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Development of Thermophotovoltaic Technology in Waste Heat Recovery: A Review of the Last Five Years

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Abstract

Reducing carbon emissions has emerged as one of the most significant challenges in achieving global sustainability goals. A substantial portion of this objective focuses on mitigating emissions resulting from the combustion of fossil fuels in industrial processes. While production activities in the industrial sector contribute significantly to carbon emissions, a large fraction of the heat generated remains underutilized. In this context, thermophotovoltaic (TPV) systems present an effective solution for waste heat recovery in high-temperature industries. This study provides a comprehensive review of advancements in high-efficiency TPV systems and their applications in industrial waste heat recovery over the past five years. Specifically, selective emitters and photovoltaic (PV) cells have been analyzed at the system level, with critical components and relevant micro/nanofabrication techniques examined to enhance energy conversion efficiency. From an application perspective, the feasibility of TPV technologies in high-temperature industries is investigated about global waste heat utilization trends, with the steel industry serving as a case study to illustrate the potential of TPV systems in waste heat recovery and contributions to carbon neutrality.

Keywords: *Thermophotovoltaic; Waste heat recovery; Iron steel industry; Micro/nanofabrication techniques, Burning.*

1. INTRODUCTION

Renewable energy is indispensable for ensuring environmental sustainability by substituting carbon-intensive fuels. In addition to supporting decarbonization, these energy sources also promote climate action and resource conservation. Although more than 440 billion USD was spent on renewable energy in the electricity sector in 2021, investments in this field increased by only 12%, and these developments are still deemed insufficient to meet climate targets. Therefore, considering the projected increase in future energy demand, researchers have suggested that a substantial improvement can only be observed if the current systems are expanded threefold [1]. Because past analyses and studies have indicated that global energy demand is expected to grow by 35% between 2010 and 2035 [2]. The acceleration of such efforts depends on the support of national and international institutions as well as technological advancements while enhancing the efficiency of existing systems in the fight against carbon emissions is also one of the crucial steps to support this endeavor.

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One of the most critical aspects to be addressed in this context is the recovery of waste heat generated in industrial processes. Waste heat refers to low-quality thermal energy that emerges during the operation of a system [3]. Systems such as machines, furnaces, and stoves emit heat into the environment during their operation. In production processes, waste heat can originate from products, heating surfaces (e.g., furnace walls or stoves), and flue gases. The methods for recovering waste heat vary depending on the needs and processes of the relevant industry. These methods include heat exchangers, recuperators, waste heat boilers, passive air heaters, regenerative systems, and economizers. Waste heat generated in industrial systems can be classified into three main categories based on the temperature levels of their sources: waste heat from low-temperature sources, waste heat from medium-temperature sources, and waste heat from high-temperature sources [4]. There are numerous systems in both practice and research for waste heat recovery, and one of these systems is TPV systems.

TPV systems are an energy generation technology that directly converts radiative heat energy into electrical energy. These systems capture thermal radiation emitted at infrared wavelengths and generate electricity through specially designed PV cells [5]. TPV systems are particularly utilized in applications that operate at high temperatures and aim to enhance energy efficiency [6]. These systems consist of key components such as the heat source, selective emitter, filters, and PV cells. In TPV systems, solar energy, as well as combustion systems and various fuel types, can be used as the heat source. The heat source plays a fundamental role in photon production for the system’s operation. The selective emitter is used to enhance the system's efficiency, while filters reflect low-energy radiations, ensuring these radiations are redirected back to the selective emitter. PV cells then convert the photon energy from the emitter into electrical energy. The resulting direct current is then converted into alternating current, making it usable in various applications. With the potential for waste heat recovery, TPV systems hold a significant place among energy conversion technologies, offering cycles that enable the generation of electricity from heat. A schematic representation of a typical TPV system is provided in Figure 1.

