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Power Generation Using Nonconventional Renewable Geothermal & Alternative Clean Energy Technologies

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1. Introduction

Advanced nonconventional renewable & alternative clean energy technologies which are used for generation of electricity have shown real promise and received renewed interest in recent years due to an increasing concern of environmental issues of greenhouse gas (GHG) emissions, being responsible for global warming & climate change, environmental pollution, and the limitations and conservation of natural energy resources. One of these innovative & emerging technologies is non-conventional, renewable and clean low-temperature geothermal energy (LTGE) technology. The vast low-temperature geothermal resources found widely in most continental regions have not received much attention for electricity generation. Continuous development of innovative drilling and ORC power generation technologies and other factors make this nonconventional and renewable energy source one of the best future viable, alternate and available source to meet the required future electricity demand worldwide, significantly reducing GHG emissions and mitigating global climate change. Section 2.1 of this chapter presents some novel applications of using LTGE resources and section 3.1 presents the fundamental concept of LTGE for power generation using ORC binary technology and discusses its limitations, environmental & economic considerations, and energy-conversion performance aspects. Another innovative alternative clean energy technology is thermoelectric (TE) power generation. Most of the recent research activities on applications of TE power generation have been directed towards utilisation of industrial waste heat (Riffat & Ma, 2003) where the cost of fuel input is cheap or free. In this large-scale application, TE power generators offer a potential alternative of green electricity generation powered by waste-heat energy that would contribute to solving the worldwide energy crisis, and the same time help reduce environmental global warming. The relatively low conversion efficiency of TE generators has been a major cause in restricting their use in electrical power generation. Recently, there has been a renewed research interest in TE technology due to emerging novel TE materials. Section 2.2 of this chapter presents innovative applications of using TE power generation technology and section 3.2 presents TE fundamental concept and discusses its limitations, energy-conversion performance, and material considerations for novel TE power generators. Thermophotovoltaic (TPV) power generation is another promising alternative clean energy source technology. There have been some causes for limiting the applications of TPV power generation technology. The improvement of TPV converters materials and total system optimization has recently attracted the attention of many research activities. Section 2.3 of this chapter presents novel applications of using TPV technology and section 3.3 presents its fundamental concept and discusses its limitations, energy performance aspects, and novel TPV system specifications.

2. Innovative features, developments & applications

2.1 Nonconventional low-temperature geothermal energy for power generation

Geothermal energy means the natural heat energy from the Earth. The source of geothermal energy is the continuous heat energy flux flowing from the interior of the Earth towards its surface. Unlike other conventional and renewable energy sources, geothermal energy has unique features, namely it is available, stable at all times throughout the year, independent of weather conditions, and has an inherent storage capability (Hammons, 2004). Distinct from fossil fuels, geothermal energy is also considered to be an environmentally friendly clean energy source which could significantly contribute to the reduction of GHG emissions by replacing fossil fuels for electrical power generation (Chandrasekharam & Bundschuh, 2008). The geothermal resources of the Earth are huge. The part of geothermal energy stored at a depth of 3 km is estimated to be 43,000,000 EJ (corresponding to 1,194,444,444 TWh) which is much larger compared to all fossil fuel resources, whose energy equivalent is 36,373 EJ, put together (Chandrasekharam & Bundschuh, 2008). The utilization of geothermal energy is usually divided into the part used for electricity generation and the part used directly for direct heating (non-electrical) applications. It was reported that geothermal energy provides approximately 0.4% of the world global power generation, with a stable long-term growth rate of approximately 5% (Ruggero Bertani, 2007) Recently, this form of renewable and green energy source has grown in 25 countries (Panea et al., 2010), with installed geothermal-electric capacity totalling up to 11 GW_e in 2010 (Ruggero Bertani, 2007), and is increasingly contributing to the electric power supply worldwide.

Geothermal energy resources vary broadly from one location to another, depending on the depth and temperature of the resource, the rock chemical composition and the abundance of ground water (Gupta & Roy, 2007). Geothermal energy sources differ in temperature from about 50 °C to 350 °C. The high-temperature geothermal resources (with temperature > 200 °C) are typically found in volcanic regions and island chains, whereas the medium-temperature (150-200 °C) and low-temperature geothermal resources (<150 °C) are usually found widely in most continental regions and by far the most commonly available geothermal resource (Chandrasekharam & Bundschuh, 2008; Gupta & Roy, 2007). The increase in temperature with depth in the Earth's crust can be expressed in terms of what is known as the geothermal temperature gradient. Down to the depths accessible by drilling with modern technology (i.e. over 10 km), the average geothermal gradient is about 2.5-3.0 °C/100 m (Dickson & Fanelli, 2005). For example, at depth around 3,000 m below ground level, the estimated temperature is 90 °C. There are, however, regions in which the geothermal temperature gradient is far from the average value. For example, in some geothermal areas the gradient is ten times the average value due to geothermal structure and composition of these areas (Dickson & Fanelli, 2005). It was estimated that the world net electricity demand is going to increase by approximately 85% from 2004 to 2030, rising from 16,424 TWh (in 2004) to 30,364 TWh in the year 2030. It was also reported that the emissions of GHG from geothermal power plants, in general, constitute less than 2% of the emission of these gases by fossil-fuelled power plants (Chandrasekharam & Bundschuh, 2008; Dickson & Fanelli, 2005). To comply with future energy demands, potential renewable & alternative energy sources should meet the following criteria: (1) the sources should be large enough to sustain a long-lasting energy supply to generate the required electricity for the country, (2) the sources should be technically and economically accessible, (3) the sources should have a wide geographic distribution, and (4) the sources should be environmentally friendly and thus should be low GHG emitters in order to make significant contribution to global warming mitigation (Chandrasekharam & Bundschuh, 2008). Low-temperature geothermal energy resources remarkably satisfy all of these criteria. This vast low-temperature/low-enthalpy geothermal energy resource has already been utilized for electric power generation by some countries, such as USA, Philippines, Mexico, Indonesia, Iceland, Austria, and Germany (Chandrasekharam & Bundschuh, 2008; Cui et al., 2009). The installations of several commercial low-temperature geothermal power systems in these countries have substantially proved the ability of low-temperature geothermal fluids to generate green electricity (Chandrasekharam & Bundschuh, 2008). In most developing countries, low-temperature geothermal resources have not received much attention for electricity generation. The main reason for not utilizing these resources by most developing countries (and several industrialized countries) for commercial exploitation is that they are not considered as economically feasible for generating electricity (Chandrasekharam & Bundschuh, 2008). Developing countries, in general, need to benefit from these new and continually improving technologies for using potential low-temperature geothermal resources for generating electricity (Chandrasekharam & Bundschuh, 2008; Galanis et al., 2009). It should be noted that for many developing countries, the use of LTGE resources is not new. Many of developing countries have been using these available resources for the past centuries for direct heating applications (Chandrasekharam & Bundschuh, 2008).

Recent increases in the cost and uncertainty of future conventional energy supplies for power generation are improving the attractiveness of low-temperature geothermal resources. Continuous development of innovative drilling and power generation technologies makes this nonconventional, renewable and clean energy source the best future viable, alternate and available source to meet the required future electricity demand worldwide, significantly reducing GHG emissions and mitigating global climate change (Chandrasekharam & Bundschuh, 2008). Generating electricity from low-temperature geothermal resources (water-dominated resources) can be effectively achieved using a Binary-Cycle technology which is also known as Organic Rankine Cycle (ORC) technology (Chandrasekharam & Bundschuh, 2008; Dickson & Fanelli, 2005; DiPippo, 2008). Low-temperature geothermal ORC technology has virtually no GHG emissions to the atmosphere (DiPippo, 2008; Hettiarachchi et al., 2007) and is an attractive energy-conversion technology due to its simplicity and its limited number of components, all of them being very common and commercially available. A number of successful & innovative ORC binary power plants were installed in different locations (e.g. remote and rural sites) worldwide which demonstrate the ability of this promising alternative technology to utilize renewable low-temperature geothermal energy sources for generating electricity. For example, two plants were installed in Nevada, USA in 1984 and 1987 with electric power generation capacity of 750 and 800 kW_e, respectively (Chandrasekharam & Bundschuh, 2008). The production wells supply geo-fluid (water) temperature at 104 ^oC with a flow rate of 60 l/s to these plants. The ORC binary fluid used was initially R-114 but due to non-availability of this working fluid the plant switched to iso-pentane in 1998. In another location near Empire, Nevada, approximately four 1 MW_e units were installed and commissioned in 1987. Two geothermal production wells with geo-fluids temperature of 137 ^oC were used (Chandrasekharam & Bundschuh, 2008). In

