

# Thermodynamic analysis of thermophotovoltaic systems used in waste heat recovery systems: an application

Zafer Utlu\* and Büşra Selenay Önal

Engineering Faculty, Department of Mechanical Engineering, Istanbul Aydın University, Istanbul, Turkey

## Abstract

Thermodynamic analysis of the thermophotovoltaic (TPV) system was carried out in our research and the results are presented. First, the TPV system was analyzed in three different regions. In the analysis, each part of the system is taken separately, while the whole system is handled separately. Within the thermodynamic analysis of each region, energy and exergy analysis were carried out and the system was analyzed from part to part. As a result of this method, a general energy and exergy efficiency of the whole TPV system is determined. Our results are supported by formulas. The  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}_{0.18}\text{Sb}_{0.82}$  cell has a higher efficiency compared to the GaSb cell at the same source temperature. This is because the reverse saturation current and the energy band gap are low and the short-circuit current is high. If TPV systems are applied for waste heat energy potential in the Turkish iron and steel industry, the energy efficiency of GaSb cell systems is 66 192 MJ per year with energy efficiency of 2.04%, the energy efficiency of  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}_{0.18}\text{Sb}_{0.82}$  cell systems is 7.31% with annual energy efficiency of 189 971 MJ can be recovered. It is aimed that the work done will be an alternative to the existing electricity generation and will form a resource for future works.

**Keywords:** thermophotovoltaic; waste heat; thermodynamic analysis; electricity production

\*Corresponding author:  
zaferutlu@aydin.edu.tr

Received 19 August 2017; revised 13 October 2017; editorial decision 18 October 2017; accepted 3 December 2017

## 1 INTRODUCTION

Increasing energy consumption, shortening the life span of fossil energy sources and damaging the environment have contributed to the search for new energy sources in the world, and to accelerate the search for maximum efficiency from the used energy sources [1, 2]. In industrial systems, waste heat comes into play in the production phase. Waste heat is the low-energy heat generated by the work done in the system. Systems such as machines, ovens and stoves emit heat for the duration of their work [3, 4]. Waste heat during production phase: from the furnace, from the heater (oven wall, stove, etc.) and from the flue gas.

Waste heat recovery paths can vary according to different industries. Waste heat recovery paths include heat exchangers, recuperators, heat boilers, passive air heaters, regenerative and economizers. Heat exchangers are often used to transfer exhaust gases to the combustion air entering the furnace.

Recuperators are heat exchangers where the waste heat from the flue gas is transferred to the combustion air. Waste heat boilers are placed in front of the hot gas and the water is heated by utilizing the energy of the waste hot gas. Passive air heaters are devices that perform heat recovery from gas for low- and medium-temperature applications. Economizers are used to recover heat from the exhaust gases used to heat liquids at low and medium temperatures [4]. In addition to this system, the use of thermoelectric and thermophotovoltaic (TPV) systems for electricity generation has become widespread. While thermoelectric systems work by direct heat conversion of heat, TPV systems aim to generate electricity by radiation. The discovery of TPV dates back to ~1956. Most literature references refer to Aigrain as a miracle of the TPV, which proposed the concept during a series of conferences in 1956 at MIT [5, 6]. Nelson has been informed by Kolm about a TPV system and a publication entitled 'Power supply for solar batteries' [7].

International Journal of Low-Carbon Technologies 2018, 13, 52–60

© The Author(s) 2018. Published by Oxford University Press.

This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited. For commercial re-use, please contact [journals.permissions@oup.com](mailto:journals.permissions@oup.com)

doi:10.1093/ijlct/ctx019 Advance Access Publication 5 January 2018

Until the mid-1970s, research in the United States focused on low-noise, independent military electric generators using fossil fuels as heat sources. In this period, three basic heat sources (solar, nuclear and combustion) and spectral control options (selective radiator, filter, PV cell front and rear surface reflector) have been described [7–10]. Industrial waste heat recovery using TPV conversion was proposed by Coutts at the end of 1990s [11]. In addition, at the end of the 1990s, basic research on the near-field TPV (NF-TPV) started. From the beginning of the 2000s, the development of miniature TPV generators under 10 W of electrical power has been accelerated. However, some of the work done in this area and the status achieved are shown in Table 1.

These studies show that TPV applications are increasingly increasing, contributing greatly to energy conversion and productivity. The applications of TPV are residential, automotive, and industrial and so on. It is seen that it has entered the sectors and brought an alternative to electricity generation.

Electricity production through waste heat radiation is an option for increasing the efficiency of thermal systems. However, in the literature this system has not found enough space due to the high cost and the difficulties of implementation. It is

also seen that the efficiency of the system is not examined in detail in the published literature. In this study, it was aimed to determine the thermodynamic efficiencies of TPV systems and to direct future studies. This study deals with thermodynamic analysis of the TPV system. TPV systems provide electricity generation by evaluating the waste heat that is generated during the production of industrial products. TPV systems, which are considered as alternatives to the existing electricity generation, are cycles that generate electricity from heat and provide waste heat recycling. A TPV system consists of a heat source, a selector-emitter, a filter, a photovoltaic cell and a cooling system. The waste heat from the high temperature heat source passes through the selective emitter and filters and reaches the photovoltaic cell. Photovoltaic cells convert photon energy from the emitter into electrical energy. The obtained linear current can be used in different fields by turning the alternating current.

