DEVELOPMENT AND CHARACTERIZATION OF SANDWICH HYBRID PHOTOVOLTAIC-THERMOELECTRIC GENERATOR USING SHINGLE AS A THERMAL BUFFER FOR EFFICIENCY IMPROVEMENT

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DEDICATION

I dedicated this work to the family of Alhaji Abubakar Baban Dhul, and my mother Hajiya Maryam Adamu.

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ABSTRACT

Photovoltaic (PV) systems suffer from significant thermal energy loss, inextricably linked to the photo-electric conversion process due to the high PV operating temperature above the 25 ^{o}C standard test conditions (STC). The direct contact of TEG with PV in the PV-TEG hybrid system also increases the temperature, this always decreases about 30 % in the system output power and about 0.1-0.5% efficiency drop for every 1 ^{o}C rise above STC. A Hybrid Photovoltaic-Thermoelectric Generators (PV-TEG) are system that can generate both electricity and heat. The TEG in the hybrid system provides a solution to significant temperature increases by cooling the PV cells and therefore increasing electrical power output. An integrated hybrid system where the PV modules are placed on the top of a shingle while the TEGs were attached to the attic side of the shingle for improved performance is proposed and investigated in this study. The objectives of the study are therefore to simulate the system using ANSYS and MATLAB Software, develop a hybrid PV-TEG system called sandwich shingle configuration for a housing roof experimentally so as to analyse the effect of the operating temperature, output voltage, and output current on TEG alone and PV alone on the system performance and to investigate the hybrid PV-TEG system power and efficiency using a single layer positioned between the PV and TEG through real-time experiment. The system consists of two-unit 100W PV panels in series, 192 TEGs (40 mm x 40 mm) placed in both series and parallel to extract excess heat-accumulating on the PV cells and 96 heatsinks at the TEG cold junction. The results indicate that the hybrid system can perform better than the PV stand-alone system in sunny, rainy, and cloudy weather conditions with an average maximum power of 185 W, 173 W, and 67.3 W. The system also achieved efficiencies of 23.72 %, 22.66 % and 21.78 %, respectively. In the field of PV surface absorptivity and photon management of hybrid PV-TEG, more research is recommended using heat pipes, nanofluid and incorporated technology to develop the TEG directly onto the backside of the PV for efficiency improvement. In conclusion, the hybrid PV-TEG system using a shingle was developed for enhanced electrical energy generation and is beneficial to both scientific and rural communities as the quest for clean and sustainable energy increased.

ABSTRAK

Sistem fotovoltaik (FV) mengalami kehilangan tenaga haba yang ketara, berkait rapat dengan proses penukaran foto-elektrik disebabkan oleh suhu operasi PV yang tinggi melebihi syarat ujian standard (STC) 25 ^{o}C. Sentuhan langsung TEG dengan PV dalam sistem hibrid PV-TEG juga meningkatkan suhu, ini sentiasa mengurangkan kira-kira 30 % dalam kuasa keluaran sistem dan kira-kira 0.1-0.5% penurunan kecekapan untuk setiap kenaikan 1 oC melebihi STC. Penjana Fotovoltaik-Termoelektrik Hibrid (PV-TEG) ialah sistem yang boleh menjana kedua-dua elektrik dan haba. TEG dalam sistem hibrid menyediakan penyelesaian kepada peningkatan suhu yang ketara dengan menyejukkan sel PV dan oleh itu meningkatkan output kuasa elektrik. Sistem hibrid bersepadu di mana modul PV diletakkan di bahagian atas sirap manakala TEG dipasang di bahagian loteng sirap untuk prestasi yang lebih baik dicadangkan dan disiasat dalam kajian ini.Oleh itu, objektif kajian adalah untuk mensimulasikan sistem menggunakan Perisian ANSYS dan MATLAB, membangunkan sistem PV-TEG hibrid yang dipanggil konfigurasi sirap sandwic untuk bumbung perumahan secara eksperimen untuk menganalisis kesan suhu operasi, voltan keluaran dan arus keluaran. pada TEG sahaja dan PV sahaja pada prestasi sistem dan untuk menyiasat kuasa dan kecekapan sistem PV-TEG hibrid menggunakan satu lapisan yang diletakkan di antara PV dan TEG melalui percubaan masa nyata. Sistem ini terdiri daripada dua unit panel PV 100W secara bersiri, 192 TEG (40 mm x 40 mm) diletakkan dalam kedua-dua siri dan selari untuk mengekstrak lebihan terkumpul haba pada sel PV dan 96 unit haba di persimpangan sejuk TEG. Keputusan menunjukkan bahawa sistem hibrid boleh berprestasi lebih baik daripada sistem bersendirian PV dalam keadaan cuaca cerah, hujan dan mendung dengan purata kuasa maksimum 185 W, 173 W, dan 67.3 W. Sistem ini juga mencapai kecekapan 23.72 %, 22.66 % dan 21.78 %, masing-masing. Dalam bidang penyerapan permukaan PV dan pengurusan foton PV-TEG hibrid, lebih banyak penyelidikan disyorkan menggunakan paip haba, cecair nano dan teknologi yang digabungkan untuk membangunkan TEG terus ke bahagian belakang PV untuk peningkatan kecekapan. Kesimpulannya, sistem PV-TEG hibrid menggunakan sirap telah dibangunkan untuk penjanaan tenaga elektrik yang dipertingkatkan dan bermanfaat kepada masyarakat saintifik dan luar bandar kerana usaha untuk tenaga bersih dan mampan meningkat.