1998, a third well with geo-fluid temperature of 152 ^{o}C was drilled to maintain the capacity of the plant at approximately 4 MW_e. The modular approach was used so that high plant availability factors of 98% and more were achievable (Hammons, 2004). In 1987, another plant was installed and commissioned in Taiwan with an electric power generation of 300 kW_e. The plant draws geo-fluids from a 500 m deep well at a temperature of 130 ^{o}C. It was reported that the power generated from this facility was sold to the national power grid at 0.04 US$/kWh (Chandrasekharam & Bundschuh, 2008). In 1986, a low-temperature geothermal ORC unit (Mulka plant) with a power capacity of 15 kW_e was commissioned in Australia. The unit was coupled to a geothermal production well which was drilled down to a depth of 1,300 m, and supplying geo-fluid at 86 ^{o}C. The unit was operated non-stop for about three and a half years, showing frequency stability and response to load changes (Rosca et al., 2010). In 1992, a binary ORC power generation unit which utilized a low-temperature geothermal water resource with a temperature ranging from 90 to 115 ^{o}C was tested at a location near Larderello, Italy. The geothermal power plant generated between 800 and 1,300 kW_e of electricity (Rosca et al., 2010). In Germany, the first low-temperature geothermal power plant using ORC technology was installed at Neustadt-Glewe, with a power capacity of approximately 230 kW_e using a geo-fluid temperature of 98 ^{o}C (Ruggero Bertani, 2007). Another plant was commissioned in Thailand in 1989, with an installed capacity of 300 kW_e. The actual production was reported to vary from 150 to 250 kW_e and the geo-fluid temperature is 116 ^{o}C with a flow rate of approximately 8 l/s (Chandrasekharam & Bundschuh, 2008). Recently, in 2006, the first binary ORC plant which utilizes a low-temperature geothermal resource at a temperature of 74^{o}C (reported by (Ruggero Bertani, 2007) to be the lowest low-temperature geothermal energy resource worldwide) was installed with a power generation capacity of 200 kW_e. In Japan, binary ORC technology was experimentally operated for 5 years starting in 1993 by NEDO (Yamada & Oyama, 2004). In Altheim, Austria, a geo-fluid of temperature 106 ^{o}C is utilized both for district heating and electric power generation using a binary plant technology as shown in Figure 1. The net electric output of this plant is 500 kW, selling to the electric grid 1.1 GWh in 2006 (Ruggero Bertani, 2007).

Fig. 1. Photograph of Altheim geothermal binary power plant in Austria (Ruggero Bertani, 2007).

2.2 Thermoelectric power generation as an alternative clean energy technology

A thermoelectric (TE) power generator is a solid-state device that provides direct energy conversion from thermal energy (heat) due to a temperature gradient into electrical energy based on "Seebeck effect". The thermoelectric power cycle, with charge carriers (electrons) serving as the working fluid, follows the fundamental laws of thermodynamics and intimately resembles the power cycle of a conventional heat engine. Thermoelectric power generators offer several distinct advantages over other power generation technologies (Riffat & Ma, 2003; Yadav et al., 2008): they are simple, compact and safe devices; they are environmentally friendly; they have very small size and virtually weightless; they are capable of operating at elevated temperatures; they are extremely reliable (typically exceed 100,000 hours of steady-state operation) and silent in operation since they have no mechanical moving parts and require considerably less maintenance; they are flexible power sources; they are suited for small-scale and remote applications typical of rural power supply, where there is limited or no electricity; and they are not position-dependent.

The major drawback of the thermoelectric power generator is its relatively low conversion efficiency (typically ~5% (Rowe & Min, 1998)). This has been a major cause in restricting their use in electrical power generation to specialized fields with extensive applications where reliability is a major consideration and cost is not. Applications over the past decade included industrial instruments, military, medical and aerospace (Riffat & Ma, 2003; Rowe & Min, 1998), and applications for portable or remote power generation (Stevens, 2001). However, in recent years, an increasing concern of environmental issues of GHG emissions, in particular global warming has resulted in extensive research into nonconventional technologies of generating electrical power and thermoelectric power generation has emerged as a promising alternative green energy technology. Enormous quantities of waste heat (low-grade) energy are discharged into the earth's environment much of it at temperatures which are typically too low to recover using conventional electrical power generators. Thermoelectric power generation (also known as thermoelectricity) offers a promising technology in the direct conversion of this low-grade thermal energy, such as waste-heat energy, into electrical power (Rowe, 2006). In this waste heat powered thermoelectric technology, it is unnecessary to consider the cost of the thermal energy input, and consequently thermoelectric power generators' low conversion efficiency is not a critical drawback (Riffat & Ma, 2003; Rowe, 1999). Thermoelectric generators have also been used to provide small amounts of electrical power to remote regions for example Northern Sweden, as an alternative to costly gasoline-powered motor generators (Rowe, 1999). In fact, more recently, they can be used in many cases, such as those used in cogeneration systems (Yodovard et al., 2001), to improve overall efficiencies of energy conversion systems by converting waste-heat into electricity (Yadav et al., 2008).

In general, the cost of a thermoelectric power generator essentially consists of the device cost and operating cost. The operating cost is governed by the generator's conversion efficiency, while the device cost is determined by the cost of its construction to produce the desired electrical power output (Riffat & Ma, 2003). Since the energy conversion efficiency of a module is comparatively low, thermoelectric generation using waste-heat energy is an ideal application. In this case, the operating cost is negligible compared to the module cost because the energy input (being the fuel) cost is cheap or free. Therefore, an important objective in thermoelectric power generation using waste-heat energy is to reduce the cost-per-watt of the devices. Moreover, cost-per-watt can be reduced by optimising the device geometry, improving the manufacture quality and simply by operating the device at a potentially larger temperature difference (Riffat & Ma, 2003). In addition, in designing high-performance thermoelectric power generators, the improvement of thermoelectric properties of materials and system optimization have attracted the attention of many research activities (Chen et al., 2005). Their performance and economic competiveness appear to depend on successful development of more advanced thermoelectric materials and thermoelectric power module designs. Vast quantities of waste heat generated from various sources are continuously discharged into the earth's environment much of it at temperatures which are too low to recover using conventional electrical power generators. Thermoelectric power generation, which presents itself as a promising alternative green technology, has been successfully used to produce electrical power in a range of scales directly from various sources of waste-heat energy. Enormous amounts of heat energy are typically rejected from industry, manufacturing plants and power utilities as gases or liquids at temperature which are too low (<450 K) to be used in conventional power generating units. In this large-scale application, thermoelectric power generators offer a potential alternative of electricity generation powered by waste-heat energy that would contribute to solving the worldwide energy crisis, and the same time help reduce environmental global warming. A photograph of a thermoelectric power generator used in natural gas field to directly produce power for cathodic protection of the well and gas line is shown in Figure 2. In this application, the thermoelectric device used the temperature difference between hot and cold legs of a glycol natural gas dehydrator cycle (Weiling & Shantung, 2004).

Fig. 2. Photograph of a thermoelectric power generator produced power for cathodic protection of the well and gas line (Weiling & Shantung, 2004).

Thermoelectric power generators have also been successfully applied in recovering waste-heat energy from steel manufacturing plants. In this application, large amounts of cooling water are typically discharged at constant temperatures of approximately 90 ^{o}C when used for cooling ingots in steel plants. When operating in its continuous steel casting mode, the furnace provides a steady-state source of convenient piped water which can be readily converted by thermoelectric power generators into electricity. It was reported that total electrical power of approximately 8 MW would be produced employing currently available modules fabricated using Bi_2Te_3 thermoelectric modules technology (Rowe, 2006). Another application where thermoelectric power generators using waste-heat energy have potential use is in industrial cogeneration systems (Riffat & Ma, 2003; Yodovard et al., 2001; Min & Rowe, 2002). For example, Yodovard et al. (2001) evaluated the potential of waste heat thermoelectric power generation for diesel cycle and gas turbine cogeneration in the manufacturing industrial sector in Thailand. It is reported that gas turbine and diesel cycle cogeneration systems produced electricity estimated at 33% and 40% of fuel input, respectively (Yodovard et al., 2001). The useful waste heat from stack exhaust of cogeneration systems was estimated at approximately 20% for a gas turbine and 10% for the diesel cycle. The corresponding net power generation was approximately 100 MW. Recently, the possibility of utilizing the low-grade heat energy generated from incinerated municipal solid waste has also been considered. For example, it was reported that an on-site experiment using a 60 W thermoelectric module installed near the boiler section of an incinerator plant, achieved an estimated conversion efficiency of approximately 4.4% (Rowe, 2006). A thermoelectric power generator produced by the Japanese Energy Conservation Center, which used waste heat as energy source to generate an electric power density of 100 kW/m^3 is shown in Figure 3. A waste heat-based thermoelectric power generator is also used in a domestic central heating system with the modules located between the heat source and the water jacket (Rowe, 2006). In this application, for example, the heat output provided by the gas/oil burner passes through the generator before reaching the central heating hot-water exchanger. The generator converts approximately 5% of the input heat energy to electrical power, the remainder of 95% transfers to the hot water heat exchanger for its intended use in heating the radiator system (Rowe, 2006).