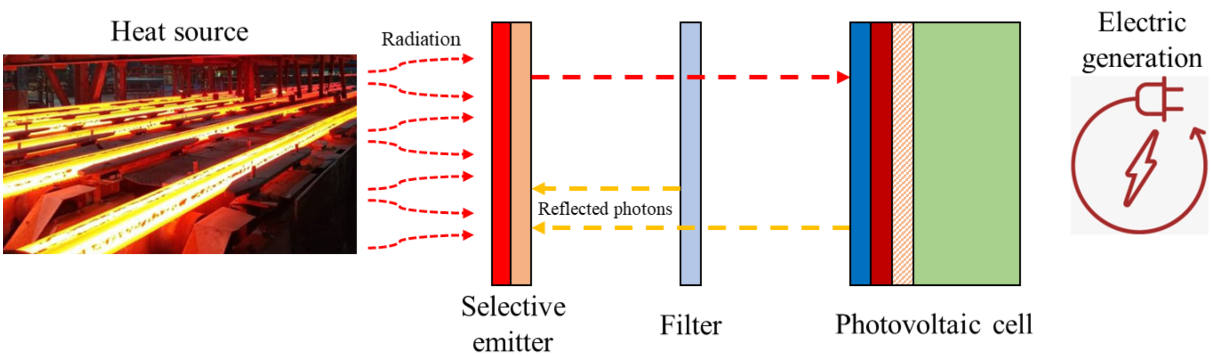


Figure 1. General schematic representation of TPV system for heat recovery.

Due to the high energy density and modular structure of TPV systems, system integrations are straightforward, and these factors particularly enable the utilization of waste heat emitted through radiation in industrial processes. On the other hand, these systems, which can also serve as an alternative to radioisotope thermoelectric generators in space technologies, can be employed in the defense industry and solar energy-focused thermal systems due to their ability to produce energy quietly. In this context, when reviewing TPV studies in the literature related to waste heat recovery, Bauer et al. [7] aimed to provide an overview of heat recovery from industrial high-temperature processes, using the glass industry in the United Kingdom as an example. The study identified the application areas of TPVs in the glass sector, evaluating them in terms of the glass industry, furnace type, process temperature, impact on the existing process, power scale, and the development efforts of TPV technology. In their study, Wang et al. [8] proposed a new hybrid system based on the TPV-thermoelectric (TE) effect. The potential application performance at heat source temperatures ranging from 700 to 1000 K was examined through experimental tests and simulations. The W-type TPV-TE waste heat recovery hybrid system demonstrated a good gain of 12.9% at 1000 K, with the output power being increased by 21.6% in series mode. Simulations for environmental applications revealed that, with a 63.7% output gain and an energy conversion efficiency of 11.23%, the heat recovery in deep space was more efficient than that on Earth. Utlu and Paralı [9] aimed to provide an overview of waste heat recovery using TPV from high-temperature processes in the Turkish industrial sector. The study reviews relevant facts about TPV technology and high-temperature industries and identifies three key locations for TPV heat recovery. For each location, the applicability of TPV's impact on the existing process and power scale is evaluated. The system, deployed for flue gas and wall heat recovery, estimates the total technical potential for energy recovery in high-temperature industries at 447.8 $PJ.year^{-1}$ using heat recovery devices. Utlu and Önal [10] conducted a thermodynamic analysis of a TPV system. They determined the overall energy and exergy efficiency of the TPV system, with results supported by formulas. At the same source temperature, they found that the In0.2Ga0.8As0.18Sb0.82 cell had higher efficiency than the GaSb cell, attributing this to the lower reverse saturation current and energy band gap, as well as the higher short-circuit current. If TPV systems were applied to the waste heat energy potential in the Turkish steel industry, they projected that GaSb cell systems would increase energy efficiency by 2.04%, resulting in an annual energy saving of 66.2 GJ. In contrast, In0.2Ga0.8As0.18Sb0.82 cell systems would improve energy efficiency by 7.31% and provide an annual energy saving of 190 GJ.