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LIST OF SYMBOL AND ABBREVIATIONS

AM	-	Air Mass
Bi2Te3	-	Bismuth telluride
CdTE	-	Cadmium telluride
CIGS	-	Copper indium gallium selenide
CoSb3	-	Copper antimony
CPV-TEG	-	Concentrated Photovoltaic-thermoelectric
DAQ	-	Data Acquisition System
DSSC	-	Dye-sensitized solar cell
GaAs	-	Gallium arsenide
GaSb	-	Gallium antimonite
GeTe	-	Germanium telluride
I-V	-	Current-Voltage
MCHP	-	Microchannel heat pipe
NI	-	National Instrument
OECD	-	Organization for Economic Cooperation and Development
PCM	-	Phase Change Material
PV	-	Photovoltaic
PV-TEG	-	Photovoltaic/thermoelectric generator
TEG	-	Thermoelectric generator
RTC	-	Real-Time Clock
SSA	-	Solar selective absorber

Greek symbols

η	-	Efficiency, %
σ	-	Electrical conductivity, S/m
α	-	Seebeck coefficient, V/K
κ	-	Thermal conductivity, W/m/K
Ω	-	Ohms

Subscripts

h	-	Hot side
c	-	Cold side
sh	-	Shingle

Nomenclature

A	-	Area, m
C	-	Concentration ratio
FF	-	Fill factor
G	-	Solar irradiance, W/m2
Isc	-	Short circuit current, A
Pin	-	Input power, W
T	-	Temperature, K
T_h	-	TEG hot side Temperature, ^oC
T_c	-	TEG cold side Temperature, ^oC
T_{sh}	-	Shingle Temperature, ^oC
Voc	-	Open circuit voltage, V
ZT	-	Figure of merit

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Renewable energy sources, such as hydroelectric energy, wind energy, solar energy, bioenergy, and geothermal energy, are energy sources replenished continuously throughout human existence [1]. These energies can be harnessed directly or indirectly from the sun for human use, they are called renewable energy sources because they are naturally replenished. Day after day, the sun shines, plants grow, wind blows, and rivers flow. While geothermal energy is heat within the earth. The word geothermal comes from the Greek words geo (earth) and therme (heat). Geothermal energy is a renewable energy source because heat is continuously produced inside the earth. People use geothermal heat for bathing, to heat buildings, and to generate electricity. In 2020, renewable energy was around 181 gigatonnes (GW), accounting for more than 29 % of global electricity production [2]. Renewable energy is a form of energy that is both clean and abundant. It emits a minimal quantity of carbon dioxide and greenhouse gases. It is also widely recognized for its potential depletion as a sustainable energy source [3]. Other energy sources, such as fossil fuels, are finite resources depleted in the future. Renewable energy can benefit developing nations by reducing their reliance on fossil fuels [4].

Solar energy is radiant Sunlight and heat used as photovoltaic or solar thermal energy. It has distinctive properties which are clean, limitless, environmentally friendly and inexhaustible. Such features has attracted the energy sector to renewable energy sources. It is the most effective option for meeting energy requirements responsibly and ensuring energy security while minimizing greenhouse gases substantially [5].

