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Recent Development of Thermophotovoltaic System for Waste Heat Harvesting Application and Potential Implementation in Thermal Power Plant

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ABSTRACT Rapid depletion of fossil fuels due to the growing demand for energy has resulted in a worldwide concern to improve energy conversion efficiency. Yet, the energy conversion of conventional fossil fuel power generation plants remains relatively low (less than 40%) and a huge amount of energy is wasted in the form of heat, leading to global warming issues. Recycling and recuperating even a small portion of energy losses could provide a huge impact on energy saving and minimize the reliance on fossil fuels. Thermophotovoltaic system appears to be a potential candidate to capture, recover, and convert waste heat energy into useful electricity. This paper presents an overview of the recent development of thermophotovoltaic technology for waste heat recovery applications. Each component in the thermophotovoltaic system including thermophotovoltaic generator/heat source, thermal emitter, spectral filter and thermophotovoltaic cells is vital and can be engineered to achieve a better heat-to-electricity conversion efficiency. Recently, researchers have shown great interest in near-field thermophotovoltaic systems where higher power intensity can be captured by the thermophotovoltaic cell, thus improving the overall system performance. Furthermore, the potential locations for energy scavenging in thermal power plants is investigated based on the on-site temperature measurement. In Malaysia, it is estimated that around 3,831 GWh of waste heat energy could be saved in operational thermal power plants. This review will contribute to the knowledge for future development thermophotovoltaic systems in waste heat recovery applications while summarizing the potential locations for energy scavenging in thermal power plants.

INDEX TERMS Thermal power plant, thermophotovoltaic, waste heat recovery.

I. INTRODUCTION

Fossil fuels are nowadays the primary source of energy for human activities and have been a driving force behind the global economic development for past centuries. Despite their great contributions, fossil fuels are limited in supply and may be entirely depleted in the future [1], [2]. According to Intergovernmental Panel on Climate Change (IPCC), the burning of fossil fuel for electricity generation accounts for 65% of global greenhouse gas emissions in 2014, leading to catastrophic changes in the global climate [3]. Therefore, reducing the reliance on fossil fuels is the key survival for the Earth while sustaining the energy supply chain.

There are two possible approaches to minimize the redundant use of fossil fuels, which are improving the energy conversion efficiency or employing renewable energy alternatives. To date, the electricity generation industries

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particularly fossil fuel-fired power generation suffer from energy conversion losses due to the complexity of energy conversion processes from chemical energy to electrical energy. The overall efficiency of a modern fossil fuel-fired power generation plant achieves only around 40% and could be as low as 30% for an older power plant [4]. This means that more than 60% of the energy input is released as waste heat at the output. The recovery of this huge amount of waste heat can substantially improve the efficiency of useful energy.

Although the current state-of-art recovery technologies such as combined heat power, economizers and recuperators are known to enhance the overall efficiency, there is still a large proportion of waste heat that these devices are unable to recover. In particular, the waste heat is released in the form of radiation from the surface of the hot equipment to the ambient environment thus reducing the overall energy efficiency of the power generation process. In this regard, thermophotovoltaic (TPV) device is a viable solution that can improve the energy conversion efficiency by converting the otherwise wasted radiant energy into useful electricity.

In this study, recent development of the TPV system for waste heat recovery applications is comprehensively reviewed. To date, the potential waste heat recovery implementation in thermal power plants using TPV technology has not been explored. Therefore, this study will identify the potential locations for the integration of TPV technology at thermal power plants in Malaysia. This review will provide an insight into the future development of TPV technology, particularly for waste heat recovery applications.

II. BRIEF HISTORY OF TPV TECHNOLOGY

The field of electricity generation with TPV dates to about six decades ago. In 1956, the first invention of elementary TPV system was proposed by Dr. Henry Kolm at Massachusetts Institute of Technology's (MIT) Lincoln Laboratory, in which an incandescent gas mantle was used as the emitter on a silicon solar cell photovoltaic converter with a conversion efficiency of 5-10% [5], [6]. In the consecutive year, Professor Pierre Aigrain disclosed the TPV concept during his series of lectures at MIT, leading to a substantial amount of research efforts in this area [6]. During the early development stage, United States Army Research had focused on TPV technology for low-noise, standalone military power generators [7]. Additionally, General Motors Defense Research also played a significant role in the early development of the TPV technology for the research on spectral control using photoconverter back surface reflector. However, both research bodies discontinued the research in TPV due to insufficient advancement and economic crisis in the mid of 1970s.

The resurgence of TPV technology in 1989 is attributed to the development of solar tandem cells [8]. Gallium antimonide (GaSb) TPV cells were placed at the bottom cell, recording a conversion efficiency of 32%. At the end of the 1990s, Yamaguchi and Yamaguchi [9] demonstrated the first TPV technology for Japan civilian and industrial waste heat applications. Further analysis on the large-scale waste heat recovery application using TPV technology was presented by Coutts [10]. Coupled with the basic research on the near-field TPV, the TPV technology for industrial waste heat recovery application has received tremendous attention ever since. An advantage of implementing TPV technology in this area is that the heat energy is freely available in steady condition [2]. Examples of the potential industries for waste heat recovery are glass manufacturing [11], iron and steel making [12]–[14] and vehicle battery [15], [16].

III. TPV SYSTEM FOR WASTE HEAT RECOVERY APPLICATION

A TPV system converts thermal energy directly into electrical energy. The TPV system operates silently with a low maintenance rate since the electricity is generated without any mechanical or moving parts. A TPV system is composed of a TPV generator/heat source, thermal emitter, spectral filter and arrays of infrared-sensitive photovoltaic cells, which is also known as TPV cells. Fig. 1 illustrates the schematic diagram for the energy conversion of a complete TPV system.