## 2 CLASSIFICATION OF WASTE HEAT

Industrial waste heat are waste heat from low temperature heat sources, waste heat from medium-temperature heat

**Table 1.** Some previous studies about thermophotovoltaic system and its main outcomes.

References	Study	Outcomes
Schubnell <i>et al.</i> [12]	Design of a thermophotovoltaic residential heating system	This study have been find that, in such a system, the expected electricity output amounts even under optimistic conditions to only ~5% of the thermal input if Si-cells are used. Using low band gap cells increases this share to ~10%. Therefore, conclude that cogeneration of heat and electricity with TPV is only viable if low-band-gap TPV-cells are available at reasonably low costs
Xuan <i>et al.</i> [13]	Design and analysis of solar thermophotovoltaic systems	The emitters made of different materials with different configurations are numerically analyzed and compared. The effects of concentration ratio, spectral characteristic of the filter, series and shunt resistance of the cell, the performance of the cooling system on the STPV systems are discussed
Bitnar <i>et al.</i> [14]	Thermophotovoltaics on the move to applications	Related developments of TPV system components such as radiation emitters, filters and photo-cells are reviewed and theoretical system simulations are compared to experimentally achieved results regarding system efficiency and the electrical output power. Novel TPV applications are suggested and the commercial potential of this technology is discussed
Xu <i>et al.</i> [15]	Experimental and theoretical analysis of cell module output performance for a TPV system	The theoretical model developed in this study is used to analyze and optimize the experimental TPV system, and consequently the output powers under two different conditions are enhanced by 20.24% and 33.99%, when a module is connected in parallel
Ferrari <i>et al.</i> [16]	Thermophotovoltaic energy conversion: analytical aspects, prototypes and experiences	This paper wish to outline the current state-of-the-art of TPV generation. A comprehensive review of all the realized prototypes reported in literature is presented highlighting the issues where the research is focused and the main strategies and solutions to achieve high values of efficiency
Ferrari <i>et al.</i> [16]	Overview and status of thermophotovoltaic systems	This study wish to outline the current state-of-the-art of TPV generation under both the analytical and the experimental point of view. In this study a deeply investigation of all the analytical aspects which involve the TPV conversion is presented; each term which composes the conversion efficiency between the introduced power with fuel and the produced electrical output is investigated
Daneshvar <i>et al.</i> [17]	Thermophotovoltaics: fundamentals, challenges and prospects	In this article has been discussed the cost and safety considerations en route to development of useful TPV systems in many places. This review also scrutinizes state-of-the-art developments, discusses the fundamental and technical challenges facing commercial adoption of TPV, and prospects of TPV
Shoaei [18]	Performance assessment of thermophotovoltaic application in steel industry	A mathematical model for the assessment of the performance of TPV application in the iron and steel industry has been developed. The total efficiency of the system was obtained to 4.12%, when GaSb cell with temperature of 27°C and slab emitters with temperature of 1257°C are used. The results of the simulation of the model in a casting process at the Mobarakeh Steel Complex have shown a potential of energy recovery of 26.987 MJ per year

sources and waste heat from high temperature heat sources. Low-temperature waste heat can be useful as a complementary way to low vapor pressure needs and preheating purpose [4, 19].

Waste gas temperature values in the medium-temperature range of industrial process equipment are shown in Table 1. Most of these mid-temperature values are obtained from combustion processes [4, 19]. Waste gas temperature values at high-temperature ranges of industrial process equipment are also shown in Table 2. All these results are obtained directly from the combustion processes [3].

### 3 TPV SYSTEMS

TPV systems are systems that generate heat energy and electric energy from high temperature waste heat and solar radiation. The solar rays on the photovoltaic cell are absorbed by the cell and turn the heat energy into electrical energy. TPV system include selective emitter, heat source, filter and a photovoltaic cell. The heat source in the system conveys the heat energy to the selective emitter and the photovoltaic cell module converts the thermal energy to electrical energy as indicated in Figure 1. This transformation is considered as an alternative to existing electricity generation. At the same time, the electric energy to be obtained is obtained from the waste heat from the production stage in industrial systems. This case saves energy and cost. In addition, waste heat released to the environment is evaluated.

The main advantages of this energy system are as follows:

- (a) It is possible to use TPV system as a combined heat and power at high fuel usage factor (close to unity due to recovery of most thermal losses);

- (b) low produced noise levels (due to lack of moving parts);
- (c) easy maintenance (similar to a common house-type boiler); and
- (d) great fuel flexibility [4, 16, 19].

#### 3.1 Heat source

The heat source is the source of photons. Heat sources with working temperatures between 1000 and 1500°C can be used in TPV systems [4, 19]. These sources include sunlight, radioactive isotopes ( $\beta$ -photons) and flaming combustion. The heat energy from the heat source passes through the selective emitter, filter and cells by radiation. The heat source comes from photovoltaic cells and allows photons to be obtained. According to Planck’s law, the power density of the light is four. It is very important to reach the temperature enough to change because of the power. For this reason, the heat sources used in TPV systems usually include burn-in systems [4, 19].

#### 3.2 Selective emitter

Selective spreader is used to increase system efficiency. The selective emitter translates the heat to the emission spectrum by providing the appropriate receiver cell sensitivity before transferring to the filters. Because the receiving cells can only use an energy absorber above the band spacing. This leads to less electricity generation.

#### 3.3 Filter

The photons from the selective emitter reach the filter before they reach the cells. The filters have the same characteristics as the selective emitter. Reflects non-energized radiation and sends the selective emitter back. Thus, the system efficiency is increased.