Various power generation systems can be combined to improve the conversion efficiency of solar irradiation into energy. Hence, creating more efficient systems and combining energy harvesting mechanisms to extract solar energy is one of the most exciting research areas as a hybrid PV-TEG system becomes necessary [6].

Thermoelectric generators (TEGs) are bi-directional energy converters that can be used as generators or coolers [7]. The TEG can convert electrical energy to thermal energy and vice versa depending on the operating configuration. Solid-state operations, gas-free emissions, maintenance-free operation, enormous scalability, zero pollution, and long-term operational reliability are some of the benefits of thermoelectric energy converters [8].

Photovoltaic (PV) and thermoelectric generators (TEG) are semiconductor devices that can be integrated to convert solar energy sources into electrical power, improving power output and system efficiency. A PV-TE hybrid system is comprised of a PV panel and a TEG that can both be used to generate electricity. Using the Seebeck effect, a temperature difference between the hot and cold sides of thermoelectric devices would result in increased electrical power output from the TEG [9].

1.2 Problem Statement

Hybrid Photovoltaic Thermal Electric Generator (PV-TEG) system's energy output is improved energy with electricity and heat. One of the critical concerns available to the photovoltaic (PV) technologies is the efficiency drop caused by relatively high operating temperatures of the PV panel when exposed to high solar irradiation during the day [10][11]. The major weakness of PV panels is the efficiency drop of 0.1-0.5% whenever the PV operating temperatures is above standards test condition (STC) values of 25°C and 1000 W/m^2 valves for every 1°C rise [12].

Therefore, the essential factors for attaining good performance and efficiency enhancement of the PV system depend primarily on effective PV cell cooling, converting the excess heat into additional power output and thermal energy [13][14]. Consequently, the following PV-TEG system problems have been identified:

1. Due to the direct contact of TEG with PV in the PV-TEG hybrid system, the thermal contact resistance between the photovoltaic-thermoelectric interfaces are the most critical to reduce PV lifespan with the operating temperature increased as the irradiance increases.

2. The high PV operating temperature decreases the output power and efficiency of the hybrid system up to 30 % power reduction and about 0.1-0.5% efficiency drop for every 1 ◦C rise above 25°C.
3. The positioning of the TEG with the PV module in the hybrid system using the shingle is a significant problem, which is critical to heat reduction and thermal energy generation.

1.3 Aim and Objectives of the Study

To develop, characterize, and analyse the hybrid PV-TEG system, converting the thermal energy created in the photovoltaic cell into useful electrical power and evaluating the combined system's energy efficiency using the roofing shingles.

Based on the identified research problem, the research focused on the following research objectives.

1. To simulate a unit TEG and the hybrid PV-TEG system using ANSYS and MATLAB Software and investigate the power and efficiency of the PV alone and TEG alone system.

2. To develop a hybrid PV-TEG system called sandwich shingle configuration using a for a housing roof experimentally so as to analyse the effect of the operating temperature, output voltage, and output current on TEG alone and PV alone systems as the solar irradiance is increased on a system performance.

This is to address the power reduction efficiency drop of 0.1-0.5% due to every 1°C rise above 25°C.

3. To investigate and recommend the hybrid PV-TEG system power and efficiency using a single layer positioned between the PV and TEG with an improved efficiency for enhanced energy generation.

1.4 Scope of the project

This study's scope is limited to the overall performance and efficiency evaluation of the hybrid PV-TEG system through experiments under real-life atmospheric conditions and simulation.

The materials used for the experiment are two (2) units of PV panels, each 100 W, One hundred and ninety-two (192) units of TEGs, ninety-six (96) units of heatsinks, thermal pastes. Arduino based and National Instrument (NI-DAQ 9014) was used for data acquisition, while LabView was used for data monitoring and visualization. RA-RS-N01-JT pyranometer was used for solar radiation measurement, while a K-type thermocouple was used for temperature monitoring.