The thermal emitter is heated up by a TPV generator or an external thermal energy source that can be harvested from solar radiation, combustion of hydrocarbon fuels or industrial waste heat [17]. The spectrum that matches the TPV cell spectral sensitivity is further channeled to a spectral filter, while others will be reflected or re-emitted back into the heat source. Next, the spectral filter only allows convertible photons to pass through in order to maximize the photon absorption by the TPV cell. Finally, the TPV cell captures the photons and converts them into electrical energy via the photovoltaic effect.

Although significant progress has been made in the last decade, coordination of multiple components in a TPV system is the main challenge for achieving a high-performance TPV system. This is mainly due to the optical and electrical losses within the system [18]. In principle, the energy of photons must be larger than the bandgap energy of the TPV cells to allow maximum electron-hole pair generation. However, some photons in the spectrum may not be absorbed by the TPV cell. Contrarily, these photons are reflected to the emitter thus causing optical losses to the system. There are two methods that have been widely considered to reduce optical losses of the system. These methods include the incorporation of selective emitter with large emittance for photon energies less than the bandgap energy or using a selective filter.

Meanwhile, the electrical losses are directly related to the electrical characteristic of the TPV cell. The TPV cell can be regarded as the core component of a TPV system since it is the component responsible for converting the thermal radiation into electrical energy. Hence, researchers have been focusing on improving the TPV cell configuration to maximize the conversion efficiency.

A. TPV GENERATOR/HEAT SOURCE

A TPV generator is often used as the heat-driven source for a TPV system. Apart from solar radiation and radioisotope,

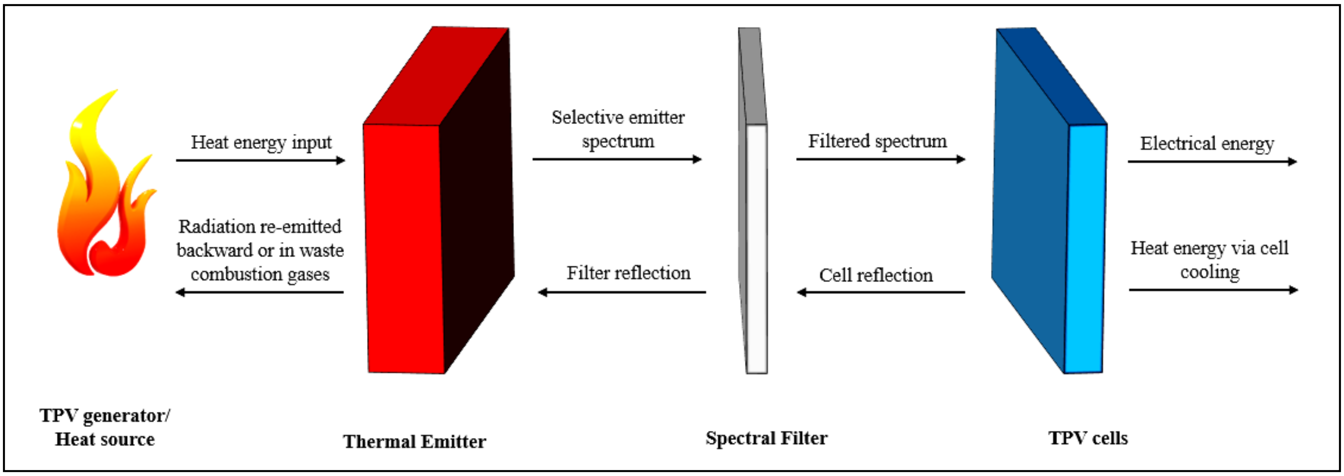

FIGURE 1. Schematic diagram of a complete TPV system.

liquid and gas fuels are employed to drive the TPV generator. These fuels are less dangerous than radioisotope radiation and the operation can be run at 24 hours per day as compared to solar radiation. Among the typical fuels used are oil [19], butane [20], [21], propane [22], [23], methane [24] and hydrogen [25]–[27]. In order to achieve a complete combustion process, a microscale combustor is considered to be a good approach. The microscale combustion was reviewed for the generator in a combustion driven TPV system [28]. In contrast to conventional combustor, microscale combustor shows more complete combustion and higher heat transfer rate [29]. Nevertheless, the main challenge of the microscale combustor compared to a conventional combustor is the high dependency on heat recirculation. Therefore, more effort is spurred to improve the recuperation of potential burning element inside the microscale combustor such as unburned mixture and heat loss to the ambient. For instance, the installation of a heat recuperator inside the microscale combustor recirculates the exhaust gas to pre-heat the fresh fuel-air mixture [30]. This provides a more uniform and higher combustor wall temperature than the design without the heat recuperator, hence significantly increases the electrical power of TPV system.

Other heat sources such as industrial waste heat with a typical working temperature lower than that of a TPV generator can be harvested directly by the thermal emitter. Moreover, implementing a TPV system to industrial waste heat maximizes the industrial energy efficiency. The Wien's law equation determines the peak wavelength (λ_p) of a particular blackbody temperature (T), as expressed in (1) [31].

$$\lambda_p = (\mu m) = \frac{2900}{T} \tag{1}$$

Equation (1) implies that when the blackbody temperature decreases, the peak emission spectrum is shifted towards longer wavelengths. Due to this circumstance, a narrow bandgap semiconductor material is desirable to operate under industrial waste heat temperatures. The bandgap energy of a semiconductor material determines the minimum amount of photon energy required to excite an electron in the lattice. Further discussions are made in the Subsection D.