**Table 2.** Waste heat values obtained from different welds at low, medium and high temperature [3, 4, 19].

Low temperature		Medium temperature		High temperature	
Heat source	Temperature (°C)	Heat source	Temperature (°C)	Heat source	Temperature (°C)
Steam condensation processes	55–88	Steam exhaust exhausts	230–480	Nickel refine ovens	1370–1650
Cooling water	–	Gas turbine exhausts	370–540	Aluminum refined ovens	650–760
Welding machines	32–88	Piston engine exhausts	315–600	Zinc refined ovens	760–1100
Injection machines	32–88	Piston engine exhausts (turbo charged)	230–370	Copper refined ovens	760–815
Annealing furnaces	66–230	Heat treatment furnaces	425–650	Steel heating furnaces	925–1050
Internal combustion engines	66–120	Drying and cooking ovens	230–600	Copper reverber oven	900–1100
Mold forming	27–88	Catalytic crackers	425–650	Open hearth furnaces	650–700
Air conditioning and cooling capacitors	32–43	Annealing oven cooling systems	425–650	Cement ovens (drying process)	620–730
Drying, cooking and curing ovens	93–232	–	–	Glass melting furnaces	1000–1550
–	–	–	–	Hydrogen facilities	650–1000
–	–	–	–	Solid waste incineration facilities	650–1000
–	–	–	–	Waste incinerator	650–1450

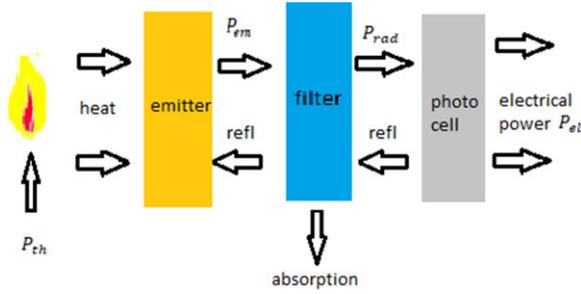


Figure 1. The schematic of the TPV system and a developed TPV prototype.

### 3.4 Photovoltaic cells

Photovoltaic cells; absorb photons from the emitter and convert them into thermal energy electrical energy. The necessity of absorbing as many photons as possible obligates the use of materials with low band gap [4, 19]. The work on TPV converters is mainly focused on silicon and germanium converters [16]. However, the quality of these elemental semiconductors is poor. The impressive advancement of the devices has led to the high performance of modern TPV devices and ultimately the resurgence of interest in this ‘area’ [16]. There are several types of photovoltaic cells. In general, GaInAs and GaInAsSb cells are used. The bandwidths of these semiconductor materials are different from each other. The GaInAs band gap equals 0.7 eV. This band gap has a very large scale for optimum efficiency and energy. In addition to these cells, InGaSb and InGaAsSb are formed by forming quaternary alloys. InGaSb has a band gap of 0.5 eV, which is a very narrow band gap. InGaAsSb can be adjusted between 0.38 and 0.7 eV depending on the ratio of the elements.

## 4 MATERIALS AND METHODS

### 4.1 Thermophotovoltaic model and calculations

The equivalent circuit of the photovoltaic system can be expressed as shown Figure 2.

The radiation current proportional to the radiation is calculated as follows:

$$I_{ph} = \int_0^{\lambda_{max}} q \cdot S \cdot F(\lambda) \cdot SR(\lambda) d\lambda \quad (1)$$

where  $\lambda$  is the wavelength of the stimulating photon.  $Q$  is the electron charge and  $\lambda_{max}$  is the cut-off wavelength corresponding to the band gap energy.  $SR(\lambda)$  is the intrinsic spectral response of the TPV cell given the sum of the reduced region and emitter.  $F(\lambda)$  is the spectral photon flux of the incoming entrainment absorbed by the TPV cell. For  $\lambda < \lambda_{max}$ ,  $F(\lambda)$  is calculated as follows [4, 19]:

$$F(\lambda) = \chi \cdot \frac{2\pi \cdot c}{\lambda^4 \left[ \frac{hc}{e\lambda kT_{Rad}} - 1 \right]} \quad (2)$$

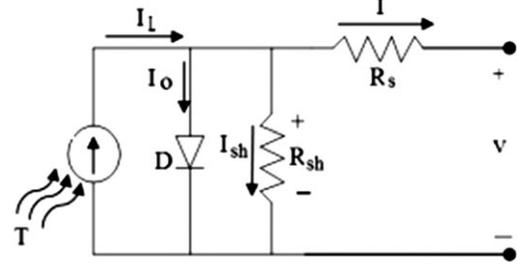


Figure 2. Photodiode equivalent circuit.

where  $T_{Rad}$  is the radiator temperature, ‘ $h$ ’ is the Planck constant, ‘ $c$ ’ is the speed of light, ‘ $k$ ’ is the Boltzmann constant and ‘ $\chi$ ’ is the effective cavity emitter that characterizes the spectral control performance in the TPV system.

This value is 0.78 based on the best reported spectral control system performance [4, 19].

The ‘ $I$ - $V$ ’ characteristic of a TPV system can be shown as follows:

$$I = I_L - I_0 \left[ e^{\frac{q}{nKT}(V+IR_S)} - 1 \right] - \frac{V + IR_S}{R_{SH}} \quad (3)$$

here, the current proportional to  $I_L$  radiation is represented by  $R_S$  series resistance, and  $R_{SH}$  is parallel resistance [3].