The hybrid PV-TEG system was developed and installed for real-time monitoring at the Block B10 Laboratory, Universiti Tun Hussein Onn Malaysia (UTHM) in Parit Raja, Batu Pahat, Johor, Malaysia (1.8586° N, 103.0856° E) from 1st November 2020 to 3oth June 2021. The research will be done with the following;

i. Two (2) units of 12V, 100W monocrystalline PV cell and a metal deck shingle will be used for the research [13].

ii. One hundred and nine-two (192) units of 40 by 40 Bismuth Telluride TEG with cold junction temperatures (T_C) of 25 °C and hot junction temperatures (T_H)of 65°C [14].

iii. The types of software for this research :

a. LabView Software, this software will be used during the laboratory experiment to serve as the data recording interface to access the experimental data from the National Instrument through the DAQ for data visualization before the analysis

b. MATLAB Software will be used to perform the data analysis and system simulation.

1.5 Outline of the Thesis

This thesis contains five chapters. The contents of each chapter are presented in the following paragraphs.

Chapter 1 discusses the motivation behind the research. The chapter contains background to the study, the problem that warrants the study, the aim of the research, the research objective, and finally, the scope of the research.

Chapter 2 reviewed the relevant literature for the achievement of the research aim. The chapter reviewed the general renewable energy sources, photovoltaic systems, thermoelectric generators, and hybrid PV-TEG. Previous studies and research done on the PV-TEG have also been reviewed.

Chapter 3 presented the methodology used in the research. This includes outdoor experiments and modelling, data collection and instrumentation. Lastly, the analysis and Simulation were done with MATLAB software.

Chapter 4 presented the result of the study based on experimental and simulations in terms of the PV, TEG and the hybrid system power and efficiency.

Chapter 5 presents the conclusion, recommendation and direction for further research is also provided in the chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This section's primary purpose focuses on the reviews of renewable energy sources, photovoltaic systems, thermoelectric generators, and hybrid PV-TEG. In addition, some previous studies and research done on the PV-EG will be reviewed. The various forms of renewable energy studies such as solar, TEG, and hybrid PV-TEG systems have been conducted to determine the potential and efficient power output performance. The increasing global demand and the adverse effect of non-renewable fossil fuels on the environment motivated considerable research. Attention in a wide range of engineering applications of renewable sources is on the increase. This chapter presents a comprehensive of the previous work done on PV-TEG and its associated challenges.

2.2 Contribution of Renewable Energy in 2020

Renewable energy use increased by 3% in 2020, while demand for all other fuels decreased [15]. The percentage increase of renewable energy sources in 2020 is depicted in Figure 2.1.

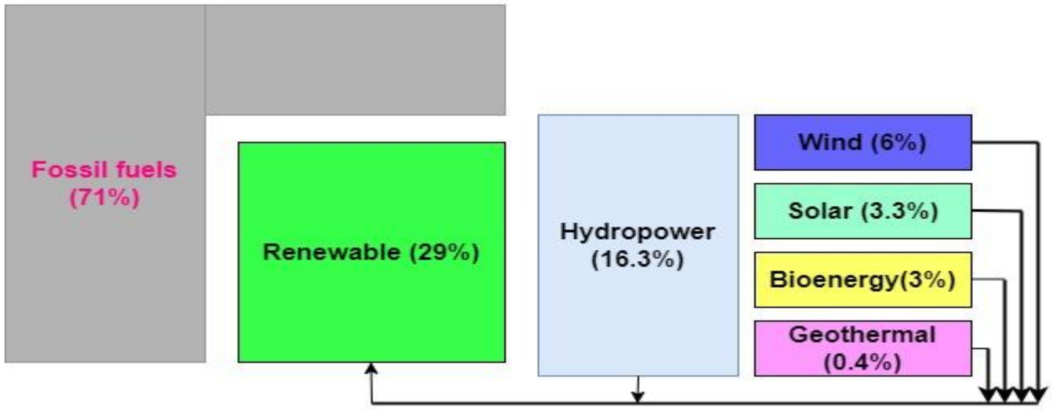

Figure 2.1: The contribution of renewable energy sources in 2020

The global energy consumption trend, as shown in Figure 2.2, predicts that the contribution of fossil fuels (petroleum, natural gas, coal) in the energy mix in 2040 will be 78% despite the faster-growing trend of non-fossil fuels (renewable and nuclear energy) [16]. This clearly indicates that more work is urgently required in the renewable energy sector for clean and sustainable energy sources.