B. TPV EMITTER

The main function of an emitter in a TPV system is to transform the heat energy from the main source into emission spectrum of photon energies which matches the TPV cell spectral sensitivity. The TPV emitter is often dubbed as the radiator, which has a temperature range typically between 800 K and 1300 K depending on the heat source temperature [32], [33]. In contrast to a conventional solar cell that exposed to solar visible spectrum, TPV emitter operates at temperature only up to 1800 K in which the radiation spectrum shifts towards infrared region of the electromagnetic spectrum [33]. Broadband and selective emitters are two types of emitters widely employed in TPV applications. A broadband emitter serves according to Plank's law equation expressed in the following equation [34]:

$$L_{e,\lambda} = \frac{2\pi hc^2}{\lambda^5 \left[exp^{\left(\frac{hc}{\lambda kT}\right)} - 1 \right]} \tag{2}$$

Equation (2) computes the spectral intensity (W/m^2/nm) of multispectral sources, where h, c, λ, k, and T are the Planck constant, speed of light in vacuum, wavelength, Boltzmann constant, and temperature, respectively. This indicates that the broadband emitter established emission of photons across wide range of wavelengths. Whereas, selective emitters are engineered to emit photons in a selective wavelength window [35]. Fig. 2 shows a comparison between broadband and selective emitters.

The selective emitters were generated with several techniques; grating structures using micro/nano-scale fabrication technique [36], magnetic polaritons [37], and metamaterials such as (i) epsilon-near zero [38], (ii) passivated platinum and alumina [17], and (iii) alternate tungsten and alumina [39]. There are several types of selective emitters that have been discussed in the literature, which are silicon carbide (SiC) [7], tungsten (W) [40], rare-earth oxide [6], and photonics crystal (PhC) [41], [42]. Among the selective

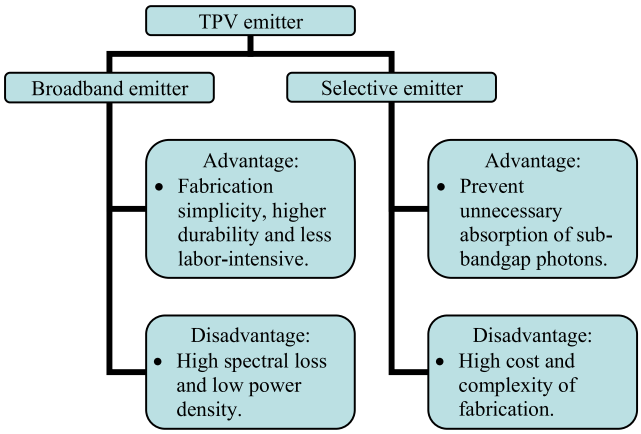

FIGURE 2. The comparison between broadband and selective TPV emitters [33], [35].

emitters, rare-earth oxide is an isolated ion, serves as the most popular candidate for selective emitter. This rare-earth oxide possesses the 4f shell valence electron, shielded by the 5s and 5p electrons from environmental effect, thus the valence electron is strongly localized by the attractive force of the nucleus [1]. Therefore, the rare-earth ions in the solid state have radiative characteristics rather than being isolated [43]. These ions behave like gaseous atom and emit line spectrum, instead of continuous spectrum [35]. The line spectrum is attractive for the selectivity of the rare-earth oxides.

In waste heat recovery application, research efforts have been devoted to narrow down the emitter spectrum to a selective wavelength either by using a microstructured surface or metamaterial emitter through doping and alloying processes [44]. Examples of widely used material for the selective emitters are rare-earth oxide, tungsten, and special metal photonic crystals. Bendelela *et al.* [45] proposed a TPV system incorporating a selective metamaterial as the selective emitter. With the combination of InAs/GaInAsSb TPV tandem cell, 41% and 11.82% conversion efficiencies were recorded for a blackbody temperature of 1500 °C and 300 °C, respectively. Zhao *et al.* [46] demonstrated a great potential of integrating indium tin oxide plasmonic emitter with InAs narrow-bandgap cell for TPV near-field waste heat recovery application. Through detailed balance analysis, Zhou reported up to 40% TPV system efficiency with a power density of 11 W/cm^2 at 900 K emitter temperature.

Near-field TPV system is advantageous for waste heat recovery application, where an emitter is placed at a sub-micron distance with a TPV cell. The near-field regime allows significant amount of radiative heat transfer received by the TPV cell, resulting in higher power density output of the system [45]–[47]. Thompson *et al.* [48] studied the effect of gap distance between an emitter and InAs-based TPV cell on the system power output. The emitter temperature and gap distance were studied in the range of 525 K to 625 K and 12 μm to 60 nm, respectively. Thompson concluded that the TPV system with a nanoscale gap distance performs much better than that of far-field TPV system, where an ~40-fold enhancement on the output power was recorded. Vongsoasup *et al.* [49] investigated the effect of incorporating near-field TPV system consists of a hyperbolic metamaterial 2D grating tungsten radiator disconnected by a cavity thickness varying between 100 nm and 500 nm from a gallium antimonide (GaSb) TPV cell. Based on the findings, the integration of this radiator in near-field TPV system improves the absorption of the cell and maximizes both power output and conversion efficiency.

Zhao *et al.* [47] proposed a new thermophotonic light-emitting diode (LED) to replace the conventional thermal emitter positioned next to the heat source. The LED can boost the radiative transfer and potentially yields higher power densities compared to the utilization of a passive thermal emitter. Despite the LED consumes the electrical power from the PV cell, the power of the electroluminescence can be higher than the consumed electric power because the LED also extracts the thermal energy to produce photons. Zhao concluded that this approach would be a great potential for waste-heat recovery applications.

In 2019, an assessment of the practicality of emitters for TPV application was conducted by Sakakibara *et al.* [50]. The assessment was based on five crucial metrics of the emitter characteristics that are excellent optical performance, ability to scale to large areas, high-temperature stability, ability to integrate into a system, and low production cost. The development progress on TPV emitter is projected to be rapidly increased over the years. Achieving these quality characteristics are important for developing high-performance TPV systems.