In the study conducted by Lu et al. [11], the performance of InAs TPV cells with external quantum efficiencies of 71% at low temperatures and 55% at room temperature at peak wavelengths was reported. The results showed a 10% power conversion efficiency at a cell temperature of 100 K. The dark and open current-voltage characteristics were measured at different cell temperatures (100–340 K) in response to heat sources within the range of 500–800 °C. The dependencies of output voltage and current, along with the spectral response of InAs TPV, were comprehensively characterized for waste heat recovery applications. In their study, Jiang et al. [12] developed a hydrogen-fueled micro-combustion system for a TPV application. The thermal performances of both deflector-equipped and deflector-less micro-combustion chambers were examined numerically and experimentally. Dimensionless height (λ) and distance (δ) were defined to determine the optimal height and placement of the deflectors. They concluded that the highest combustion efficiency was achieved when the parameters δ and λ were 0.3 and 0.9, respectively. Additionally, the heat from the exhaust gases was recycled to preheat the fresh H_2-air mixture, increasing the average wall temperature. A hybrid system consisting of a graphene-based thermionic energy converter (GTEC) and TPV was proposed by Liao et al. [13] to recover waste heat from the anode of the GTEC for additional power generation. In the study, the overall maximum efficiency of 0.584 was achieved by optimizing the temperature of the cathode, while the local maximum power density was observed to increase with rising cathode temperature. Comparisons were made between the current study and previous works. The current study demonstrated that the proposed system could achieve higher performance than a single GTEC and TPV operating under the same temperature differences. The researchers also examined the effects of thermal losses at the anode and radiative recombination losses of the PV cell on the system's performance. The local maximum power density was obtained as 2.06 $W.cm^{-2}$, with an efficiency of 0.251. Zhao et al. [14] proposed a solid-state near-field thermophonic system. The system consists of a light-emitting diode (LED) on the hot side and a PV cell on the cold side, with some of the power generated by the PV cell being used to forward-bias the LED. Operating in the near-field regime, the system was shown to have a power density and conversion efficiency that significantly exceeded the performance of existing solid-state approaches for low-grade waste heat recovery. When the gap distance was 10 nm, and the hot and cold sides were at temperatures of 600 K and 300 K, respectively, the produced electrical power density and thermal-electrical conversion efficiency were shown to reach 9.6 $W.cm^{-2}$ and 9.8%, respectively. These results demonstrate a significantly better performance compared to current record-breaking thermoelectric generators.

2. THE MAIN COMPONENT OF THE THERMOPHOTOVOLTAIC SYSTEMS

2.1 Heat Source

The heat sources used in TPV systems are fundamental energy providers for photon generation. These sources, typically operating at temperatures between 1000°C and 1500°C, are critical components that determine the efficiency of the system. Various heat sources, such as flame combustion, radiative isotopes (e.g., β-photons), and concentrated sunlight, are commonly used in TPV systems. According to Planck's law, the radiative power density is directly proportional to the fourth power of temperature, making the attainment of sufficient temperature levels crucial for the performance of TPV systems. Therefore, combustion systems capable of achieving high temperatures are often preferred in TPV systems, as they enable efficient photon production at elevated temperatures, thereby optimizing the electrical energy conversion processes [15].

2.2 Selective Emitter

A typical heat source used in TPV systems generates an emission spectrum following Planck's law. However, since PV cells can only absorb photons with energy above the bandgap, only a limited portion of the incoming energy can be converted into electrical energy. This highlights the importance of design improvements to optimize system efficiency. Selective emitters play a critical role in enhancing the efficiency of TPV systems. These components convert the incoming thermal energy into an emission spectrum that is compatible with the sensitivity of the receiver cell, thus making the energy conversion process more efficient. In this way, focusing the receiver cell solely on the convertible energy can significantly enhance system performance [16].

2.3 Filter

The filter in TPV systems functions similarly to a selective emitter. It is used to reflect radiation that does not have sufficient energy to create electron-hole pairs in photovoltaic cells. These low-energy radiations are redirected back to the emitter. This process helps maintain the emitter's temperature, thereby contributing to the system's energy efficiency. As a result, energy losses are minimized, and the conversion of available thermal energy into electrical energy is made more efficient [17].