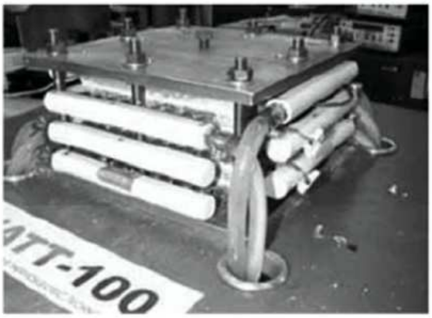

Fig. 3. Photograph of a thermoelectric power generator produced by the Japanese Energy Conservation Center, which used waste heat as energy source to generate an electric power density of 100 kW/m^3 (Weiling & Shantung, 2004).

Waste-heat energy can also be utilized proportionally from 20-50 kW wood- or diesel-heated stoves (Nuwayhid et al., 2003), especially during the winter months in rural regions where electric power supply is unreliable or intermittent, to power thermoelectric generators. For example, a thermoelectric power generator to produce electricity from stove-top surface temperatures of 100-300 ^oC was designed and evaluated (Nuwayhid et al., 2003). In this application, two commercially available thermoelectric modules were considered and 100 W of electric power output was targeted for a minimum domestic use. A similar application is reported in (Rowe, 2006). In this application, thermoelectric power generators were used to generate small amounts of electrical power to remote regions for example Northern Sweden, as an alternative to costly gasoline powered engine generators. The generator uses heat from a wood-burning stove with the cold-side cooled with a 12 volt, 2.2 W fan. The generator produces approximately 10 watts of electric power. The utilization of waste-heat energy from exhaust gases in reciprocating internal combustion engines (e.g. automobiles) is another novel application of electricity generation using thermoelectric power generators. Although a reciprocating piston engine converts the chemical energy available in fossil fuels efficiently into mechanical work a substantial amount of thermal energy is dissipated to the environment through exhaust gas, radiation, cooling water and lubricating oils. For example, in a gasoline-powered engine, approximately 30% of the primary gasoline fuel energy is dissipated as waste-heat energy in the exhaust gases; waste-heat energy discharged in the exhaust gases from a typical passenger car travelling at a regular speed is 20-30 kW (Riffat & Ma, 2003). A comprehensive theoretical study concluded that a thermoelectric generator powered by exhaust heat could meet the electrical requirements of a medium sized automobile (Rowe, 1999). It was reported that among the established thermoelectric materials, those modules based on PbTe technology were the most suitable for converting waste-heat energy from automobiles into electrical power (Rowe, 1999). Wide-scale applications of thermoelectricity in the automobile industry would lead to some reductions in fuel consumption, and thus environmental global warming, but this technology is not yet widely proven (Riffat & Ma, 2003).

2.3 Thermophotovoltaic alternative energy technology for direct power generation

A thermophotovoltaic power generator is also a solid-state device which provides direct energy conversion from radiant energy (radiative heat) emitted from a heated object into electrical power. In photovoltaic (PV) energy-conversion systems, electric energy is directly generated out of photons that are absorbed by the PV cell. In conventional PV systems these photons (in the visible range wavelengths) originate from the sun of a temperature of approximately 6000 K and at a distance of approximately 150 x 10^6 km, but also other photon sources can be used. Another potential alternative is the use of photons having near- or infrared radiation wavelengths emitted by a heat source (at a distance of perhaps only a few centimeters) as used in combustion-driven systems in industry or in residential heating systems. Since these photons originate from a thermal source this type of photovoltaic energy conversion is called thermophotovoltaic (TPV) energy conversion. The electric power density of the TPV cells is typically much higher than that of solar energy driven PV cells since the radiation intensity of combustion-driven radiant sources can be made much greater than that of the sun. For example, Coutts (1999) reported that the power density of a typical solar PV device is of the order of 0.1 W/cm^2, whereas that for a TPV device is potentially to be 5-30 W/cm^2. In TPV devices or systems, an object, typically a selective emitter, is heated to temperatures typically higher than 1000 K; 1300-2000 K is considered a practical range. The resulting radiation (in form of photons) is absorbed by semiconductor photovoltaic (PV) cells which convert photons into electricity. Photons not absorbed by the TPV cells are reflected back by a reflector (a photon recirculating device) to the emitter (Coutts, 1999; Lal & Blakers, 2009). The main components of a TPV device and energy conversion processes involved in the operation of it will be discussed in more detail in later sections of this chapter.

The study of TPV energy conversion might date back to more than 40 years. Coutts (1999) and Nelson (2003) reported that the possibility of using infrared radiation and converting it to electricity using TPV technology was first appreciated by Professor Pierre Aigrain. In particular, Aigrain proposed this direct energy conversion concept during a series of lectures on a number of technical topics given while he was a visiting professor at MIT (Cambridge, MA) in late 1960 and early 1961. A substantial research effort followed the Aigrain disclosure in the 1960s. For example, the MIT faculty authored a series of conference papers (e.g. IEEE Photovoltaic Specialists Conference) and journal articles related to this technology (Coutts, 1999; Nelson, 2003). The US Army at Fort Monmouth played a significant role in advancing TPV technology. More particularly, the US Army needed portable power sources with a low noise, and TPV was an excellent candidate for this application (Nelson, 2003). Nelson (2003) also reported that General Motors (GM) was the most active industrial contributor in TPV technology development during this early period. Figure 4 shows an advanced silicon concentrator solar cell based TPV prototype system (Qiu & Hayden, 2006). In the mid 1970s, the pace of TPV development slowed significantly when the US Army chose another technology (thermoelectric) to satisfy the need for concealed power sources. According to the US Army, TPV development was not sufficiently advanced when compared with the older, more reliable thermoelectric approach. TPV technology development, benefited from the energy crises of the 1970s during which time worldwide interest was focused on renewable energy sources. TPV has experienced a revival since the early 1990s mainly because of the technology revolution and availability of high-performance TPV energy converters (Coutts, 1999) and the technological improvements in the area of selective emitter and low bandgap PV cells (Chia & Feng, 2007). More recently, there has been a renewed interest in the TPV clean power generation technology due to an increasing concern of environmental issues of GHG emissions, the limitations of energy resources, and, more particularly, the attractive features of this technology over other technologies as an alternative source of clean energy.

Fig. 4. Photograph of a silicon concentrator solar cell based TPV prototype system (Qiu & Hayden, 2006).

Like TE power technology, TPV power generators offer numerous potential distinct advantages over other technologies (Coutts, 1999; Chia & Feng, 2007; Badescu, 2005; Qiu & Hayden, 2006): they are silent, flexible, and reliable power sources; they are simple, compact, safe and transportable and have high power density; they are clean and environmentally friendly, if the heat source is fuelled by clean energy resource (e.g. solar, nuclear, biofuel, waste heat, etc.), or have low-emissions with low-emission burner-fuel system; they have fuel versatility and are characterized by a rapid start-up; they have no mechanical moving parts and require considerably less maintenance; they are suited for small-scale and remote applications typical of rural power supply, where there is limited or no electricity; and they are independent of the sun (if non-solar heat sources are used).

TPV energy conversion technology offers a potential application in direct generation of electricity in portable or remote power generation, stand-alone domestic gas-furnaces, silent electrical power supplies on recreational vehicles, hybrid electric vehicles, cogeneration of electricity and heat, and many others (Coutts, 1999; Nelson, 2003). Coutts (1999) reported that the greatest potential for TPV power generation is in its application to large-scale recovery of high-temperature waste heat from many industrial processes, such as glass, aluminum, steel, castings, etc. In this waste heat powered TPV technology, it is unnecessary to consider the cost of the thermal energy input. The application of this alternative clean technology in converting waste-heat energy directly into electrical power can also improve the overall efficiencies of energy conversion systems. There have been some causes for limiting the applications of TPV power generation technology. For example, Lal and Blakers (2009) reported that the main limiting factors of TPV systems are spectral filtering, TPV conversion efficiency, the optimization of individual components rather than the system as a whole, adequate systems modeling and thermal management. It was also reported that an important commercial limitation of TPV technology is the difficulty of accessing suitable cost-effective solar cells (Lal & Blakers, 2009). Therefore, in designing high-performance thermophotovoltaic power generators, the improvement of thermophotovoltaic converters materials and total system optimization have recently attracted the attention of many research activities. Their performance and economic competiveness appear to depend on successful development and demonstration of more advanced and innovative TPV converters materials and system designs.