C. TPV FILTER

The integration of a selective filter into TPV system offers an advantage in terms of spectral shaping and control of the spectral emission received from the emitter. Tailoring down the excessively high photon energies to a range slightly above the TPV cell bandgap energy may reduce the thermalization losses and therefore enhance the cell conversion efficiency [32], [50], [51]. Therefore, the filter will only allow convertible photons to pass through while reflecting the non-convertible photons that deteriorate the cell performance. Notably, the selective filter is useful for a TPV system that consists of a broadband emitter. On the other hand, the use of filter to promote photon recycling from a selective emitter is optional. Nevertheless, lots of research works had considered the integration of a TPV filter in the TPV system to enhance the overall performance. This enhancement is proven with an increment in a factor of 5 using an ideal selective filter of 100% reflectance. By reflecting the non-convertible photons back to the emitter, the infrared radiation losses are reduced and the thermal emitter is reheated, resulting in a better cell performance [21]. Moreover, when a highly idealized filter was applied to a TPV cell with absorber layer having a bandgap energy of 0.9 eV, Catchpole *et al.* [52] reported that up to 99.7% of the emitted photons with energies higher than the bandgap energy were absorbed.

The spectral control of a filter was reviewed by Coutts *et al.* [35] with three types of filter; plasma filter, back-surface reflector and resonant filter array. They claimed that when a plasma filter is paired with a dielectric edge filter, the latter reflects photons in the range of plasma wavelength of around 3 μm. A back surface reflector should have high reflectivity and conductive substrate to minimize contact resistance but not significantly influencing the optical absorption. Then, the resonant filter array implements inductive resonance of metal film-based bandpass filters with nearly 100% reflectance at wavelength more than 2 μm. Similarly, Tong *et al.* [53] proposed that the utilization of intermediate frequency filters such as rugate filter, PhC filter, and plasma reflector recycle the low energy photons back to the emitter. Bitnar *et al.* [54] numerically proposed that the replacement of quartz filter by an IR reflective filter under higher emitter temperature results in a 10% increment of electrical power. Quite recently, Omair *et al.* [55] reported an InGaAs (0.75 eV) TPV cell efficiency of approximately 29.1% using band-edge spectral filtering under an emitter temperature of 1207 °C. They implemented a rear reflector to reflect low-energy photons back into the heat source. Compared to a cell efficiency of 15.4% for a typical GaSb (0.72 eV) TPV cell at an emitter temperature of 1260 °C [56] without spectral filtering, this improvement is considered significant.

Other than that, more filters are demonstrated with the functions for increased spectral and system efficiencies, wider filtered bandwidth, higher emission power for the selective emitter, energy emission recycling and spectral control [17], [57], [58], [59], [60]. Previous studies have been focusing on designing TPV filters for high-temperature heat sources [42], [50], [51], [60]. However, a thorough investigation of the TPV filter that operates at waste heat temperature still falls short.

D. TPV CELLS

The selection of TPV cell material relies on the heat source temperature of the system. The TPV cells operate at the optimum efficiency by spectrally matching the TPV cell energy bandgap (E_g) to the emitter spectrum generated by the heat source. In this regard, narrow-bandgap semiconductor of III-V materials is widely employed to fabricate the TPV cell due to the capability of absorbing photons in the infrared region. A typical semiconductor E_g suitable for TPV application is between 0.3 and 0.8 eV. Such a range of bandgaps corresponds to relatively unfamiliar materials such as Gallium Antimonide (GaSb), Indium Arsenide (InAs), Indium Gallium Antimonide (InGaAs), and many more.

For decades, many research efforts have been focused on GaSb-based materials [61]–[64]. In 2014, Fraas *et al.* [13] successfully demonstrated a GaSb TPV cell with power density output of 1.5 W/cm^2 per cell generated from a hot glowing radiant tube burner (1275 °C). The finding estimated a potential of over 3.1 GW worldwide electricity production with TPV heat recovery system in steel industry. Nevertheless, advances in semiconductor materials encourage researchers to explore different kinds of materials as the TPV cells for low-temperature operation with waste heat sources.

Krier *et al.* [65] demonstrated that $InAs_{0.6}Sb_{0.13}P_{0.26}$/InAs heterojunction device with cut-off wavelength of 3.75 μm can operate under a radiator temperature as low as 345 °C. Following Krier's work, Lu *et al.* [66] reported a cell conversion efficiency of 3.6% with fabricated InAs TPV cells under 950 °C radiation temperature. It was suggested that InAs material can be used as an intermediate layer in a multi-junction TPV cell. Meanwhile, the bandgap of InGaAs TPV cell can be engineered to match the spectrum generated from a low temperature waste heat source. Ming *et al.* [67] investigated on InGaAs-based TPV cells with bandgaps ranging from 0.6 eV to 0.74 eV under 1323 K temperature. Cell efficiencies of 19.1% and 16.4% were reported for (0.6 eV) $In_{0.68}Ga_{0.32}As$ and (0.74 eV) $In_{0.53}Ga_{0.47}As$ TPV cells, respectively. Despite the lattice-mismatch problem is a concern for InGaAs material [68], MIM InGaAs TPV cell can be a potential candidate to harvest low temperature waste heat sources.

Lofti *et al.* [69] investigated an interband cascade TPV consist of InAs, GaSb and AlSb semiconductor materials. The study proposes a new cascaded TPV cell design and demonstrates a great potential for low-temperature heat sources. This design contributes to the enhancement in photon energies for wide spectrum regime. Voznyy *et al.* [70] utilized a colloidal quantum dots as the active layer of the TPV cell. The result shows remarkable stable behavior when the cell temperature exceeds 100 °C. The cost of fabrication of TPV cells for mass production remains a big challenge. Lu *et al.* [71] proposed a metamorphic buffer layer approach to develop GaInAsSb/GaAs TPV cell for waste heat recovery applications. This approach enables high quantum efficiency while reducing the cost of mass production for waste heat recovery.