2.4 Photovoltaic Cell

PV cells are used to absorb photon energy from the emitter and convert it into electrical energy. In these cells, the bandgap of the material plays a crucial role. The energy of photons obtained from the heat source is typically low, and therefore, for these photons to be effectively absorbed by the PV cell, the material's bandgap needs to be small. If the photon energy is greater than the material's bandgap, a portion of the photon energy is converted into an electron-hole pair, while the remaining energy is lost as heat. This situation highlights the necessity of using a filter. The selection of cells to be used in TPV systems is of critical importance. The use of different heat sources (photon sources) requires modifications in the semiconductor material and PV cell design. To absorb more photons, materials with a low bandgap should be preferred [15,18].

3. INDUSTRIAL WASTE HEAT USE AND TPV APPLICATIONS

3.1 General Status of Industrial Waste Heat

Energy conversion losses account for approximately 88% of the global energy supply, with about 50% of this being waste heat [19]. According to the energy classification definition made by Ammar et al. [20], a high-temperature heat source is defined as heat that can be captured by industrial processes, whereas a low-temperature heat source refers to heat that cannot be recovered and discarded in the process. As shown in Figure 2, Forman et al. [21] have investigated the distribution of waste heat to estimate the global waste heat potential. Due to the combustion of fossil fuels, industrial and transportation processes generate large amounts of high-grade waste heat. The heat source temperature for TPV systems holds a promising application in high-temperature industries, with the source temperature needing to be above 900-1000 °C. There is significant potential for waste heat recovery in industrial activities, and energy efficiency and emission reduction in the industrial sector are key factors in achieving a low-carbon transition. Despite its vast potential, industrial waste heat recovery is currently not being adequately recycled. A study conducted in 2016 reported that the energy-to-waste heat ratio in Germany was on average 13%, while according to 2013 data, the United States experienced an energy loss of approximately 61% [21,22]. In China, it was identified in 2021 that a coal-fired cogeneration plant with a large capacity alone accounted for more than 45% of the waste heat, with exhaust gas waste heat constituting more than 30% of the heat input and flue gas waste heat accounting for more than 15% [23]. In the steel industry, the recovery rates of high, medium, and low-grade waste heat are known to be 44.4%, 30.2%, and 2%, respectively [24]. Therefore, capturing large amounts of waste heat is essential for improving energy efficiency and reducing carbon emissions [25].

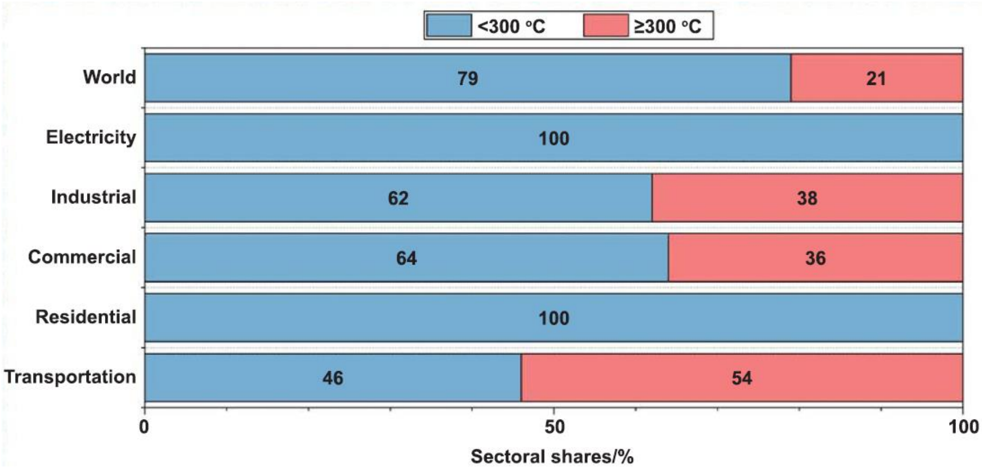


Figure 2. Sectoral shares of waste heat distribution [21].