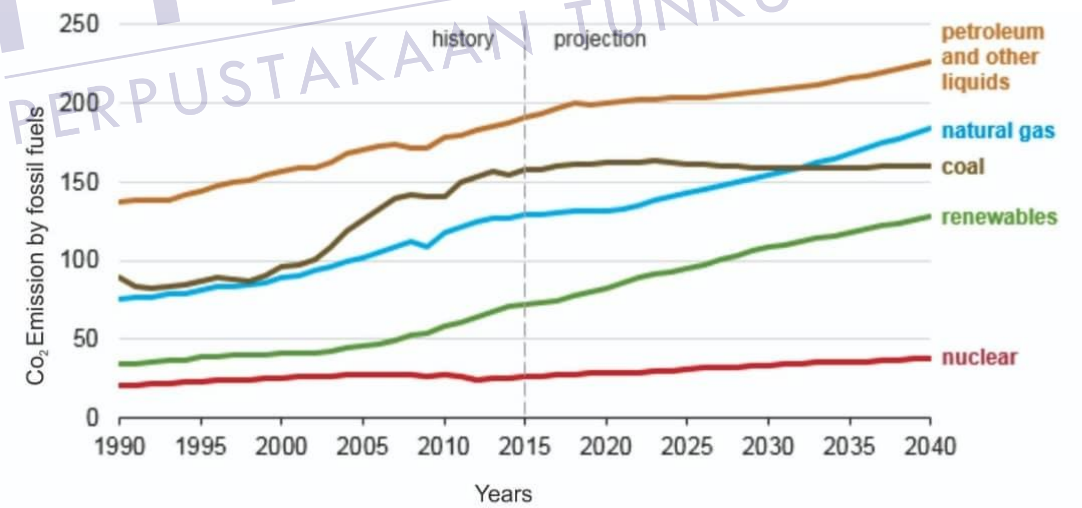

Figure 2.2: World energy consumption by source up to 2040.

The world's energy resources include traditional fossil fuels such as petroleum ,coal, natural gas, coal, oil, gas, modern solar energy and nuclear energy [17]. Fossil fuels meet the majority of energy needs [18]. These are relatively inexpensive and simple to explore and exploit, and they will continue to be the dominant form of energy, accounting for roughly 60% of additional energy in 2035 [19]. However, the major issue with fossil fuels is that they contribute to climate change by emitting tons of carbon dioxide (CO_2) and other pollutants during combustion. According to Figure 2.3, global energy-related CO_2 emissions are expected to hit 43.2 billion metric tons by 2040 [20].

Furthermore, the fossil fuel-based power generation system is non-renewable; the consumed reserves are not naturally replenished. The amount of available energy resources on this globe is minimal. The primary energy sources, such as coal, mineral oil, and natural gas, rapidly disappear due to ever-increasing usage [21].

The international energy outlook 2017 (IEO) Reference case forecasts increased global consumption of commercially available energy across all fuel sources through 2040, except for coal, where demand is flat. Renewable energy sources are the world's fastest-growing energy source, with demand increasing by an average of 2.3 % per year between 2015 and 2040. Nuclear power is the world's second-fastest-growing energy source, with consumption rising by 1.5 % annually during that period.

Although non-fossil fuel usage is projected to grow quicker than fossil fuel consumption, by 2040, fossil fuels would account for 77 % of total energy consumption. Natural gas is anticipated to witness the fastest fossil fuel in the coming years. Natural gas consumption worldwide is increasing at a rate of 1.4 % per year. Natural gas has a strong competitive position due to abundant natural gas reserves and growing production, particularly tight gas, shale gas, and coal-bed methane. The world's primary source of energy usage is still primarily petroleum-based liquid fuels. However, the share of liquid energy usage in global energy demand will reduce from 33% in 2015 to 31% in 2040. Oil costs have been continuously rising, prompting many energy consumers to switch to more energy-efficient devices and, where possible, to abandon liquid fuels. Global coal use remains steady in the IEO2021 Reference case, despite considerable growth in the 2000s [22]. Natural gas, renewable energy, and nuclear power (in China) are gradually replacing coal in industrial operations, and demand for coal is dwindling. China is the world's largest coal consumer; however, from 2015 to 2040, China's coal consumption is predicted to reduce by 0.6 % each year, while coal consumption in the organization for economic cooperation and development (OECD) countries as a whole is projected to fall by 0.6 % per year.