Quite recently, Li *et al.* [72] investigated bismuth telluride growth on single-crystalline Si (Bi_2Te_3/Si) under very low source temperature (207 °C) and recorded an open-circuit voltage and short-circuit current of 1.756 mV and 104.693 μA, respectively. The finding provides a possible method to harvest heat source with radiation temperatures as low as near room-temperature. Table 1 summarizes the highlights and challenges of the recent development of TPV cells for waste heat recovery applications.

Although III-V semiconductor materials have been extensively utilized, Chen *et al.* [74] claimed that a III-V semiconductor materials are prone to parasitic phonon-polariton heat transfer. which is detrimental to TPV system efficiency. Chen suggested the replacement of the III-V semiconductor materials with a non-polar semiconductor such as germanium. In contrast to Chen, Lim and associates [75], [76] demonstrated an improvement in TPV cell conversion efficiency by coupling surface phonon-polariton with multi-layered graphene and InAs. Lim's approaches enhanced the radiative heat transfer at the vacuum gap. Similarly, Wang *et al.* [77] reported a significant enhancement

TABLE 1. Recent development of TPV cells for waste heat recovery application.

Ref.	Year	Material	E_g (eV)	Temperature (ºC)	Highlights	Challenges
[72]	2020	Bi_2Te_3/Si	0.15-0.17	27-207	• Demonsrated a Bi_2Te_3/Si TPV cell by using p-type single-crystalline Si wafer. • Reported an optimal thickness of Bi_2Te_3 thin films around 310 nm.	• Absence of tunneling junction at the interface prevents generated holes to pass through, reducing the output current. • Possible defects in Bi_2Te_3 thin films.
[73]	2019	GaSb	0.72	1000	• Demonstrated a GaSb TPV prototype with ~1.5% energy efficiency under 1000 ºC. • Can be used effectively with higher waste heat temperatures.	• Low cell efficiency due to high-temperature exposure. Installation of a cooling system is needed. • The gap distance between the TPV cell and source of radiation affects cell performance.
[71]	2019	GaInAsSb/GaAs	0.53	800	• The metamorphic buffer layer approach in molecular beam epitaxy process enables high quantum efficiency and reduces mass production cost.	• Poor sidewall resistivity • Low shunt resistance
[66]	2018	InAs	0.35	500-1000	• Reported a 3.6% power conversion efficiency under 950 ºC thermal sources. • Demonstrates higher performance when lowering the cell temperatures	• Performance strongly dependent on the dark current of the TPV cell. • Limited hole charge carrier lifetime causes reduction in EQE
[69]	2017	Interband cascaded InAs/GaSb/AlSb	0.4	527	• Three-stage devices shows higher conversion efficiency as compared to two-stages that is 9.6% and 6.5%, respectively.	• High series resistance due to the sidewall leakage • Device design and fabrication need improvisation.
[70]	2016	Lead sulfide colloidal quantum dots	0.75	800	• Demonstrated a power conversion efficiency of 2.7% • Good performance stability up to 140 ºC.	• Improvement of well-passivated colloidal quantum dots films. • Elimination of less stable organic ligands.
[65]	2015	$InAs/InAs_{0.6}Sb_{0.13}P_{0.26}$	0.32	345-950	• An efficiency of 3% was recorded under blackbody temperature of 950 ºC. • Able to operate at 345 ºC when using 65 single cells in a series interconnection.	• High series interconnection resistance • Optimization of top contact electrode is needed.

of TPV performance due to surface phonon-polaritons in graphene and boron-nitride. Overall, these studies provide important insight into the effect of parasitic phonon-polariton on TPV cell performance.

Recent development in TPV cell aims to achieve higher conversion efficiency by converting low-temperature waste heat into electricity. According to the literature, numerous materials with narrow bandgap have been widely explored to find the possibilities of integrating these materials with such low-radiant energy sources. Licht *et al.* [78] reviewed on the performance of narrow bandgap materials for waste heat harvesting applications. Nevertheless, the incorporation of narrow bandgap material comes with certain challenges. For example, the dark saturation current in TPV cell is increased by narrowing down the bandgap energy due to the recombination effect across the bandgap [2]. More researches on the effect of dark current are essential to provide a better insight on the factors affecting the TPV cell performance. Other than the cell bandgap, Feng *et al.* [79] investigated the effect of near-field TPV system on the TPV cell dark current parameter. It was found that the domination of evanescent waves developed from the total internal reflection and surface polariton increases the saturation current due to radiative recombination. Hence, both of the cell bandgap and the vacuum gap distance are the tradeoffs for obtaining high performance TPV cell with low dark current.

IV. TPV IMPLEMENTATION IN WASTE HEAT HARVESTING APPLICATION

There are several approaches of implementing TPV device for the waste heat recovery application. In particular, the temperature from industrial waste heat has been reported in the range from 30 °C to 1650 °C, according to US Department of Energy [80]. For instance, Fraas *et al.* [13] demonstrated a TPV system with high power density for iron and steel industrial waste heat recovery at 1100 °C by sandwiching the TPV devices between hot steel billets to capture most of the radiant waste heat energy. Additionally, the TPV device can possibly be deployed to any semi-transparent furnace areas as well as integrating TPV cells between the hot surface and insulators in glass industries [81].