3. Fundamental concepts and energy conversion performance aspects

In the following sections, the fundamental concepts, energy-conversion performance aspects and other considerations of the nonconventional renewable low-temperature geothermal power generation, thermoelectric clean power generation, and thermophotovoltaic power generation are presented and discussed.

3.1 Fundamental concept and energy performance aspects of low-temperature geothermal power generation using binary ORC technology

A schematic diagram showing a low-temperature geothermal ORC binary-fluid system used for electric power generation is shown in Figure 5. In this system, the first (primary) fluid being the geo-fluid (brine) is extracted from the low-temperature geothermal resource through the production well. The geo-fluid carries the heat from the liquid-dominated resource (thus called the geo-fluid heat carrier) and efficiently transfers this heat to the low-boiling point (BP) organic working fluid (the secondary/binary fluid) using an effective heat exchanger. Shell-and-tube heat exchangers are widely used (Chandrasekharam & Bundschuh, 2008). The Organic Rankine Cycle (ORC) is a thermodynamic Rankine cycle that uses the organic working fluid instead of steam (water). In this binary-fluid system, the low-boiling point organic liquid absorbs the heat which is transferred by the geothermal fluid and boils at a relatively much lower temperature (compared to water) and as a result develops significant vapor pressure sufficient to drive the axial flow or radial inflow turbine. The turbine is coupled to an electric generator which converts the turbine mechanical shaft power into electrical power. The organic working fluid expands across the turbine and then is cooled and condensed in the condenser before it is pumped back as a liquid to the heat exchanger using a condensate pump to be re-evaporated, and the power cycle repeats itself. One of the most important performance criteria in low-temperature geothermal ORC power generation technology requires the optimal selection of the ORC organic working fluid. Organic fluids used in binary ORC technology have inherent feature (compared to water) and that is they have low boiling temperature and high vapor pressure at relatively low temperatures, compared with steam (water) (Dickson & Fanelli, 2005).

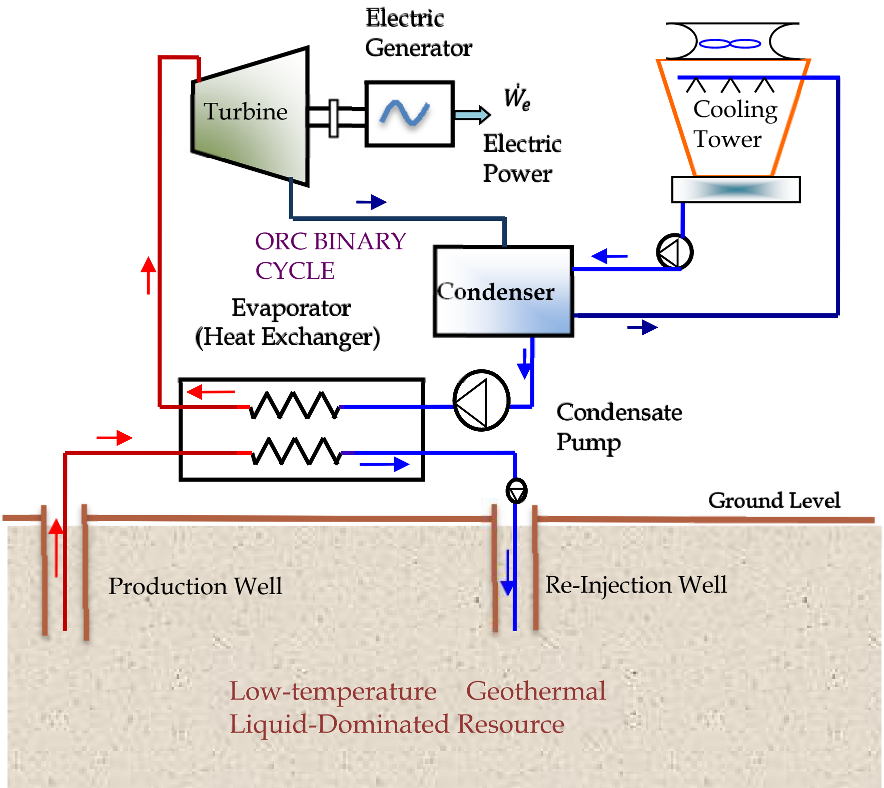

Fig. 5. A schematic diagram showing the basic concept of a low-temperature geothermal binary ORC system for electrical power generation.

Typical ORC organic fluids may include pure hydrocarbons (e.g. pentane, butane, propane, etc), refrigerants (e.g. R134a, R218, R123, R113, R125, etc), or organic mixtures (Panea et al., 2010; Saleh et al., 2007; Hung, 2001; Wei, 2007). The optimal energy conversion performance of a low-temperature geothermal ORC power generation system depends mainly on the type of organic fluid being used in the system. The selection of the type of organic fluid is typically based on the following criteria (Chandrasekharam & Bundschuh, 2008; Hettiarachchi et al.,2007; Saleh et al., 2007):

- The ORC organic fluid should result in high thermal efficiency by allowing maximum utilization of the available low-temperature geothermal heat source.
- It should be environmentally friendly; less in ozone depletion potential (ODP) and global warming potential (GWP).

- It should be safe (non-flammable and no-toxic) and non-corrosive.
- It should have a low-boiling temperature and should evaporate at atmospheric pressure.
- It should lead to optimum design and cost effectiveness of the ORC system.
- It should not react or disassociate at the pressures and temperatures at which it is used.
- It should have suitable thermal stability and high thermal conductivity.
- It should have appropriate low critical temperature and pressure.
- It should result in low maintenance.
- It should have small specific volume, low viscosity and surface tension.

It should be noted that many binary ORC fluids may not meet all these criteria (Chandrasekharam & Bundschuh, 2008) but the selection of the organic fluid should be optimized, in terms of the above requirements, while meeting the demanded power generation. In general, binary ORC systems exhibit great flexibility, high safety (installations are perfectly tight), and low maintenance (Wei, 2007). It was reported that the selection of suitable organic fluids for application in binary ORC systems for generating electricity still deserves extensive thermodynamic and technical studies (V. Maizza & A. Maizza, 2001).

3.1.1 Environmental & economic considerations of low-temperature geothermal binary ORC power technology

In general, geothermal energy is relatively pollution-free and considered to be a clean technology (Dickson & Fanelli, 2005) and it tends to have the largest technological potential compared to other renewable energy sources (Hammons, 2004). In particular, GHG emissions are typically zero when low-temperature geothermal energy reservoirs are utilized using ORC binary technology, since all of the produced geo-fluid is injected back into the reservoir (Hammons, 2004). One of the effective ways of getting rid of hazardous chemical constituents of geothermal water (e.g. trace metals) is re-injection. Low-temperature geothermal binary power generation systems are far less environmentally intrusive than alternative power generation systems in several respects, for example they are essentially zero-GHG emission systems and have low land usage per installed megawatt (DiPippo, 2008). As far as physical environmental effects, geothermal projects may cause some kind of disruption activities as other same size and complexity of civil engineering projects. Also, the locations of excavations and sitting of boreholes and roads will have to be taken into account, soil and vegetation erosion, which may cause changes in ecosystems, has to be watched. It should be noted that many geothermal installations are in remote areas where the natural level of noise is low and any additional noise is very noticeable (Dickson & Fanelli, 2005). There is a relatively larger production of waste-heat energy in geothermal systems, and this needs to be dissipated in an environmentally acceptable way. In low-temperature geothermal binary ORC power systems the thermal impact is much reduced by disposing of waste geothermal water using deep re-injection approach so that the thermal impact of the waste heat becomes insignificant (Dickson & Fanelli, 2005). Appropriate measures should be applied to prevent leakage of the binary working fluid from ORC power generation units to the environment (Yamada & Oyama, 2004); normally the installations of these units are made perfectly tight to meet high safety standards.