The open circuit voltage is calculated as follows:

$$V_{oc} = \frac{nkT_{Cell}}{q} \cdot \ln \left( \frac{I_{sc}}{I_0} + 1 \right) \quad (4)$$

where  $n$  is the ideal factor,  $T_{cell}$  is the cell temperature and  $I_0$  is the reverse saturation current

$$V_{mp} = V_{oc} - \frac{kT}{q} \ln \left[ \frac{V_{mp}}{kT/q} + 1 \right] \quad (5)$$

The fill factor is calculated from the ratio of the maximum power, the short-circuit current and the open circuit voltage:

$$FF = \frac{V_{mp} \cdot I_{mp}}{V_{oc} \cdot I_{sc}} \quad (6)$$

The efficiency of a TPV system is calculated as follows:

$$\eta = \frac{I_{sc} \cdot V_{oc} \cdot FF}{P_{Inc} - P_{Ret}} \quad (7)$$

here,  $P_{inc}$  expresses the power of radiation from the photovoltaic cell, the power reflected by the  $P_{retcell}$ .

The energy efficiency of the system is calculated as follows:

$$\eta_e = \frac{P_{cell}}{P_{Inc}} \quad (8)$$

here,  $\eta_e$  refers to the system efficiency, the power generated by the  $P_{cell}$  TPV system.

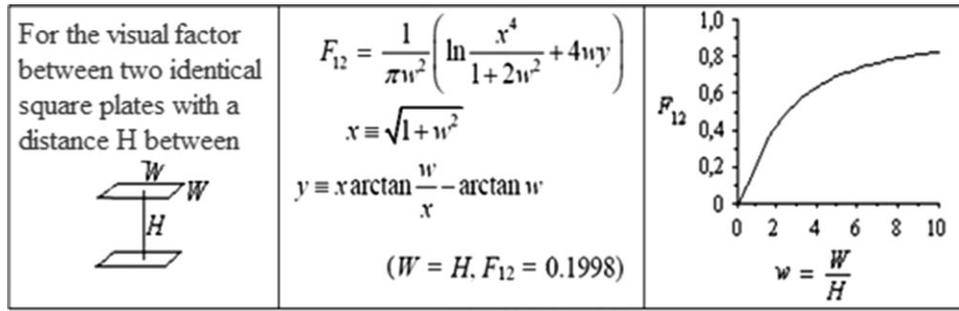


Figure 3. High vision factor for TPV applications in iron and steel industry [4, 19].

Another important parameter for spectral control is a good visibility factor between IR emitter and IR PV layer. In Figure 3, the ratio of the emitter width  $W$  to the distance  $H$  between the dielectric filter and the IR emitter is shown to be a function of the  $F_{12}$  vision factor. As can be seen from Figure 3, if the  $W/H$  ratio is  $>8$ , the visual factor will be above 80% [4, 19].

### 4.2 Thermodynamic analysis of TPV system

First, the TPV system was analyzed in three separate regions. In the analysis, each part of the system was evaluated separately. In addition, the whole system has been dealt with. The first region is the thermodynamic analysis of the energy source that reaches the filter by radiation of the heat source. The second region is where the filter, selective-emitter and photovoltaic cells, considered as photovoltaic systems, take place. The third region, which is expressed as the last zone, is considered to be the part where electric energy is stored. Within the thermodynamic analysis of each region, energy and exergy analysis were conducted and the system was investigated by induction method. Initially, the following formulas are obtained if we examine the first region.

#### 4.2.1 Heat source

The power input by the heat source to the system is calculated as follows:

$$P_{in} = \dot{m}_{fuel} \times LHV \tag{9}$$

The fuel charge entering the system is calculated as follows:

$$P_{fuel} = P'_{GAP} + Q_{th,gas} \tag{10}$$

The fuel efficiency of the system is the rate at which the fuel power enters the system by the heat source:

$$\eta_{cc} = \frac{P_{fuel}}{P_{in}} \tag{11}$$

Fuel loss is the difference between the power input by the system heat source and the fuel output:

$$P_{fuel,loss} = P_{in} - P_{fuel} \tag{12}$$

The exergy fuel is calculated as follows:

$$EX_{fuel} = \left[ - \left( \sum_P n_{k,P} \times \Delta g_{fk,R} - \sum_R n_{k,R} \times \Delta g_{fk,R} \right) + \sum_P n \times EX_{k,P}^{ch} - \sum_R n \times EX_{k,R}^{ch} \right] \tag{13}$$

The exergy entering the system from the heat source is calculated as follows:

$$EX_{in} = \left( 1 - \frac{T_a}{T_s} \right) \times I_s \tag{14}$$

$$EX_{fuel,loss} = EX_{in} - EX_{fuel} \tag{15}$$

#### 4.2.2 Selective emitter

The formulas for the photovoltaic system we have defined as the second region are as follows.

The thermal power output from the selective emitter is defined as follows:

$$Q_{th,gas} = \dot{m}_{gas} \times h_{gas} - \dot{m}_{air} \times h_{air} \tag{16}$$

#### 4.2.3 Optical filter

Radiant power entering the optical filter; equal to the emitter surface multiplied by the radiant power density:

$$P_{rad} = \rho_{rad} \times S_{em} \tag{17}$$

Radiant power density is expressed by Stefan–Boltzmann law:

$$\rho_{rad} = \epsilon \cdot S_{em} \cdot 2\pi \int_0^\infty I(\lambda, T_{em}) \cdot d\lambda = \epsilon \cdot S_{em} \cdot 2\pi \int_0^\infty \frac{hc^2}{\lambda^5} \left[ \exp\left(\frac{hc}{\lambda k_b T_{em}}\right) - 1 \right]^{-1} \cdot d\lambda \tag{18}$$

$$k_b = 1.380 \times 10^{-23} \text{J}K^{-1} \text{ (Boltzmann constant)}$$

$$h = 6.626 \times 10^{-34} \text{J} (\text{Planck constant})$$

$$c = 2.99 \times 10^8 \text{ms}^{-1} (\text{speed of light})$$

The radiant efficiency entering the optical filter is the ratio of radiant power to fuel power:

$$\eta_{\text{RAD}} = \frac{P_{\text{RAD}}}{P_{\text{fuel}}} \quad (19)$$

The radiant exergy efficiency is expressed as follows:

$$\eta_{\text{ex,RAD}} = \frac{EX_{\text{RAD}}}{EX_{\text{fuel}}} \quad (20)$$

The filter efficiency is expressed as follows:

$$\eta_F = \frac{P_{\text{GAP}}}{P'_{\text{GAP}}} \quad (21)$$

$P_{\text{abs}}$  is taken as  $\eta_F = 1$  when neglected.