A. HYBRID TPV SYSTEM

Recently, researchers have spurred research efforts in harvesting waste heat through a hybrid TPV power generation system. The advantage of a hybrid TPV system includes exposure to high-temperature waste heat in continuous

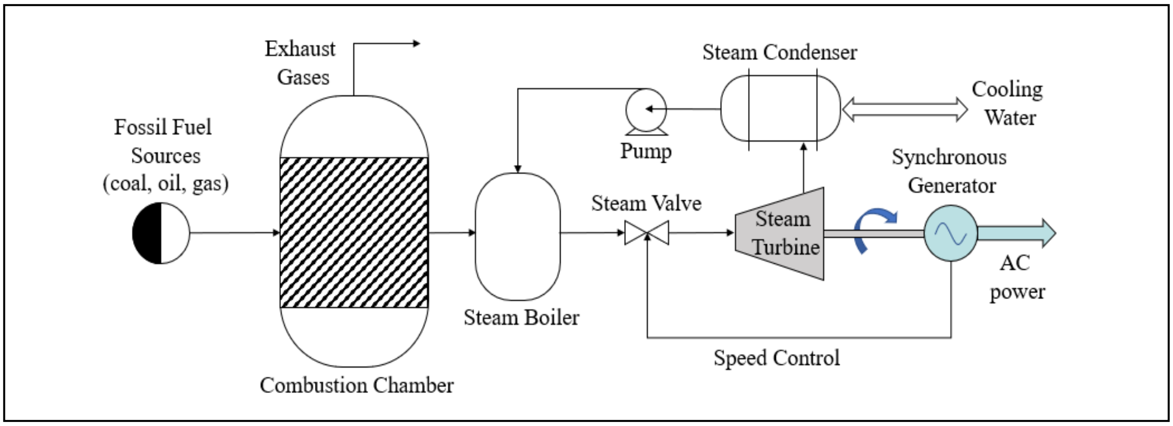

FIGURE 3. The block flow diagram of a typical fossil fuel-fired, thermal power plant.

operation with a steady condition. Thermoelectric generator (TEG), Brayton-Rankine combine cycle (TBRC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), direct carbon fuel cell (DCFC), and direct carbon SOFC (DC-SOFC) are among the reported systems which are paired with TPV system. For example, Chubb and Good [32] investigated a TPV-TEG hybrid system and found that the system generates larger output power density as compared to stand-alone TEG or TPV system. Besides, the integration of TPV system at the exhaust waste heat of SOFC outperforms other SOFC-based coupling systems [82], [83].

Nowadays, many reported hybrid TPV systems demonstrate improvement in the power output; however, to develop a high-performance hybrid system comes with several challenges. Table 2 presents the challenges in developing a hybrid TPV system.

TABLE 2. Recent development in hybrid TPV system.

Ref.	Year	Hybrid system	Operating temperature (K)	Challenges
[84]	2020	SOFC	1073	• Vacuum gap is limited to nanoscale due to the fluctuation dynamics at extreme near-field region
[85]	2019	TBRC	600 – 1000	• Expensive TPV emitter material and manufacturing
[86]	2018	DC-SOFC	1073 – 1173	• High cost of manufacturing • Challenges in fabricating efficient catalyst.
[32]	2018	TEG	~1200	• Large temperature difference between TPV and TEG system decreases the system efficiency.
[87]	2017	TEG	400 – 1400	• Performance depends on thermal characteristics (fuel-air equivalent ratio) of the burner
[88]	2017	DCFC	973	• Hybrid system performance depends on the DCFC temperature and number of slabs in DCFC
[83]	2016	SOFC	1073	• The design of SOFC current density and heat leak ratio is important to obtain high-performance hybrid system
[89]	2016	MCFC	923	• Higher operating temperature of MCFC is required to increase the hybrid system performance

B. TPV IMPLEMENTATION IN THERMAL POWER PLANT

A thermal power plant operates with the principle of Rankine cycle in a complex design system. Fossil fuels such as coal, natural gas and petroleum are the main energy sources which are exploited to translate water into steam through combustion process. The steam is generated either in a combustion engine or a boiler, depending on the fuel source. Heating the steam in a constant high-pressure condition produces superheated steam with high energy which rotates the blades of a steam turbine. This makes the steam to lose the energy and expand as the pressure is dropped rapidly. The residual steam is then reverted into water by condensation and recycled to the combustion chamber. The rotating steam turbine is connected with an electrical generator to convert the kinetic energy into electrical energy. Fig. 3 illustrates the process flow diagram of a typical thermal power plant.

Due to the complex Rankine cycle, a huge amount of energy is lost through the conversion process. The typical efficiency of power plants in developing countries remains around 32-35% [50]. Numerous studies have investigated both energy and exergy analyses to demonstrate complete magnitudes, location, and causes of losses in a thermal power plant [90], [91]. On top of that, significant assessment of individual component efficiency can also be observed. Exergy is defined as the available potential energy that is capable of doing work but degraded in the process. However, this study will emphasize only on the energy analysis. This is because a TPV system can only harvest external heat loss of the process.

Most recently, Kumar [92] published a comprehensive review on the energy, exergy, exergoeconomic and economic analysis of different types thermal power plants. Thermal

TABLE 3. Energy analysis and percent loss ratio for thermal power plants.