In recent years, global steel demand has increased significantly. This growth is expected to continue with the rise in population and gross domestic product (GDP) [26–28]. The distribution of fuel types used in steel production between 2010 and 2021 according to the Net Zero Scenario is shown in Figure 3 [29]. Upon examining the figure, it can be observed that the use of coal as an energy input in steel production is dominant, which results in high levels of carbon emissions [30–32]. Considering that a significant portion of the heat required for the production process is not fully utilized, it is crucial to take action on this issue. Currently, only about 25% of the waste heat produced by steel plants is recovered by some commercial technologies [33]. It is also estimated that the use of cogeneration heat recovery systems in the steel industry could have a global power generation potential of more than 3.1 GW [5].

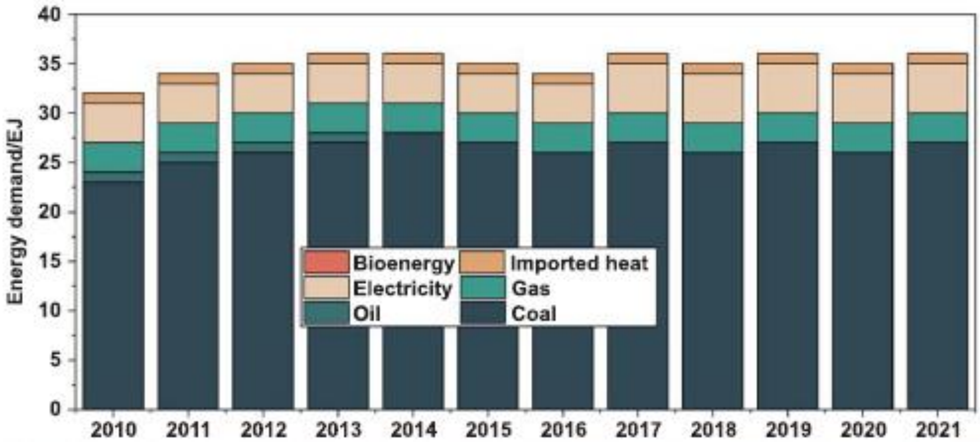
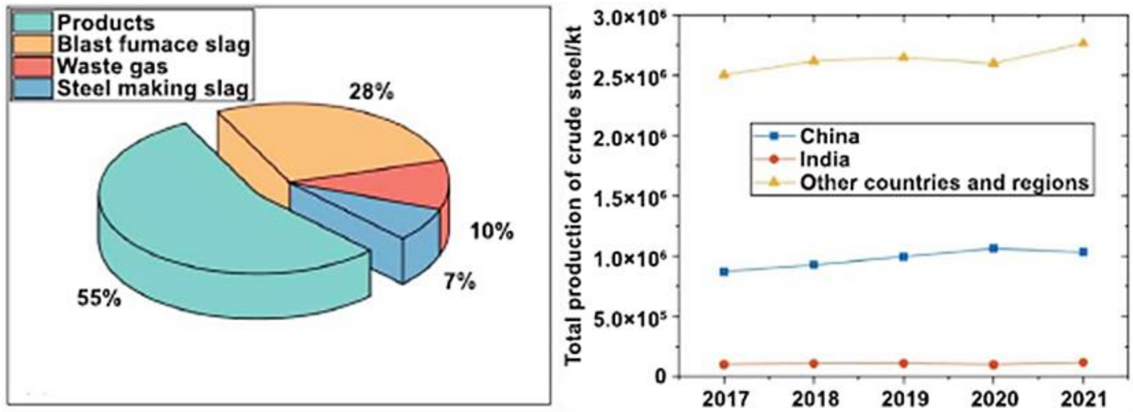


Figure 3. Energy demand for iron and steel by fuel in the Net Zero Scenario, 2010–2021 [29].

As shown in Figure 4(a), steel plants generate high-temperature waste heat stored in products, slag, and exhaust gases [34]. Among these, slag is a byproduct of the steel-making process and is discharged at a high temperature of approximately 1450-1550 °C [35], containing large amounts of high-grade thermal energy. Table 1 shows the waste heat recovery for different processes in the steel industry [24]. Due to its solid-state and high-temperature properties, sensible heat is largely not recovered, except for the high furnace slag in pig iron production and converter slag in steel production. However, high-pressure steam recovery through dry quenching exists. Additionally, techniques for recovering high-grade waste energy and heat (above 1000 °C) are applied through processes such as cogeneration for chemical energy, power, or heat production via gas turbine power plants from coke oven gas, blast furnace gas, and basic oxygen furnace gas. Despite this, global crude steel production has continued to show an increasing trend in recent years [36], and the changes are shown in Figure 4(b). In this trend, the full utilization of waste heat is becoming increasingly important, and more actions need to be taken to address the recovery of waste heat from all aspects. Additionally, while the methods mentioned above recover waste heat through direct thermal conversion, TPV systems generate electricity through thermal radiation.