The filter exergy efficiency is expressed as follows:

$$\eta_{\text{ex,F}} = \frac{EX_{\text{GAP}}}{EX'_{\text{GAP}}} \quad (22)$$

Spectral power from optical filter:

$$P'_{\text{GAP}} = P_{\text{RAD}} - Q_{\text{back}} \quad (23)$$

$$\begin{aligned} P'_{\text{GAP}} &= \epsilon \cdot S_{\text{em}} \cdot \int_0^\lambda I(\lambda, T_{\text{em}}) \cdot \tau(\lambda) d\lambda \\ &= \epsilon \cdot S_{\text{em}} \cdot \int_0^\lambda \frac{2\pi hc^2}{\lambda^5} \left[ \exp\left(\frac{hc}{\lambda k_b T_{\text{em}}}\right) - 1 \right]^{-1} \cdot \tau(\lambda) \cdot d\lambda \end{aligned} \quad (24)$$

Spectral efficiency can be expressed as follows:

$$\eta_{\text{GAP}} = \frac{P'_{\text{GAP}}}{P_{\text{RAD}}} \quad (25)$$

#### 4.2.4 Photovoltaic cell

Power entering the photovoltaic cell:

$$P_U = P_{\text{GAP}} - P_{\text{loss}} = P'_{\text{GAP}} - P_{\text{loss}} - P_{\text{abs}} \quad (26)$$

$P_{\text{abs}}$  are often neglected.  $P_{\text{loss}}$  is the power loss from the optical filter to the photovoltaic cell when the spectral power passes through it.

The power from the photovoltaic cell is defined as the electrical power:

$$P_{\text{el,dc}} = V_{\text{OC}} \times I_{\text{SC}} \times \text{FF} \quad (27)$$

$$V_{\text{OC}} = \frac{k_b T_{\text{em}}}{e} \cdot \ln\left(\frac{I_L}{I_0} + 1\right) \quad (28)$$

$$I_{\text{SC}} = e \cdot \int_0^\infty \Phi(\lambda) \text{EQE}(\lambda) d\lambda \quad (29)$$

where EQE ( $\lambda$ ) is the external quantum efficiency and is the photon probability value of the wavelength absorbed by the cell.  $\Phi(\lambda)$  is the photon flux.

Visibility factor efficiency is the spectral ratio of the power entering the photovoltaic cell:

$$\eta_{\text{VF}} = \frac{P_U}{P_{\text{GAP}}} \quad (30)$$

The efficiency of photovoltaic cell is the ratio of the electrical power to the photovoltaic cell:

$$\eta_{\text{PV}} = \frac{P_{\text{el,dc}}}{P_U} \quad (31)$$

The electrical current from the photovoltaic cell is the linear current. The linear current is converted by means of an alternating current transformer.

The electrical exergy of the system is expressed as follows:

$$EX_{\text{electrical}} = V_{\text{oc}} \times I_{\text{sc}} \quad (32)$$

The alternating current efficiency of the system is expressed as follows:

$$\eta_{\text{dc/ac}} = \frac{P_{\text{el,ac}}}{P_{\text{el,dc}}} \quad (33)$$

The overall electrical efficiency of the TPV system is equal to the product of the above stated efficiencies:

$$\eta_{\text{EL,TPV}} = \eta_{\text{CC}} \cdot \eta_{\text{RAD}} \cdot \eta_{\text{GAP}} \cdot \eta_F \cdot \eta_{\text{VF}} \cdot \eta_{\text{PV}} \cdot \eta_{\text{dc/ac}} \quad (34)$$

#### 4.2.5 Cooling system

The formulas for the part where the electric energy we have defined as the third region is stored, and where the cooling system is located as follows.

The TPV generator is based both on the cooling circuit of the PV cells and on the heat recovery:

$$Q_{\text{TH,HX-PV}} = (1 - \eta_{\text{PV}}) \cdot P_U \quad (35)$$

$$Q_{\text{TH,HX-CP}} = \epsilon \cdot \eta_{\text{cc}} \cdot (1 - \eta_{\text{RAD}} \cdot \eta_{\text{GAP}}) \cdot P_{\text{in}} \quad (36)$$

The thermal exergy of the system is shown as follows:

$$EX_{\text{thermal}} = \left(1 - \frac{T_a}{T_c}\right) \times (h_c \times A_c \times (T_c - T_a)) \quad (37)$$

In systems where heat and power coexist (CHP) systems, TPV yield is expressed as follows.