In addition, fossil fuels are being depleted in an unsustainable manner. Furthermore, governments worldwide encourage this industry to keep prices low, putting strain on the currency. Considering clean energy is a requirement for long-term growth, expanding technologies to employ renewable energy sources to replace fossil fuels effectively has become necessary [23].

Renewable energy sources are in the spotlight in the energy industry, given the rising energy demand, rising energy prices, and a strengthening of global warming remedies. Renewable energy has emerged as the world's fastest-growing energy source in the previous decade, with usage expected to rise by 2.8 % per year between 2012 and 2040. On the other hand, nuclear power will grow at a pace of 2.3 % per year over the same period [24]. The Energy-related CO2 emission by fuel types, 1990-2040 is depicted in Figure 2.3.

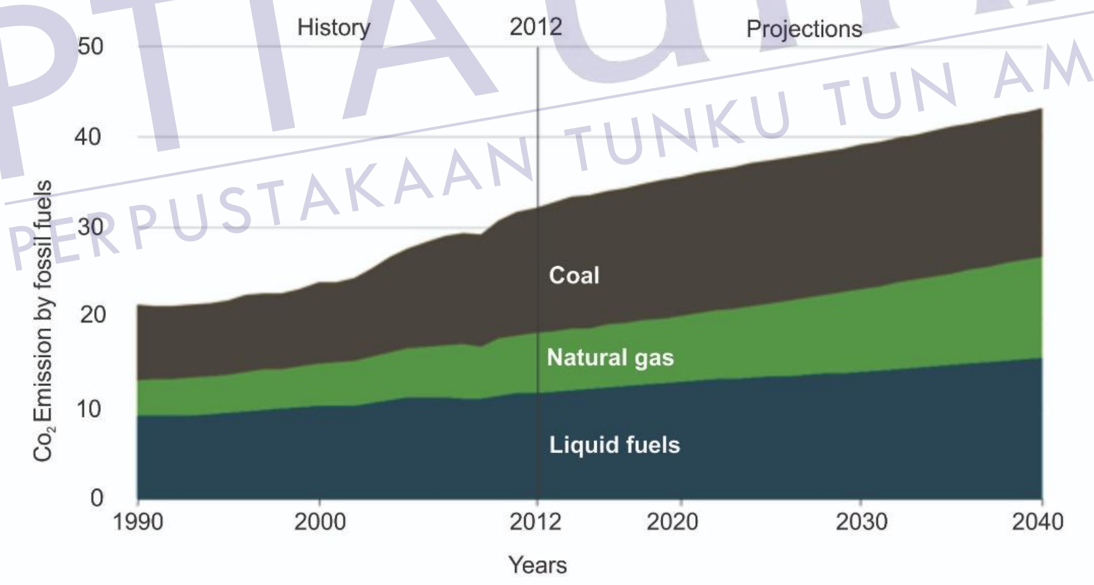

Figure 2.3. Energy-related CO_2 emission by fuel types, 1990-2040.

2.3 Solar Energy

Solar energy is a vast renewable energy source. A sustainable energy from renewable energy is a promising emerging energy worldwide to mitigate fossil fuel pollution [25][26]. Solar energy is a limitless and eternal energy source. The amount of solar energy absorbed by the globe is roughly 1.8 x 1010 MW, which is millions of times higher than the world's current rate of energy use [27][28]. Solar energy is one of the most potential non-conventional energy sources since it can continually satisfy all of the world's current and future energy requirements [29]. It is a clean energy source available in practically every corner of the planet, considerably lowering greenhouse gas emissions. Photovoltaic systems, solar thermal, solar heating, and other technologies can all be used to harness the sun [30].

In essence, solar energy has the potential to meet the world's energy needs if harvesting and supply technologies are readily available. Every year, about four million exajoules (1 EJ = 1018J) of solar energy reach the globe, with 5,104 EJ quickly ready to be harvested. Despite its enormous potential and growing popularity, solar energy's contributions to the world energy supply remain negligible [31][32]. The hybrid PV-TEG system is one way to freely harvest the available solar thermal energy and improve PV cell efficiency, it will be achieved by integrating PV systems with thermoelectric generators (TEG).