(a) (b)

Figure 4. Data on world waste heat; (a) distribution of high temperature waste heat in the iron and steel industry [34]. (b) Changes in world crude steel production from 2017 to 2021 from the World Steel Association [37].

Table 1. Recovery and use of waste heat originating from different processes in the Iron-Steel industry [24].

Process	Total Amount [GJ.t^{-1}.s^{-1}]	Recovered Amount [GJ.t^{-1}.s^{-1}]	Recovered Rate [%]
Coking	0.93	0.08	8.2
Sintering/pelletizing	1.56	0.28	18.0
Iron production	8.00	4.62	57.8
Steel production	1.81	0.81	44.8
Rolling	1.01	0.28	27.2

3.2 Waste heat recovery systems and the place of thermophotovoltaic application in these systems

Energy sources are utilized to produce additional heat or to generate electrical and mechanical power. Waste heat can be discharged at various temperature levels; conventionally, higher temperatures correspond to higher-quality waste heat, facilitating the optimization of waste heat recovery processes. Consequently, it is crucial to determine the maximum recoverable heat from a process with the highest potential and to ensure the optimal efficiency of the waste heat recovery system. To achieve this, various systems are employed to manage waste heat recovery in thermal applications and these systems can be categorized in Figure 5 considering their working temperature range and utilizing purpose. TPV systems are employed to directly convert radiant energy into electricity, analogous to the functionality of solar panels and the main advantages and disadvantages are presented as in Table 2.

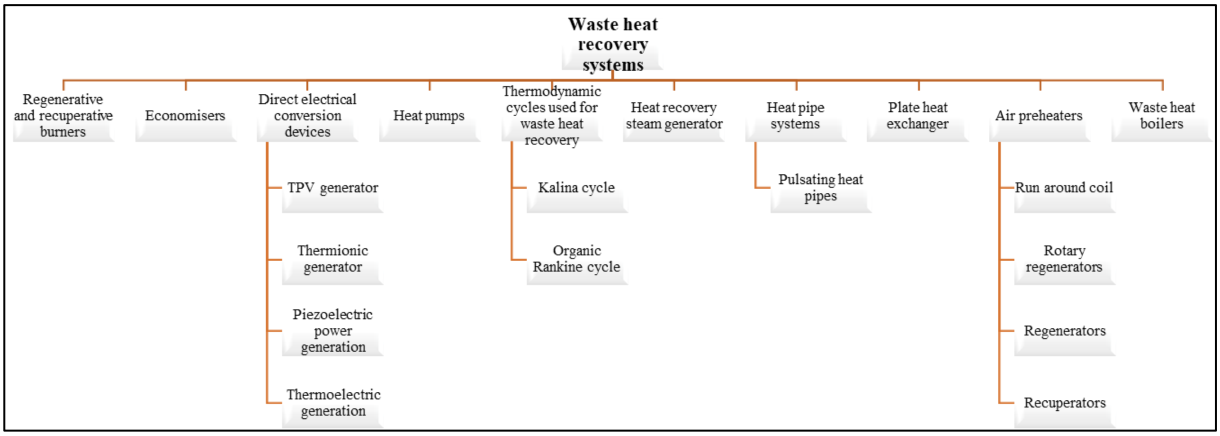


Figure 5. Classification of waste heat recovery systems [38].

Table 2. Advantages and disadvantages of TPV waste heat recovery systems [38,39].