Generating electricity using geothermal ORC technology is very cost-effective and reliable (Chandrasekharam & Bundschuh, 2008; Dickson & Fanelli, 2005). Table 1 compares electrical energy costs produced by various renewable energy technologies. The cost of geothermal energy for generating electricity is favourable compared to other energy sources. The reported costs of low-temperature based small geothermal power plants vary from 0.05 to 0.07 US$/kWh for units generating < 5 MW_e (Chandrasekharam & Bundschuh, 2008).

Renewable Energy Source	**Current Energy Cost (US cents/kWh)**	**Turnkey Investment Cost ($US\$/kW_e$)**	**Potential Future Energy Cost (US cents/kWh)**
Geothermal	2-10	800 – 3,000	1-8
Wind	5-13	1,100 – 1,700	3-10
Solar photovoltaic	25-125	5,000 – 10,000	5-25
Solar thermal	12-18	3,000 – 4,000	4-10
Biomass	5-15	900 – 3,000	4-10
Tidal	8-15	1,700 – 2,500	8-15
Hydro	2-10	1,000 – 3,000	NA

Table 1. Energy and investment costs for electric power production from different renewable energy sources (Hammons, 2004; Dickson & Fanelli, 2005).

The unit cost of electricity generated from low-temperature geothermal based small power plants is compared in Table 2. Moreover, the unit cost of electricity from small-scale geothermal plants (< 5 MW_e) is much lower than the average cost of 0.25 US$/kWh supplied through diesel generators (Chandrasekharam & Bundschuh, 2008). The total investment for a geothermal power plant mainly includes the following types of costs: (1) cost of exploitation, (2) cost of drilling, (3) cost of power plant (capital cost of design and construction), and (4) operating & maintenance costs (Chandrasekharam & Bundschuh, 2008). The first two types are referred to as subsurface costs whereas the other two are referred to surface costs. For small-scale geothermal power plants (< 5 MW_e) utilizing low-temperature resources, the subsurface cost typically accounts for approximately 30% of the total investment costs whereas the surface cost accounts for the remaining 70%.

Net Power (kW_e)	**Capital Cost ($US\$/net\ kW_e$)** Geothermal Resource Temperature (°C)			**O&M Cost (US$/year)**
	100	**120**	**140**	
100	2,786	2,429	2,215	21,010
200	2,572	2,242	2,044	27,115
500	2,357	2,055	1,874	33,446
1000	2,143	1,868	1,704	48,400

Table 2. Unit cost of electricity generated from low-temperature based small power plants (Chandrasekharam & Bundschuh, 2008; DiPippo, 2008).

Generating electricity using low-temperature geothermal ORC technology is very reliable due to its advanced technological aspects. However, the maintenance costs and shutdowns could be reduced when the technical complexity of the plant is on a level that is accessible to local technical personnel or to experts who are readily available (Dickson & Fanelli, 2005). As mentioned before, geothermal ORC power generation plants are normally constructed and installed in small modular power generation units. These units can then be linked up to create power plants with larger power production rates. Their cost depends on a number of factors, but mainly on the temperature of the geothermal fluid produced, which influences the size of the ORC turbine, heat exchangers and cooling system. It was reported (Dickson & Fanelli, 2005) that the total size of the plant has little effect on the specific cost, as a series of standard modular units is linked together to obtain larger power capacities. It was also reported (Panea et al., 2010) that the modular units have a satisfying economic efficiency, because modular construction reduces installation time and costs. Ultimately, the economic viability of the geothermal power plant depends on its ability to generate revenue in the long-term.

3.1.2 Ideal and actual energy performance of low-temperature geothermal binary power generation systems

The theoretical overall performance of low-temperature geothermal binary systems can be evaluated using the fundamental thermal efficiency of a heat engine, given as (Cengel & Boles, 2008)

$$\eta = \frac{\dot{W}_{net,out}}{\dot{Q}_{geo,in}} \tag{1}$$

also,

$$\eta_{th} \equiv 1 - \frac{\dot{Q}_{cond}}{\dot{Q}_{geo,in}} \tag{2}$$

where, $\dot{W}_{net,out}$ is the net power output delivered by the geothermal power system (in kW); $\dot{Q}_{geo,in}$ is the thermal power supplied by the geo-fluid from the available geothermal resource (in kW); and $\dot{Q}_{cond}$ is the thermal energy rejected in the condenser (in kW). For quick estimate purposes, a correlation is proposed (Dickson & Fanelli, 2005) to calculate the actual net power output (with rough accuracy) as a function of the available thermal power from the geo-fluid flow and inlet temperature of the geo-fluid, given by

$$\dot{W}_{net,act} = \left(\frac{1}{278}\right)\left[\left(0.18T_{geo,in} - 10\right)\dot{Q}_{geo,in}\right] \tag{3}$$

Substituting Eq. (3) in Eq. (1), the estimated thermal efficiency of the low-temperature based geothermal power generation system, as a function of geo-fluid inlet temperature (in ^{o}C) at the production well, is given by

$$\eta_{th} \approx \left(\frac{1}{278}\right)\left(0.18T_{geo,in} - 10\right) \tag{4}$$

For example, using Eq. (4) it can be estimated that a thermal efficiency of approximately 5.5% could be achieved for power generation with a geo-fluid extracted from a low-temperature geothermal resource available at 140 ^{o}C. The thermal efficiency as a function of the low-temperature geothermal heat resource temperature, T_H (in K), and ambient temperature, T_a (in K) is given by (DiPippo, 2007)

$$\eta_{th} \cong \left(\frac{58}{100}\right)\left(\frac{T_H - T_a}{T_H + T_a}\right) \tag{5}$$

So for example, with a geothermal heat resource temperature of 140 °C and ambient temperature of 20 °C, the thermal efficiency is estimated to be 10%. It should be noted that Eq. (5) is valid for resource temperatures between 100 and 140 °C. The estimated net power output delivered by the geothermal power system can also be determined using (DiPippo, 2007)

$$\dot{W}_{net,out} \cong 2.47\dot{m}_{geo}\left(\frac{T_H - T_o}{T_H + T_o}\right)(T_H - T_C) \tag{6}$$

Where, $\dot{m}_{geo}$ is the geo-fluid mass flow rate. As can be noted from Eq. (5), for low-temperature geothermal resources, the power plant thermal efficiency is very dependent on the ambient temperature, which determines the heat sink temperature. It should be also noted that the above correlations given by Eqs. (3) through (6) provide quick estimate of the thermal efficiency and net power output, and therefore for more accurate calculations and system performance predictions, a detailed thermodynamic energy balance analysis should be performed to predict the net power, the available geothermal heat, and overall thermal efficiency using Eq. (1). Low-temperature geothermal binary power generation plants tend to have low thermal efficiencies: 10-13% reported by (DiPippo, 2008), 2.8-5.5% reported by (Gupta & Roy, 2007), and 5-9% reported by (Hettiarachchi et al., 2007) since the geothermal energy is produced at low enthalpy levels. Maximizing generating power capacity is normally sought from these power plants by maximizing the geo-fluid flow rate (depending on the capability of the production well) with a limited geo-fluid temperature available from the geothermal resource. It was reported (Chandrasekharam & Bundschuh, 2008) that low-temperature geothermal production wells with geo-fluid temperature < 150 °C and geo-fluid flow rate > 900 l/min could generate electric power ranging from 50 to 700 kW_e. When appropriate, multiple production wells could be installed using the same low-temperature geothermal energy reservoir so that a number of ORC power generation units could be cascaded to obtain larger power production rates from the plant (Gupta & Roy, 2007). Limited by the second-law of thermodynamics, the ideal (absolute maximum) efficiency of a thermoelectric power cycle, such as the low-temperature geothermal ORC power cycle, operating as a reversible heat engine between a heat source at a temperature T_H and a heat sink at a temperature T_L is Carnot efficiency, given as (Cengel & Boles, 2008)

$$\eta_c = \eta_{\max} = 1 - \frac{T_L}{T_H} \tag{7}$$

For example, for an ORC power system using a geo-fluid extracted from a low-temperature geothermal heat source at 140 °C (413.15 K) and a heat sink (condenser) at 40 °C (313.15 K), the maximum ideal Carnot efficiency can be calculated using Eq. (7) to be approximately 24.2%. For an actual (irreversible) geothermal ORC cycle operating between the same temperature limits would have lower efficiency. Another measure of the performance of the low-temperature geothermal ORC power plant can be obtained using the Second-Law of thermodynamics in the form of exergetic efficiency, η_{ex}, given as

$$\eta_{ex} \equiv \frac{\dot{W}_{net}}{\dot{E}x} \tag{8}$$

The exergetic efficiency in Eq. (8) is defined as the ratio of the actual net power output from the power generation system to the maximum theoretical power that could be extracted from the geo-fluid at the geothermal resource state. This involves determining the rate of exergy carried by the geo-fluid to the ORC power system. Typically, the design and operation of geothermal binary power generation systems should be optimized in order to increase their thermal and exergetic efficiencies guided by the Carnot ideal efficiency.