#### 4.2.6 General TPV efficiency

$$\eta_{\text{CHP,TPV}} = \eta_{\text{EL,TPV}} + \eta_{\text{TH,TPV}} \quad (38)$$

$$\eta_{CHP,TPV} = \eta_{cc} \cdot [\eta_{RAD} \cdot \eta_{GAP} \cdot \eta_F \cdot \eta_{VF} \cdot \eta_{PV} \cdot \eta_{dc} + \varepsilon \cdot (1 - \eta_{RAD} \cdot \eta_{GAP} + (1 - \eta_{RAD}) \cdot \eta_{GAP} \cdot \eta_F \cdot \eta_{VF})] \quad (39)$$

The exergy efficiency of the system can be expressed as follows:

$$\eta_{ex,TPV} = \frac{EX_{output}}{EX_{input}} = \frac{Vm \cdot Im - \left(1 - \frac{T_a}{T_c}\right) \cdot (h_{ca} \cdot A_c \cdot (T_c - T_a))}{\left[\left(1 - \frac{T_a}{T_s}\right) \cdot I_s\right] \cdot A_c} \quad (40)$$

## 5 TPV APPLICATIONS IN IRON AND STEEL INDUSTRY

Since TPV is a technology that requires a heat source with a high temperature, it can be used in industries where a process is run in such a case. A simple application of TPV is waste heat recovery in high temperature industries such as glass or steel industry. An example of waste heat recovery through a TPV cell is the continuous casting of hot-rolled steel plates in the steel industry. The starting temperatures of these plates are cooled to a temperature of 1200°C and lower than 1000°C. If the TPV cells are to be placed on hot plates during the cooling process, an electric current can be generated by the emission process [18]. A mathematical model has been implemented to demonstrate the effect of TPV application in the steel industry. The model verified the experimentally measured data. Supporting the experimental

measurements proved the applicability of the model to the assessment of energy recovery in the steel industry [18]. In the process of steel production, a large amount of waste heat comes into play. This necessitates assessment of waste heat. Utilizing waste heat, it is possible to generate electricity by means of photovoltaic cells.

It has been determined that TPV applications in the iron and steel sector in Turkey can provide energy efficiency. In the iron and steel industry, it has been determined that the annual TPV systems have a recoverable energy potential of 11.44 TJ, 2.04% for energy efficient GaSb-cell TPV systems and 7.31% for InGaAsSb-cell TPV systems [4, 19]. It is more appropriate to apply waste heat, TPV applications from industrial areas because the waste heat amount obtained from the iron and steel industry is higher and the steel products are more recycled in machinery, construction, automotive sector and electrical products.

In our work, a theoretical model was used for industrial systems. This model is designed to be used in the iron and steel industry and to evaluate waste heat from this sector. Figure 4 shows a schematic picture of energy conversion when the TPV system is applied in the iron and steel industry.

In practice, GaSb and InGaAsSb cells were used as photovoltaic cells. The energy band gap, cell area, acceptor density and donor density were taken as the cell parameters. The variation of the band intervals was calculated and the yield was evaluated. The constant parameters at 300 K cell temperature used in the calculations are given in Table 3.

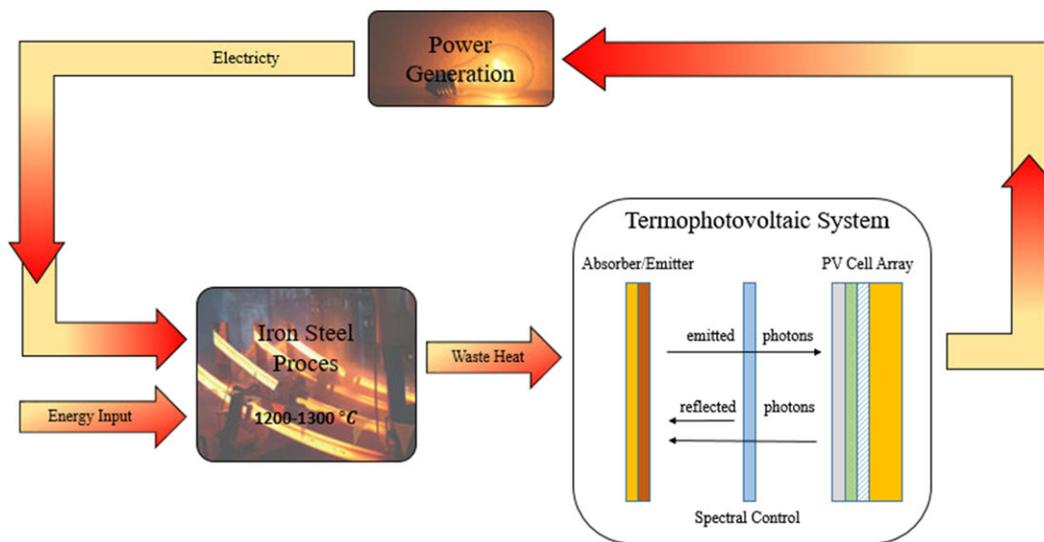


Figure 4. Energy recycling by TPV application in the iron and steel sector.

Table 3. Constant cell parameters [4, 19].

	$E_g$ (eV), energy band gap	$S$ (cm <sup>2</sup> ), cell area	$X$	$N_a$ (cm <sup>-3</sup> ), acceptor density	$N_d$ (cm <sup>-3</sup> ), donor density	$I_0$ (A)
GaSb	0.72	1	0.78	$5 \times 10^{19}$	$2 \times 10^{18}$	$1.26 \times 10^{-10}$
In <sub>0.2</sub> Ga <sub>0.8</sub> As <sub>0.18</sub> Sb <sub>0.82</sub>	0.555			$2 \times 10^{19}$		$1.91 \times 10^{-7}$

**Table 4.** Power values returned to the cell and reflected from the cell due to the radiator temperature.

$T_{\text{rad}}$ (K)	1256	1473	1973
GaSb			
$P_{\text{ret}}$ (W/m <sup>2</sup> )	9.96	17.27	42.90
$P_{\text{inc}}$ (W/m <sup>2</sup> )	10.97	20.75	66.80
InGaAsSb			
$P_{\text{ret}}$ (W/m <sup>2</sup> )	8.1	13.23	33.03
$P_{\text{inc}}$ (W/m <sup>2</sup> )	10.97	20.75	66.80