Advantages	Disadvantages
TPV systems enable direct electricity generation without mechanical moving parts, reducing maintenance requirements.	The efficiency of TPV systems is limited by the spectral response of the photovoltaic cells and the performance of selective emitters.
They exhibit high efficiency when recovering waste heat from high-temperature sources.	High-temperature-resistant photovoltaic cells and spectral filters are costly.
When spectral matching between the heat source and the TPV cell is optimized, significant energy conversion efficiency can be achieved.	Their effectiveness decreases at medium and low temperatures, making them less advantageous than other waste heat recovery technologies in certain applications.
TPV systems are suitable for micro-scale applications and can be easily integrated into compact systems.	

The economic feasibility of TPV systems plays a crucial role in their widespread adoption and commercial viability. A comprehensive cost analysis of TPV systems involves several key parameters, including initial capital investment, operation and maintenance costs, and the energy savings or revenue generated over the system's lifetime. The installation costs of TPV systems vary depending on factors such as the type of semiconductor materials used, the efficiency of the optical components, and the characteristics of the waste heat source. While advanced semiconductor materials (e.g., InGaAs or GaSb-based cells) offer high conversion efficiencies, their production costs remain a significant barrier to the large-scale deployment of TPV technology. However, as manufacturing processes advance and material innovations continue, these costs are expected to decrease over time. Another critical economic factor is the payback period of TPV systems, which refers to the time required for the system's total cost to be offset by the energy savings or revenue it generates. TPV systems can achieve relatively short payback periods, particularly in applications where a continuous waste heat source is available, such as industrial waste heat recovery. For instance, converting infrared radiation emitted from industrial furnaces into electricity through TPV technology not only enhances energy efficiency but also reduces fossil fuel consumption, leading to lower operational costs.

Furthermore, the operation and maintenance costs of TPV systems are generally lower compared to conventional energy conversion technologies. Since TPV cells do not contain moving parts, wear and mechanical failures are minimal. However, to ensure long-term system stability and performance, periodic maintenance such as cleaning of optical components and monitoring system efficiency remains essential. In conclusion, the economic feasibility of TPV systems must be carefully evaluated in terms of initial investment and payback period. Technological advancements are expected to reduce manufacturing costs, making TPV systems more accessible. In particular, their application in waste heat recovery demonstrates significant potential for improving energy efficiency and reducing overall energy expenditures.

3.3 TPV Applications for Waste Heat in the Iron-Steel Industry

Although advanced recovery technologies increase overall efficiency, a significant amount of waste heat is still not being utilized. Specifically, waste heat is often released into the environment in the form of radiation [40], which reduces the system's energy efficiency. TPV systems, on the other hand, offer a promising solution by converting this radiation energy—otherwise wasted—into usable electrical energy, thereby enhancing energy conversion efficiency [41]. For example, TPV systems could be used during the continuous casting of hot-rolled steel plates. These plates typically have an initial temperature of around 1200 °C and cool down to below 1000 °C. TPV systems can generate electricity by utilizing the radiation produced in annealing furnaces as an energy source through PV cells placed on hot steel plates. Such a system has the potential to generate approximately 440 kW of power for steel plates with a surface area of 50 m^2 [42]. Lewis et al. reported that infrared radiation emitted by a black body at 1127 °C, with a wavelength below 1.8 μm, could provide around 3.4 $W.cm^{-2}$ of radiation energy. Using GaSb IR-sensitive TPV cells developed by JX Crystals Inc., it was found that at least 1 $W.cm^{-2}$ of electricity could be generated from radiation energy in steel production facilities [43]. Furthermore, a study by Utlu et al. [44] showed that the integration of cogeneration systems for waste heat recovery in Turkey's steel industry could recover approximately 29.88 MJ of waste heat annually using GaSb cells, while In0.2Ga0.8As0.18Sb0.82 cells could recover 1.076 MJ per year. In a study by Onwuemezie and Darabkhani [45], a hydrogen-fueled blast furnace was designed to reduce carbon emissions, and a portion of the energy input from the hydrogen obtained via electrolysis was also provided by the electricity produced from the radiation emitted by the furnaces, with 61.1 kW of energy supplied to the electrolysis system via the TPV system.