3.2 Fundamental concept and energy performance aspects of waste-heat (low-grade) direct energy conversion into electricity using thermoelectric clean technology

As introduced previously, thermoelectric power generation is based on a phenomenon called "Seebeck effect". When a temperature difference is established between the hot and cold junctions of two dissimilar materials (metals or semiconductors) a voltage is generated. In fact, this phenomenon is applied to thermocouples that are extensively used for temperature measurements. Based on this Seebeck effect, thermoelectric devices can act as electrical power generators. A schematic diagram of a simple thermoelectric power generator operating based on Seebeck effect is shown in Figure 6.

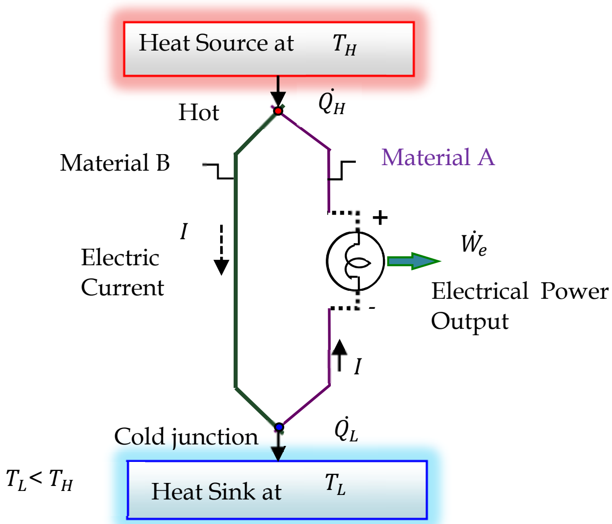

Fig. 6. A schematic diagram showing the basic principle of a simple thermoelectric power generator operating based on Seebeck effect.

As shown in Figure 6, heat is transferred at a rate of $\dot{Q}_H$ from a high-temperature heat source maintained at T_H to the hot junction, and it is rejected at a rate of $\dot{Q}_L$ to a low-temperature sink maintained at T_L from the cold junction. Based on Seebeck effect, the heat supplied at the hot junction causes an electric current to flow in the circuit and electrical power is produced. Using the first-law of thermodynamics (energy conservation principle) the difference between $\dot{Q}_H$ and $\dot{Q}_L$ is the electrical power output $\dot{W}_e$. It should be noted that this power cycle intimately resembles the power cycle of a heat engine (Carnot engine), thus in this respect a thermoelectric power generator can be considered as a unique heat engine (Cengel & Boles, 2008). Figure 7 shows a schematic diagram illustrating the main components and arrangement of a conventional single-stage thermoelectric power generator. As shown in Figure 7, the TE power generator is composed of two ceramic plates (substrates) that serve as a foundation, providing mechanical integrity, and electrical insulation for *n*-type (heavily doped to create excess electrons) and *p*-type (heavily doped to create excess holes) semiconductor thermoelements. In thermoelectric materials, electrons and holes operate as both charge carriers and energy carriers. There are very few modules without ceramic plates, which could eliminate the thermal resistance associated with the ceramic plates, but might lead to mechanical fragility of the module.

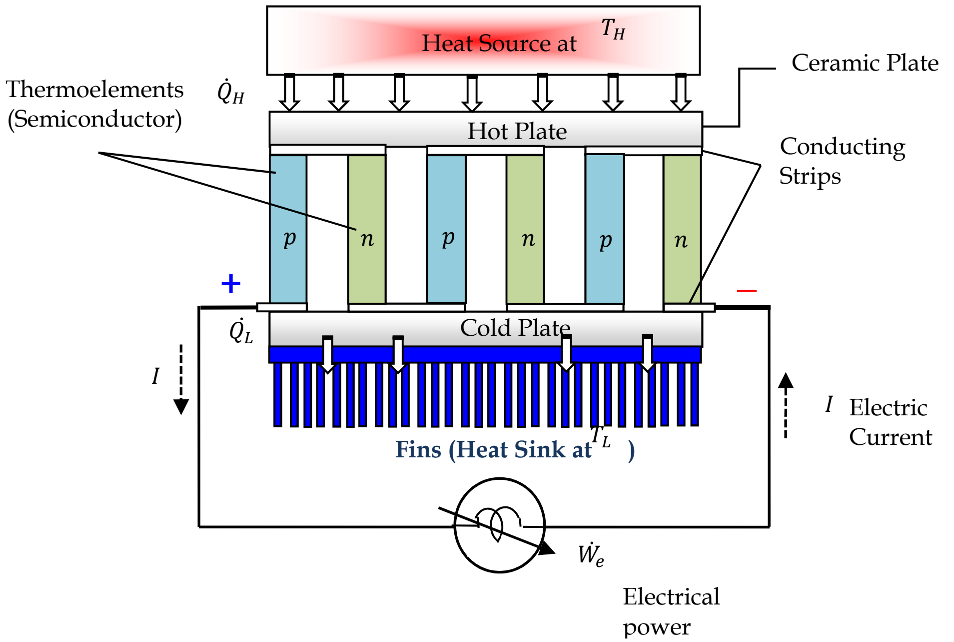

Fig. 7. A schematic diagram illustrating arrangement and main components of a typical TE power generator.

The ceramic plates are commonly made from alumina, but when large lateral heat transfer is required, materials with higher thermal conductivity (e.g. beryllia and aluminum nitride) are desired. The semiconductor thermoelements (e.g. silicon-germanium, lead-telluride based alloys) that are sandwiched between the ceramic plates are connected thermally in parallel and electrically in series to form a thermoelectric device (module). More than one pair of semiconductors are normally assembled together to form a thermoelectric module and within the module a pair of thermoelements is called a thermocouple (Riffat & Ma, 2003). The junctions connecting the thermoelements between the hot and cold plates are interconnected using highly conducting metal (e.g. copper) strips as shown in Figure 7. The sizes of conventional thermoelectric devices vary from 3 mm² by 4 mm thick to 75 mm² by 5 mm thick. Most of thermoelectric modules are not larger than 50 mm in length due to mechanical consideration. The height of single-stage thermoelectric modules ranges from 1 to 5 mm. The modules typically contain from 3 to 127 thermocouples (Riffat & Ma, 2003). There are multistage TE devices designed to meet requirements for large temperature differentials. Multi-stage thermoelectric modules can be up to 20 mm in height, depending on the number of stages. Photographs of single- and multi-stage thermoelectric modules are shown in Figure 8. The power output for most of the commercially-available thermoelectric power generators ranges from microwatts to multi-kilowatts (Riffat & Ma, 2003; Rowe, 1999). For example, a standard thermoelectric device consists of 71 thermocouples with the size of 75 mm² can deliver electrical power of approximately 19 W (Riffat & Ma, 2003).

(a) (b)

Fig. 8. Photographs of (a) single-stage, and (b) typical pyramid three-stage configuration TE modules (Sources: http://www.customthermoelectric.com, http://www.ferrotec.com).

3.2.1 Energy conversion & performance aspects of TE power generators

The performance of thermoelectric materials can be expressed using (Rowe, 2006)

$$Z = \frac{\alpha^2}{kR}, \quad (9)$$

where Z is the thermoelectric material figure-of-merit , α is the Seebeck coefficient given by

$$\alpha = -\frac{\Delta V}{\Delta T}. \quad (10)$$

R is the electric resistivity and k is the total thermal conductivity. This figure-of-merit may be made dimensionless by multiplying by $\bar{T}$ (average absolute temperature of hot and cold plates of the thermoelectric module, K), i.e.,

$$Z\bar{T} = \frac{\alpha^2 \bar{T}}{kR} \quad (11)$$

The term α^2/R is referred to as the electrical power factor. In general, a thermoelectric power generator exhibits low efficiency due to the relatively small dimensionless figure-of-merit ($Z\bar{T} \leq 1$) of currently available thermoelectric materials. The thermal efficiency of a thermoelectric power generator defined as the ratio of power delivered to the heat input at the hot junction of the thermoelectric device, is given by (Rowe, 2006)

$$\eta_{th} = \frac{\dot{W}_e}{\dot{Q}_H} \tag{12}$$

Limited by the second-law of thermodynamics, the ideal (absolute maximum) efficiency of a thermoelectric power generator operating as a reversible heat engine is Carnot efficiency, given by Eq. (7). The maximum actual conversion efficiency of an irreversible thermoelectric power generator can be estimated using (Min & Rowe, 2004)

$$\eta_{TE} = \eta_{Carnot}\left[\frac{\sqrt{1+Z\bar{\bar{T}}}-1}{\sqrt{1+Z\bar{\bar{T}}}+T_L/T_H}\right] \tag{13}$$

The value of the figure-of-merit is usually proportional to the conversion efficiency. The dimensionless term $Z\bar{T}$ is therefore a very convenient figure for comparing the potential conversion efficiency of modules using different thermoelectric materials.