At 1256 K radiator temperature, 300 K cell temperature and under ideal conditions, TPV system efficiencies were calculated to be 22.17% for GaSb cells and 27.96% for In<sub>0.2</sub>Ga<sub>0.8</sub>As<sub>0.18</sub>Sb<sub>0.82</sub> cells. While system efficiency is achieved by the absorbed energy ratio of the generated energy, the energy efficiency is calculated by the overall recoverable energy ratio of the generated energy. Therefore, displaying similar images of system efficiencies does not reflect energy efficiency results, energy efficiency is calculated as 2.04% in GaSb-cell TPV systems and 7.31% in In<sub>0.2</sub>Ga<sub>0.8</sub>As<sub>0.18</sub>Sb<sub>0.82</sub> cell TPV systems.

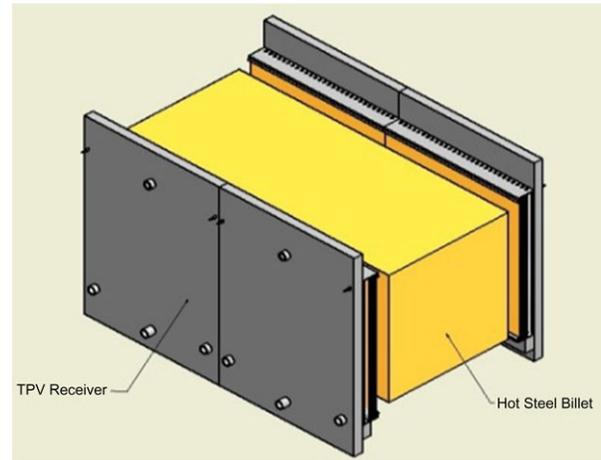
The variation of the band spacing of GaSb and In<sub>0.2</sub>Ga<sub>0.8</sub>As<sub>0.18</sub>Sb<sub>0.82</sub> cells with temperature is calculated as given in the following equations [4, 19]:

$$E_g(\text{GaSb}) = 0.7276 - (3.990 \times 10^{-4})(T - 300) \quad (41)$$

$$E_g(\text{In}_{0.2}\text{Ga}_{0.8}\text{As}_{0.18}\text{Sb}_{0.82}) = 0.5548 - (1.952 \times 10^{-4})(T - 300) \quad (42)$$

It has been shown that in the study of observing changes in yields under normal conditions, in the case of warming and cooling of the cell, while the possibility of warming the cells in case the temperature of the selective emitter and the filter-passing large assemblies or working environment is higher than the room temperature, the efficiency decreases in case of increasing cell temperature [4, 19]. In case of using ideal selective spreaders and filters for cell types we use in TPV systems, the power values that are reflected and reflected to the cell surface depending on the source temperatures are given in Table 4.

For the theoretical calculations, we will use steel logs for calculations in the dimensions of 0.16 m × 0.16 m and 5.6 m in length and equal to 1 MT. In terms of Turkey's steel production, the year 2014 production totalled 34.04 million metric tons. If we calculate it as hourly production, this value is equal to ~3940 pieces. If we assume that the TPV module area is applied along the length of 0.15 m × 0.15 m and 5.6 m, this will give us an area of 6619.2 m<sup>2</sup> if the TPV module schematically shown in Figure 5 is placed on both surfaces of the TPV module logs. GaSb termofotovoltaic cells produce a power of 1 W/cm<sup>2</sup> when exposed to high-infrared radiant energy. When we calculate together with the field value we find, we can say that the recoverable power of the waste heat energy potential in the Turkish iron and steel industry is ~66 192

**Figure 5.** Four planar TPV modules placed on two layers of steel [20].

MW. If we use InGaAsSb cell instead of GaSb in the calculations, the produced power is 2.87 W/cm<sup>2</sup>. In this case, the total generated power will be ~189 971 MW.

## 6 CONCLUSION

Assessment of waste heat in industrial systems will provide both energy and cost savings. In this study, industrial waste heat is restored to the system with TPV system. The TPV system is a system that converts thermal energy into electrical energy. In our study, selective emitter, filter, photovoltaic cell and cooling system which constitute the TPV system were analyzed separately and energy and exergy analysis were performed. Our work is supported by formulas. The energy analysis is solved by the first law of thermodynamics while the exergy analysis is performed by the second law of thermodynamics.

The TPV system was evaluated by dividing into three parts by this induction method. The first region is the thermodynamic analysis of the energy heat source up to the radiation and the filter. For this region, heat source energy and general analysis are done. The second region is the region where the filter, selective emitter and photovoltaic cells, considered as photovoltaic systems, take place. For these regions, formulas were created by analyzing energy and exergy of each system element. The third zone, which is expressed as the last zone, is considered to be the zone where electric energy is stored. In the third part, thermal exergy analysis is included in the cooling system. In the last part, general energy and exergy analysis and efficiency analysis of the TPV system have been done.

TPV application was made on the industrial steel industry. Utilizing this industry's high-temperature waste heat, which has a significant share in Turkey, electricity is generated. Waste heat source, selective spreader, filter and cell are necessary for electricity production. These cells absorb photons from the emitter and convert them into thermal energy electrical energy. In the study, the effects of cell temperature, cell type, radiator

temperature parameters on cell efficiency were examined in TPV systems.