The industrial sector significantly contributes to China's increasing energy consumption and CO_2 emissions, as the country is both the largest producer and consumer of steel [46]. Steel production accounts for 10-15% of China's total energy use and 15-20% of its industrial energy consumption [47,48]. Xuan et al. [49] analyzed China's energy consumption and CO_2 emissions in the steel industry, projecting trends from 2010 to 2030. The study highlighted that integrating TPV devices, along with high-efficiency emitters and PV cells, into high-temperature steel production processes could enable waste heat recovery rates exceeding 40% under optimal conditions.

The steel industry provides abundant waste heat sources across various processes and temperature ranges, creating a highly suitable working environment for TPV devices. Waste heat recovery holds significant economic value, and TPV systems offer a promising opportunity for such applications. Since steel production is primarily dependent on coal-based heat sources, the use of TPV systems for waste heat recovery could reduce coal consumption and increase cogeneration efficiency.

4. CONCLUSION

This review summarizes the key findings of recent research on TPV efficiency from a system-level to a component-level perspective. It also addresses the global use of industrial waste heat and examines the application of TPV components for waste heat recovery in the steel industry. Research on TPV emitters dates back to the 1990s, initially focusing on simple rare earth elements and bulk emitters. Since 2010, studies have shifted toward integrating filtering functionality directly into emitters, leading to the development of increasingly advanced selective emitters. Research today continues with a focus on precision and efficiency. Particularly, structural designs at the micro/nanoscale using metamaterials enable spectral modulation. Modern approaches have replaced traditional iterative design processes, utilizing machine learning methods that allow for rapid reverse design of structures.

At the beginning of the 21st century, it was experimentally demonstrated that narrow bandgap materials like GaSb and InGaSb could efficiently support TPV performance. Although these materials offer relatively high efficiency, they have not yet made TPV a competitive thermoelectric conversion method. Current research focuses mainly on producing multi-junction PV cells from III-V group semiconductor materials on the periodic table. When these advanced PV cells are combined with emitters and rear reflectors, they can theoretically achieve efficiencies above 50%, and in practice, over 40%. To optimize a TPV system, it is essential to first develop stable, high-efficiency PV cells and design selective emitters with thermally stable structures. Additionally, components like rear reflectors can be used to minimize heat loss.

High-temperature industries, such as those primarily involved in steel production, generate significant amounts of waste heat and present a promising opportunity for TPV system implementation. Unlike traditional waste heat recovery methods, TPV systems capture radiative energy and can significantly increase conversion efficiency. In the context of global energy savings and emission reductions, TPV technology is expected to see broader industrial applications in the future. TPV systems are particularly suitable for high-temperature industries like steel production. The radiative energy generated from these processes can be directed to PV cells through a selective emitter, producing electricity, while the unused heat is reflected to the heat source, increasing its temperature.

However, there are three main challenges in the TPV research and development process: stability, efficiency, and cost. Stability issues arise from the difficulty of maintaining system performance at temperatures above 1000 °C. Emitters and PV cells tend to experience performance degradation in such environments over extended periods. Research on emitter stability focuses on material doping methods, while mandatory cooling is a common strategy to enhance the thermal stability of PV cells. In terms of efficiency, TPV systems currently perform poorly, with much of the work being limited to numerical simulations or basic experiments, and few examples of fully integrated systems. The production of large-scale emitters and PV cells remains challenging and costly, negatively affecting the economic viability of TPV technology.

Current estimates of TPV waste heat recovery potential in the literature are typically based on idealized conditions. Future development of TPV technology will focus on improving system efficiency and enhancing stability through practical tests in high-temperature environments. TPV systems have significant potential to reduce carbon emissions. TPV technology is applicable not only for electricity generation, cogeneration, and waste heat recovery but also for solar and latent heat energy storage systems. In all these scenarios, optimized TPV components are expected to provide higher energy efficiency and further reduce carbon emissions.

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No	Full Name	ORCID ID	Author's Contribution
1	Emrehan Gürsoy	0000-0003-2373-3357	1, 2, 3, 4, 5
*In the contribution section, indicate the number(s) that correspond to the relevant contribution type.			
1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing 5- Critical revision			

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