estimated by comparing the electrical output to the incident solar energy. The following graph shows the potential difference resulting from the temperature difference between the hot and cold ends:



Ethical and Safety Considerations

While the experiment does not involve human or animal subjects, several safety measures are implemented:

Protective eyewear and gloves are used during reflector alignment and module handling.

Thermal insulation is applied to prevent accidental burns from high-temperature surfaces.

Electrical safety protocols are followed to avoid short circuits or equipment damage.

Environmental impact is minimal, as the system relies solely on renewable solar energy.

7. Conclusion and recommendations:

In this project, a solar system was successfully designed and implemented using a parabolic reflector to concentrate sunlight at its focal point. A thermal chamber was placed at the focus, containing thermoelectric materials arranged between inner and outer layers. Upon exposure to solar radiation, the system generated a significant temperature gradient across the thermoelectric materials, resulting in the production of electrical energy. A voltage output of 25 volts was recorded, confirming the effectiveness of the thermoelectric conversion process. This system represents a promising step toward sustainable and clean electricity generation, especially in regions with high solar irradiance such as northwest Syria. The use of low-cost materials like Bismuth Telluride, with potential performance enhancement through copper or nickel additives, further supports the economic and technical viability of the design. The success of this project opens new opportunities for developing decentralized energy solutions in rural or off-grid areas. To develop this project, we recommend improving the thermoelectric materials by experimenting with new or composite materials such as PbTe, or introducing elements such as copper or nickel to improve the Seebeck coefficient and electrical conductivity. Increasing the number of thermoelectric pairs to generate higher voltages and expand production capacity. In addition, Using effective cooling techniques for the cold end, such as heat sinks or water cooling, to maintain a large temperature difference. Integrating the system with energy storage units, such as batteries or supercapacitors, to store the generated electricity

REFERENCES

Baghel, N., & Kumar, A. (2025). Sustainable thermoelectric materials for solar energy applications: A review. Solid State Sciences, 160, 107784.

Ao, S., Chen, Z., Chen, H., Zhang, L., Wang, Y., Zhang, Y., ... & Peng, T. (2025). High-performance biomass-based solar-thermal hydrogel based on silkworm excrement for water evaporation and thermoelectric integration application. Journal of Materials Chemistry A, 13(20), 15149-15156.

Maniruzzaman, A. F. M., & Al-Saleem, K. (2025). Renewable energy and energy justice in the Middle East: international human rights, environmental and climate change law and policy perspectives. The Journal of World Energy Law & Business, 18(1), jwae021.

Temizel, C., Irani, M., Canbaz, C. H., Palabiyik, Y., Moreno, R., Balikcioglu, A., ... & Alkouh, A. (2018, December). Technical and economical aspects of use of solar energy in oil & gas industry in the Middle East. In SPE International Heavy Oil Conference and Exhibition (p. D022S028R001). SPE.

Madkhali, H. A., Hamil, A., & Lee, H. (2017). Validation, optimization and simulation of a solar thermoelectric generator model. Journal of Electronic Materials, 46(12), 6756-6768.

Development and Performance Analysis of a Thermoelectric Solar Concentrator for Direct Thermal-to-Electric Energy Conversio

Bamroongkhan, P., Lertsatitthanakorn, C., & Soponronnarit, S. (2019). Experimental performance study of a solar parabolic dish photovoltaic-thermoelectric generator. Energy Procedia, 158, 528-533.

Malwad, D., & Tungikar, V. (2020). Experimental performance analysis of an improved receiver for Scheffler solar concentrator. SN Applied Sciences, 2(12), 1992.

Intravised, K., Tundee, S., Ounasing, S., & Poojeera, S. (2025). Electric Generation Using a Combined Thermoelectric-Solar Tracking Multifaceted Parabolic Dish Concentrator. ES Energy & Environment, 28, 1564.

Intravised, K., Tundee, S., Ounasing, S., & Poojeera, S. (2025). Electric Generation Using a Combined Thermoelectric-Solar Tracking Multifaceted Parabolic Dish Concentrator. ES Energy & Environment, 28, 1564.

Mouaici, K., Fersadou, B., Arslan, K., Kahalerras, H., & Traiche, M. (2025). Technological Limit of Solar Concentration Technique Applied to Hybrid Photovoltaic-Thermal Solar Collector Equipped With Thermoelectric

Generator Incorporating Ternary Nanofluid. Journal of Solar Energy Engineering, 147(2), 021004.

Ahmed, O. E., Emam, M., Abdelrahman, M. A., & Attia, A. A. (2022). Studying the coupling of a concentrator photovoltaic cell with thermoelectric generator. Journal of Al-Azhar University Engineering Sector, 17(63), 577-589.

ABBAS, W. N., ALJİBORY, M. W., & HASHİM, H. T. (2023). Experimental Investigation of Photovoltaic–Thermoelectric Generator (PV-TEG) Integrated Hybrid System Performance. Journal of Current Researches on Engineering, Science and Technology, 9(1), 145-160.

Jiang, B., Zhao, J., Qian, J., Zhang, S., Qiang, X., Wang, L., ... & Wu, X. (2022). Antisymmetric Seebeck effect in a tilted Weyl semimetal. Physical Review Letters, 129(5), 056601.

Lindorf, M., Mazzio, K. A., Pflaum, J., Nielsch, K., Brütting, W., & Albrecht, M. (2020). Organic-based thermoelectrics. Journal of materials chemistry A, 8(16), 7495-7507.

Shi, X. L., Li, N. H., Li, M., & Chen, Z. G. (2025). Toward Efficient Thermoelectric Materials and Devices: Advances, Challenges, and Opportunities. Chemical Reviews, 125(16), 7525-7724.

Gayner, C., & Kar, K. K. (2016). Recent advances in thermoelectric materials. Progress in Materials Science, 83, 330-382.