Ref	Type of thermal power plant	Capacity (MW)	Potential energy losses	Working temperature (°C)	Energy losses (MW)	Percent loss ratio (%)
[93]	Natural gas-fired	1000	Condenser	38	306.90	70.55
			Boiler	541	67.62	15.54
			Heaters	200.6-243.3	39.308	9.036
			Turbine	317.2-538	17.05	3.91
			Piping	n/a	4.125	0.94
[94]	Fuel oil-fired	396	Condenser	70	133.60	65.97
			Net power	n/a	53.32	26.33
			Boiler	520	12.632	6.24
			Piping	n/a	1.67	0.82
			Heaters	188.3-221	0.856	0.42
			Turbine	87.3-345.4	0.452	0.22
[95]	Coal-fired	348.5	Condenser	29.8	276	79.35
			Boiler	540.0	67	19.93
			Turbine	287.2-540.0	1.1	0.3
			Piping	n/a	0.3	0.02
			Heaters	94.3-154.6	2.0	0.4
[96]	Coal-fired	300	Condenser	38.02	356.01	49.42
			Boiler	538	62.65	8.69
			Turbine	n/a	15.29	2.12
			Heater	n/a	0.97	0.13
[97]	Coal-fired	110	Condenser	48.15	183.02	76.28
			Boiler	531	47.69	19.88
			Others	n/a	2.78	1.16
[98]	Coal-fired	200	Condenser	45.6	337.35	79.34
			Boiler	813.1	42.9	10.16
			Heaters	245-320	7.32	1.72
			Generator	n/a	4.1	0.98
			Piping	n/a	30.643	7.21
[99]	Coal-fired	300	Condenser	n/a	411.29	51.57
			Turbine output	n/a	302.976	37.99
			Turbine	n/a	20.4	2.59
			Boiler	537	52.96	6.64

power plants can be divided into four categories that are coal-fired power plants, natural gas-fired power plant, cogeneration system and combined-cycle power plants. In addition, Table 3 summarizes the potential heat loss determined from previous work based on the energy analysis on various type of thermal power plants.

The studies presented thus far provide evidence that the majority of heat loss in a thermal power plant is located at the condenser section, followed by the boiler and turbine section. The boiler section has the highest temperature, whereas the condenser normally operates at near-room temperature. Even though the condenser section contributes to major energy losses as waste heat in the thermal power plant system, the temperature condition makes any recovery technologies impossible to be deployed. In particular, TPV system recorded the lowest possible heat source temperature of 345 °C with InAs TPV cell [65]. Therefore, the studies concluded the huge potential for TPV implementation in thermal power plant which can be done at boiler and turbine section. A small portion of energy recovered from this section would be a tremendous contribution for the power plant energy conversion efficiency.

1) POTENTIAL ENERGY SCAVENGING FOR POWER PLANTS IN MALAYSIA

Electricity can be regarded as one of the most valuable forms of energy to developing countries such as Malaysia. According to The National Energy Balance 2016 [100], Malaysia recorded a total electricity consumption of 144,024 GWh with an annual growth rate of 8.9%. In particular, the electricity demand in Malaysia is driven primarily by the industry sector (47%), followed by commercial (30.8%), residential (21.6%), agriculture (0.4%) and transport (0.2%). This demand relies heavily on fossil fuel-fired thermal power plant for power generation [100].

In 2017, Malaysia recorded a total electricity generation of 128,928 GWh from 26 working power plants [100]. The types of these power plants are combined cycle gas turbine, coal plants and gas plants with total installed capacity of 9,431.43 MW, 9,066 MW, and 1,892.5 MW respectively [101]. However, the typical efficiency of power plants remains around 32% − 35% due to the complex Rankine cycle [96].

Assuming 35% of total efficiency, Malaysia's power plants generate waste energy of 239,437.71 GWh. This wasted energy can either be recovered back into the process as a pre-heating medium or reused to generate electricity through commercialized waste heat recovery technologies. Yet, there are still 80% of this waste energy will be released in the form of latent heat, conduction, convection and radiation. Even if the TPV technology can harvest only 2% of the waste energy in the form of radiation, Malaysia could save up to 3,831 GWh. Therefore, recovery of waste heat for electricity generation is crucial to improve the overall system energy efficiency.

2) WASTE HEAT TEMPERATURE MEASUREMENT AT THERMAL POWER PLANT IN MALAYSIA

A temperature measurement at the potential waste heat location in one of the coal-fired thermal power plants located in Malaysia was conducted and analyzed. It was observed that the waste heat in the form of radiations exists at the hot spot area. For instance, waste heat can be found around super critical boiler, superheated steam pipeline, air preheater, bottom ash hopper, and turbine generator building.

Infrared (IR) camera was employed to measure waste heat dissipations at the bottom ash hopper and turbine building area. While temperature measuring methods such as thermocouples, thermistors and resistance temperature detector are dangerous to operate, IR camera is safe to use since no direct contact with the hot equipment or material is needed. In addition, wider range of temperature measurement up to 1500 °C can be achieved using an IR camera. In this study, FLIR T440 IR camera was chosen to measure the thermal radiation of waste heat in the thermal power plant. A temperature ranging between −20 °C to 1200 °C with an accuracy of 2°C deviation can be measured using FLIR T440 IR camera. Fig. 4 shows the measurement taken at the bottom ash hopper area (a) and turbine building area (b).

From Fig.4, the dissipated waste heat temperature was found to be around 470 °C at both locations. The bottom ash surface is made of steel material with an emissivity of approximately 0.95 due to the coating and oxidation of the surface area. Waste heat temperature of up to 470 °C was found at both end-side of the bottom ash hopper with an area of approximately 1 m × 1 m. Whereas, the steam pipeline in Fig. 4(b) recorded a temperature of up to 475 °C. These measurements indicate the possibility of implementing TPV cell arrays to harvest the thermal radiations and convert them into usable electricity. For example, Simovski and Mirmoosa reported an efficient InSb based TPV system that can operate with emitter temperatures between 400 °C and 600 °C. A voltage and current density of 80 mV and 55 Acm^{-2} was recorded respectively under 500 °C emitter temperature. Krier *et al.* demonstrated an InAs-based TPV cell prototype that respond to a blackbody temperature as low as 500 °C with reasonable power efficiency.