The main conclusions drawn from present study may summarize as follows:

- The  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}_{0.18}\text{Sb}_{0.82}$  cell has a higher efficiency compared to the GaSb cell at the same source temperature. This is because the reverse saturation current and the energy band gap are low and the short-circuit current is high.
- The effects of high temperature waste heat sources, different cell structures and other cell parameters emitted from iron-steel processes on energy conversion in TPV energy conversion systems are calculated.
- If TPV systems are applied for waste heat energy potential in the Turkish iron and steel industry, the energy efficiency of GaSb cell systems is 66 192 MJ per year with energy efficiency of 2.04%, the energy efficiency of  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}_{0.18}\text{Sb}_{0.82}$  cell systems is 7.31% with annual energy efficiency of 189 971 MJ can be recovered.
- This application can reduce the amount of fuel burned at the same time while generating electricity within the iron and steel sector, and can also prevent environmental pollution.
- TPV systems have the two most important advantages of today's widely used PV systems; the first of these is that cells have higher power density by producing more efficient electricity due to the different band spacing.
- Another advantage is that although PV systems can only use the sun for 8 h a day, TPV systems can generate electricity for 24 h in continuous processes such as iron-steel.
- At the end of, the project is a theoretical and the formulas are obtained by analyzing the energy and exergy of each component.
- It has been determined that TPV applications in the direction of the obtained data can be applied to industrial systems, provide energy efficiency and provide an alternative to electricity production.

## ACKNOWLEDGEMENTS

This study was produced from the project 114R088 which is carried out within the scope of The Scientific and Technological Research Council of Turkey (TUBITAK) 1001 from the project titled 'Development of Electricity Energy Production Technology by Thermophotovoltaic Methods Utilizing Existing Waste Heat Potential in Thermal Systems'. We would like to thank TUBITAK for their support to the Project.

## REFERENCES

- [1] Utlu Z, Hepbasli A. Assessment of the Turkish utility sector through energy and exergy analyses. *Energy Policy* 2007;**35**:5012–20.
- [2] Yıldıran İN, Öner SD, Cetin B *et al.* (2016). *Gpu Computing Of 2-D Laplace Equation Using Boundary Element Method*.
- [3] Utlu Z, Hepbaşlı A. A review and assessment of the energy utilization efficiency in the Turkish industrial sector using energy and exergy analysis method. *Renew Sust Energy Rev* 2007;**11**:1438–59.
- [4] Utlu Z. Investigation of the potential for heat recovery at low, medium, and high stages in the Turkish industrial sector (TIS): an application. *Energy* 2015;**81**:394–405.
- [5] Steinhüser A, Hille G, Kügele R *et al.* (1999). Photovoltaic-Hybrid Power Supply for Radio Network Components. In: *Proceeding of the Intelec'99*, Copenhagen, 6–9 Juni.
- [6] Lodhi M, Vijayaraghavan P, Daloglu A. An overview of advanced space/terrestrial power generation device: AMTEC. *J Power Sour* 2001;**103**:25–33.
- [7] Bauer T, (2001). Chapter 3. Overview of the technology. In: *Thermionics Quo Vadis, An Assessment of the DTRAs Advanced Thermionics Research and Development Program*, National Academy Press, pp. 15–32. USA [Online] <http://books.nap.edu/>.
- [8] Volz W. (2001). Entwicklung und Aufbau eines thermophotovoltaischen Energiewandlers (in German). *Doctoral Thesis*. Universität Gesamthochschule Kassel, Institut für Solare Energieversorgungstechnik (ISET).
- [9] Fraas LM, Avery JE, Huang HX *et al.* Thermophotovoltaic system configurations and spectral control. *Semicond Sci Technol* 2003;**18**:165–73.
- [10] Horne E. (2002). Hybrid thermophotovoltaic power systems. EDTEK, Inc., US. *Consultant report*, P500-02-048F.
- [11] Yamaguchi H, Yamaguchi M. (1999). Thermophotovoltaic potential applications for civilian and industrial use in Japan. In: *Proceeding of the 4th NREL Conference on Thermophotovoltaic Generation of Electricity*, Denver, Colorado, 11–14 October 1998. American Institute of Physics, pp 17–29.
- [12] Schubnell M, Benz P, Mayor JC. Design of a thermophotovoltaic residential heating system. *Solar Energy Mater Solar Cells* 1998;**52**:1–9.
- [13] Xuan Y, Chen X, Han Y. Design and analysis of solar thermophotovoltaic systems. *Renew Energy* 2011;**36**:374–87.
- [14] Bitnar B, Durisch W, Holzner R. Thermophotovoltaics on the move to applications. *Appl Energy* 2013;**105**:430–8.
- [15] Xu X, Ye H, Xu Y *et al.* Experimental and theoretical analysis of cell module output performance for a thermophotovoltaic system. *Appl Energy* 2014;**113**:924–31.
- [16] Ferrari C, Melino F, Pinelli M *et al.* Overview and status of thermophotovoltaic systems. *Energy Procedia* 2014;**45**:160–9.
- [17] Daneshvar H, Prinja R, Kherani P. Thermophotovoltaics: fundamentals, challenges and prospects. *Appl Energy* 2015;**159**:560–75.
- [18] Shoaie E. Performance assessment of thermophotovoltaic application in steel industry. *Solar Energy Mater Solar Cells* 2016;**157**:55–64.
- [19] Utlu Z, Parali U. Investigation of the potential of thermophotovoltaic heat recovery for the Turkish industrial sector. *Energy Convers Manag* 2013;**74**: 308–22.
- [20] Fraas ML. (2014). In: *40th IEEE Photovoltaic Specialists Conference Colorado Convention Center*. pp. 5–12.