3.2.2 Considerations of novel thermoelectric materials for TE power generators

A large amount of research in thermoelectric materials has focused on increasing the Seebeck coefficient and reducing the thermal conductivity, especially by manipulating the nanostructure of the thermoelectric materials. Because the thermal and electrical conductivity correlate with the charge carriers, new means must be introduced in order to conciliate the contradiction between high electrical conductivity and low thermal conductivity as indicated by Weiling and Shantung (Weiling & Shantung, 2004). Among the vast number of materials known to date, only a relatively few are identified as thermoelectric materials. Today's most thermoelectric materials, such as Bismuth Telluride (Bi_2Te_3)-based alloys and Lead Telluride (PbTe)-based alloys, have a $Z\bar{T}$ value of around unity (at room temperature for Bi_2Te_3 and 500-700K for PbTe). However, at a $Z\bar{T}$ of 2-3 range, thermoelectric power generators would become competitive with other power generation systems (Riffat & Ma, 2003; Weiling & Shantung, 2004). In general, effective thermoelectric materials should have a low thermal conductivity but a high electrical conductivity. Rowe (2006) reported that conventional thermoelectric materials (those which are employed in commercial applications) can be conveniently divided into three groupings based on the temperature range of operation. Alloys based on Bismuth (Bi) in combinations with Antimony (An), Tellurium (Te) or Selenium (Se) are referred to as low temperature materials and can be used at temperatures up to around 450 K. The intermediate temperature range – up to around 850 K is the regime of materials based on alloys of Lead (Pb) while thermoelements employed at the highest temperatures are fabricated from Silicon-Germanium (SiGe) alloys and operate up to 1300 K. Although these materials still remain the cornerstone for commercial and practical applications in thermoelectric power generation, significant advances have been made in synthesising new materials and fabricating material structures with improved thermoelectric performance. Efforts have focused primarily on improving the material's figure-of-merit, and hence the TE conversion efficiency, by reducing the lattice thermal conductivity (Rowe, 2006).

Attempts are also being made to improve the competitiveness of thermoelectrics in directions other than by improving the figure-of-merit. In particular, efforts have focused on increasing the electrical power factor, decreasing cost and developing environmentally friendly materials. For example, considering the electrical power factor as the dominant parameter, it has initiated a search for materials with high power factors rather than conversion efficiency. Considerable success has been made in synthesising materials, particularly attractive for waste-heat recovery. For example, it is reported in (Rowe et al., 2002) that the rare earth compounds $YbAl_3$, although possessing a relatively low figure-of-merit, has a power factor at least double that of any other reported in the literature, which operates over the temperature range of a waste heat source. MgSn has almost the same performance but costs less than 25% of the price (Rowe, 2006). Another recent direction to improve the competitiveness of thermoelectric materials, other than by improving the figure-of-merit, is by developing novel thermoelectric module shapes. As discussed previously, thermoelectric modules have typically plate-like shapes (see Fig. (8)) and fabricated from bulk semiconductors such as Bi_2Te_3 and PbTe, making them rigid and unsuitable for covering relatively large surfaces that are curved or non-flat (e.g. circular tubes) used in waste heat recovery applications. Also, this conventional configuration is suitable for applications where the flow of heat is perpendicular to the ceramic plates. In addition, in order to improve thermal contact to heat sources of arbitrary geometry, it is desirable to fabricate thermoelectric modules which can conform easily to a surface. Therefore, recent research has been focused on developing novel flexible- and cylindrical-based shapes of thermoelectric power generators. For example, Yadav et al. (2008) proposed and demonstrated the use of flexible and cost-effective thermoelectric power generator based on thin film thermoelectric on flexible fiber substrates. Min and Rowe (2007) have also recently developed a novel tube-shape thermoelectric module for power generation.

3.3 Fundamental concept and energy conversion aspects of direct generation of electricity using thermophotovoltaic alternative technology

The basic theory and operation of a thermophotovoltaic power generation system is shown in Figure 9. The TPV system mainly consists of the following components: (i) a high-temperature source of heat, (ii) a radiator (absorber/emitter component), (iii) a reflector (spectral controller), (iv) a semiconductor converter, (v) a low-temperature heat-sink, and (vi) an electrical load with a power conditioner, as shown in Figure 9. Typical fuel sources used in driving TPV systems includes (Coutts, 1999): (1) solar-fuelled TPV, bio-fuelled TPV, (3) nuclear-fuelled TPV, (4) liquid-hydrocarbon-fuelled TPV, (5) diesel-fuelled TPV, (6) propane-fuelled TPV, and (7) natural-gas-fuelled TPV. In a TPV device, the high-temperature heat source (e.g. a flame generated from a burner) produces thermal energy which is then absorbed by the emitter (radiator). The absorbed heat is then radiated (emitted) in form of high-energy photons by the emitter which is received and absorbed by the TPV semiconductor converter. There are basically two different types of emitters, namely broadband emitters and selective emitters. Blackbody is considered to be a typical broadband emitter. Selective emitters normally exhibit a high emittance in the spectral range utilizable for the TPV converter photocells (Chia & Feng, 2007). Some of the unabsorbed long-wavelength photons can be recirculated, using the reflector (also known as spectral filter), back to the emitter to be reabsorbed for maximum conversion efficiency. The TPV semiconductor converter (photovoltaic cell) then converts the photons into electrical power when connected to an electrical load. The optional heat sink is used to dissipate the low-grade heat to cool the converter.

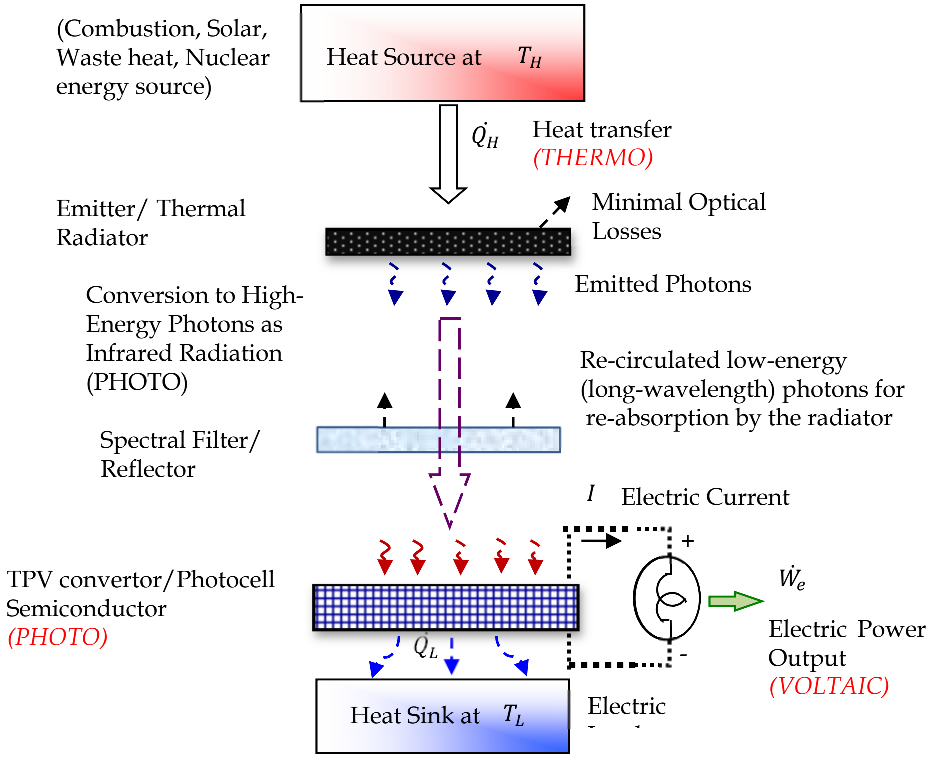

Fig. 9. A schematic diagram illustrating the basic concept of a simple thermophotovoltaic electric power generation system.