3) TPV INSTALLATION AND BENEFITS

According to the energy analysis and on-site temperature measurement, the potential location of the TPV system

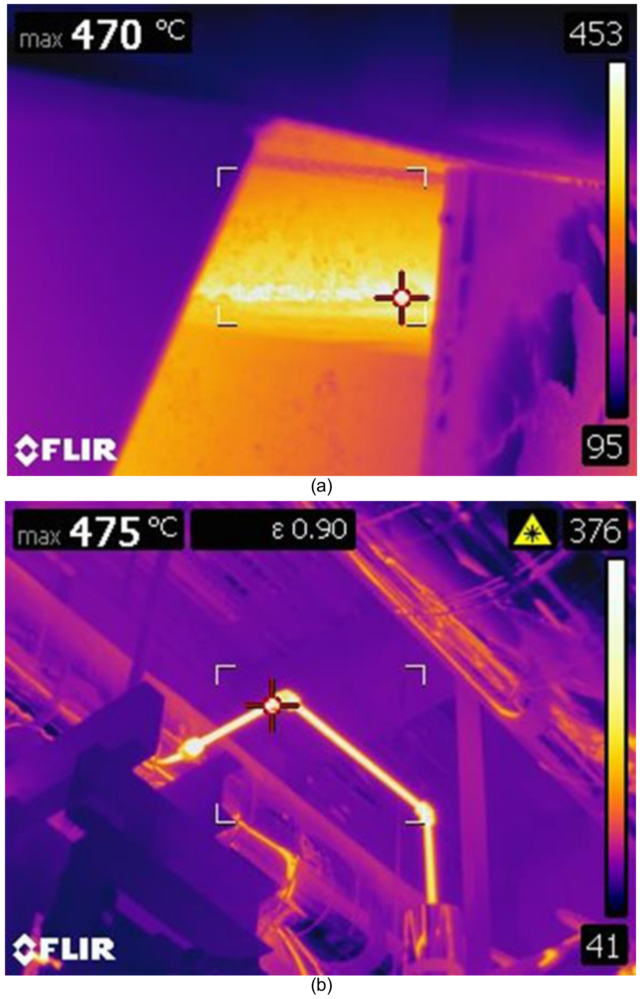

FIGURE 4. **Waste heat temperature measurements at (a) bottom ash hopper and (b) turbine building in Malaysia's coal-fired power plant using FLIR IR Camera.**

installation in thermal power plant is determined to be in the hot spot area where high temperature processes greater than 345 °C are involved. In this review, the temperatures are referred to as the internal operating condition that happens within closed-process equipment. Since the main concern of the TPV system is the source temperature radiation and the implementation can only be done at the outer part of the equipment, one would expect that the temperature on the surface of the equipment to be lower than that as prescribed. This is due to the robust equipment design material such as stainless steel and the installation of the insulation layer to maintain the operating temperature of the process.

One of the possible ways to implement the TPV system is that by removing the insulation layer on the surface of the equipment and placing a series of TPV cells in between the hot surface area and the insulator. In this way, the TPV cells can absorb the radiation heat directly on the surface of the equipment. However, a comprehensive study is needed to consider the effect of temperature on cell performance by implementing a cooling system for the TPV cell. Another way is that by placing a high or super-conductive material of selective radiator with a suitable radiance on the hot surface of the equipment. The TPV cell arrays are then placed in a proportional direction to the radiator at a set distance.

The widespread implementation of TPV cells arrays for power-related activities such as in thermal power plant improves the nation's power industry landscape. In particular, higher power generation efficiency and more reliable power supply can be achieved with TPV system implementation, since power loss from heat dissipation can be effectively cut down. Moreover, successful implementation of TPV cell arrays minimizes energy loss from conventional thermal power plants by effectively converting dissipated heat into usable electrical energy. Upon generation, electrical energy from TPV cell arrays can be channeled for power plant usage, reducing dependence on conventional electrical sources and lowering operational costs.

V. CONCLUSION AND RECOMMENDATION

In conclusion, a review of the recent development of TPV system and components for waste heat recovery application has been successfully presented. The system is assembled from a heat source, emitter, filter and TPV cells. Particularly, the available waste heat temperature in waste heat recovery application is lower than a normal TPV working temperature, causing low radiant energy emitted to the TPV cells. For this reason, the development of near-field TPV system, as well as the choice of suitable TPV emitter and TPV cell material that could operate at low-temperature source, are vital. In contrast to broadband emitter, selective emitters show the advantage of spectral shaping on selective wavelength. Moreover, the use of selective filter will also reduce optical losses. For TPV cells, a material with bandgap energy between 0.2 and 0.7 eV is suitable for source temperature below 1000 °C. The review has articulated several recommendations for future studies that are important for the development of TPV technology, that are:

- Dark current investigation on narrow-bandgap TPV cells. Narrower bandgap material has a high saturation current due to lattice-mismatched effect, resulting in higher recombination of charge carrier. Research in this area would provide better insight of charge carrier mobility in a narrow bandgap TPV cell material.
- Selective filter development. The main advantage of incorporation a TPV filter is to protect the cell from thermalization effect while allowing near-bandgap photons to be absorbed. This research scope will contribute to the enhancement of TPV cell conversion efficiencies.
- Cooling system for near-field TPV. Due to the exposure of high radiant energy, thermalization of TPV cell may happen and leads to performance deterioration. An effective cooling system should be investigated for near-field TPV system to prevent further heat dissipation.

Next, the potential heat losses in a thermal power plant was investigated and identified based on energy analyses in previous literature and on-site temperature measurement in Malaysia's coal-fired power plant. The studies show that most of the energy is lost to the surrounding through condenser. However, the temperature is almost at room temperature, making TPV implementation nearly impossible in this area. Nevertheless, TPV can be implemented on the second and third highest contribution of energy losses that are boilers and turbines. The possible method of implementation was discussed. In a nutshell, this review provides an insight for the readers on the development of TPV technology, in the interim of exploring the possibilities of implementing such clean and renewable electricity generation technology.

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