3.3.1 Energy-conversion aspects of TPV power generation systems

A thermophotovoltaic power generator is also a thermodynamic heat engine so that its thermal efficiency is given previously by Eq. (12). The output electric power $\dot{W}_e$ can be expressed in terms of DC electric current and voltage generated by a TPV system, as

$$W_e = IV \qquad Z = \frac{\alpha^2}{kR} \tag{14}$$

Lal and Blakers (2009) reported that the energy-conversion efficiency of the TPV system can be expressed as the ratio of electrical power output to the power required to keep the blackbody radiating emitter at a constant temperature, given by

$$\eta_{TPV} = \frac{I_{SC}V_{OC}FF}{\left(P_{radiated} - P_{returned}\right)} \tag{15}$$

Where, the power returned is the power recirculated by the reflector (spectral filter) and the Fill Factor (FF) of the photocell converter is given by

$$FF = \frac{I_{mp} V_{mp}}{I_{sc} V_{oc}} \quad (16)$$

Also, limited by the second-law of thermodynamics, the ideal efficiency of a thermal power cycle, which takes place as the TPV power system continuously performs, operating as a reversible heat engine is Carnot efficiency given previously in Eq. (7). In general, the higher the temperature of the heat source, the higher the ideal efficiency at a fixed heat-sink temperature. More specifically, Coutts (1999) reported Carnot efficiency in terms of the emitter (radiator) absolute temperature, T_{emit}, and the TPV photocell converter absolute temperature, T_{cell} , given by

$$\eta_{\max} = 1 - \frac{T_{cell}}{T_{emit}} \quad (17)$$

For example, for a TPV system performing between a radiator temperature at 500 ^{o}C (773.15 K) and photocell at 40 ^{o}C (313.15 K), the maximum efficiency of the TPV system can be calculated using Eq. (17) to be approximately 60%. However, for a real TPV power cycle operating between the same two temperature limits would have lower efficiency due to its thermal losses and inherent irreversibilities. In general, the ideal efficiency sets the upper limit for the thermodynamic performance of a TPV system and aids in optimizing designs and performances of these power generation systems. The overall energy conversion efficiency of a TPV system is the product of the discrete efficiencies mainly of the heat source, the emitter (radiator), the reflector, and the converter, given by (Chia & Feng, 2007)

$$\eta_{TPV} = \eta_{HS} \eta_E \eta_R \eta_C \quad (18)$$

Datas and Algora (2009) indicated that the overall efficiency of a TPV system cannot generally be formulated as the multiplication of the efficiency of each of the isolated components that makes up the system. It is because the relationship between these components is very complex and the efficiency of each component depends on all of them. They (Datas & Algora, 2009) recommended that the whole TPV system has to be considered simultaneously in determining its overall conversion efficiency. Badescu (2005) reported that experimental results showed that the overall TPV system efficiency is typically between 11 and 26% as far as broad-band (i.e. blackbody) emitters are considered.

3.3.2 Thermophotovoltaic system performance specifications

As discussed earlier, the TPV system mainly consists of four discrete components (excluding the load and optional heat sink), the possibly most complicated, in terms of technology, of which is the semiconductor photocell converter as reported by Coutts (1999). The incident radiation on the TPV photocell converter is typically provided by a radiating surface at a temperature in the approximate range of 1300-1800 ^{o}C (Coutts, 1999). During TPV energy conversion, the photon energy of the thermal radiation must be matched to the bandgap of the TPV converter photocells. It was reported (Qiu & Hayden, 2006) that most of the studies on TPV have focused on developing low-bandgap photocells (0.50–0.74 eV) such as GaSb and GaInAsSb photocells. These photocells are capable of converting a significant portion of infrared radiation from thermal radiators at a typical radiator temperature of 1473–1723 K, which is of interest to practical combustion systems. It was also reported (Qiu & Hayden, 2006) that the typical range of bandgaps for achieving high conversion efficiencies using emitter temperatures of 1000-2000 K is between 0.5 and 0.75 eV or slightly higher. Lal and Blakers (2009) reported that ideally, TPV photocells would have a bandgap of 0.6-0.9 eV to take into account of the temperature range of 1300-2000 K for a practical TPV emitter. The conventional silicon photocells have low cost (~ US$ 0.1/cm^2), high efficiency (> 20% under sunlight) (Lal & Blakers, 2009) and commercially available in large quantities (Qiu & Hayden, 2006), but the operating bandgap of 1.1 eV exceeds the optimum value. Lal and Blakers (2009) recommended the use of novel silicon silver photocells technology since it offers a method of fabricating highly efficient (>20%) thin silicon photocells in TPV systems. Silver-based photocells can be made up to a factor of 10 times thinner than conventional silicon photocells; current silver photocells have typical length 50-120 mm, width of 0.5-2 mm and thickness 20-100 μm (Lal & Blakers, 2009). The development of a low-cost low-bandgap TPV photocell which is described in (Heide et al., 2009). Chan et al. (2010) reported that in recent years, most of the research on TPV systems has been directed towards relatively lower-temperature (900-1100 ^oC) applications. Chan et al. (2010) also reported important benefits of using lower-temperature TPV as compared to its high-temperature counterpart; namely, (1) low-bandgap photocells convert a much larger portion of the infrared spectrum into electricity, thus enhancing output power density and maximizing efficiency, (2) the reduced temperature induced stresses, larger spectrum of available materials, and better material stability thus extending the possible design space. It was reported (Coutts, 1999) that the radiated spectrum extends across a wide wavelength range and, for a radiator temperature of 1500 K, the peak in the radiated spectrum occurs at about 2.5 μm. The emissivity is unity over the entire spectral range for a blackbody radiant surface. Badescu (2005) reported that using broadband emitters (radiators) is simpler than using selective emitters, it is easier to manufacture, may be more durable, and is less labor-intensive. Qiu and Hayden (2007) reported that an optical filter (reflector) reflects the non-convertible infrared energy back to the radiator and thus the use of an optical filter improves the spectral efficiency for optimal TPV system performance.

4. Conclusion

An increasing concern of environmental issues of greenhouse gas emissions, being responsible for global warming & climate change, environmental pollution, and the limitations and conservation of natural energy resources have recently resulted in extensive research into innovative nonconventional renewable & alternative clean energy technologies for generating electrical power. Some of these innovative & emerging technologies include: renewable low-temperature geothermal energy, thermoelectric and thermophotovoltaic green power generation technologies. This chapter introduced and presented fundamental concepts of these technologies. Innovative features, applications, limitations, specifications, and energy performance aspects of these nonconventional power generation technologies were also presented and discussed. A number of successful renewable and clean low-temperature geothermal energy binary ORC plants were installed in different locations worldwide which demonstrated the ability of this promising green technology for generating electricity. The vast low-temperature geothermal resources found widely in most continental regions have not received much attention for electricity generation. Continuous development of innovative drilling and ORC power generation technologies and other factors make this nonconventional, renewable and clean energy source one of the best future viable, alternate and available source to meet the required future electricity demand worldwide, significantly reducing GHG emissions and mitigating global climate change. Much of the recent research activities on applications of TE power generation have been directed towards utilisation of industrial waste heat. In this large-scale application, TE power generators offer a potential alternative of green electricity generation powered by waste-heat energy that would contribute to solving the worldwide energy crisis, and the same time help reduce environmental global warming. Future developments in this area seem to focus onto finding more innovative TE materials that could handle higher temperatures from various industrial heat sources at a feasible cost with more efficient energy performance. Future developments of more novel TE module geometries and configurations would make this technology more practical and attractive in applications where sources of waste heat have arbitrary shapes. There have been some causes for limiting the applications of TPV power generation technology. Some of the limiting factors of TPV systems applications and advancement are spectral filtering, low TPV conversion efficiency, the optimization of individual components rather than the system as a whole, adequate systems modeling and thermal management. One of the future TPV technology developments would be in designing high-performance TPV power generators, the improvement of TPV converters materials and total system energy-conversion optimization.

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The failure of the UN climate change summit in Copenhagen in December 2009 to effectively reach a global agreement on emission reduction targets, led many within the developing world to view this as a reversal of the Kyoto Protocol and an attempt by the developed nations to shirk out of their responsibility for climate change. The issue of global warming has been at the top of the political agenda for a number of years and has become even more pressing with the rapid industrialization taking place in China and India. This book looks at the effects of climate change throughout different regions of the world and discusses to what extent cleantech and environmental initiatives such as the destruction of fluorinated greenhouse gases, biofuels, and the role of plant breeding and biotechnology. The book concludes with an insight into the socio-religious impact that global warming has, citing Christianity and Islam.

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