The hybrid PV-TEG system produces better power, is more efficient, and emits less waste heat. It is developed to convert the maximum amount of solar irradiation into electrical power. PV cells usually use a small proportion of incoming solar irradiation to generate electricity while turning a significant portion of the irradiation into waste heat. As a result, the temperature of the PV cells rises, reducing the energy efficiency of the PV system. Figure 2.4 displays a hybrid PV-TEG configuration. The proposed system comprises of a TEG with a heat-sink that uses waste heat energy from the PV system to maximize power generation and decrease PV cell temperatures, increasing the efficiency of the hybrid PV-TEG system's energy conversion.

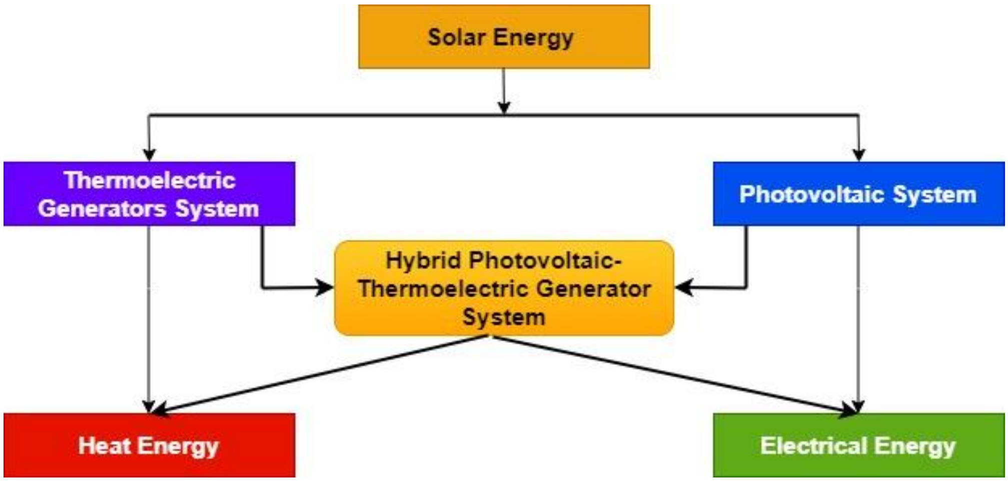

Figure 2.4: Solar Energy Conversion System

2.4 Solar Thermal

Solar thermal energy is produced by converting solar radiation into thermal or electrical energy for industries, businesses, and homes applications [33]. Figure 2.5 shows the solar radiation collection and conversion process of solar thermal. Solar collectors are used to collect solar radiation. After that, the radiations can be stored or directly used for warming the air or water for domestic, industrial or commercial use [34].

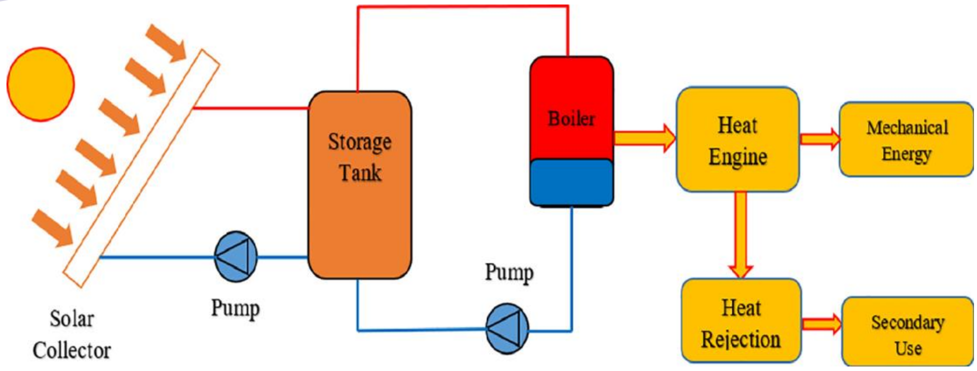

Figure 2.5: Solar thermal conversion system [34].

Solar thermal technology is utilized for the following applications: solar water heating, solar district heating and cooling, solar refrigeration, and solar desalination. There are four types of solar thermal energy technologies available in the market [35]:

1) Parabolic troughs; These concentrate sunlight onto a receiver tube containing a working liquid
2) Fresnel mirrors; Use multiple flat mirrors to concentrate solar sunlight onto a receiver tube
3) Power towers; An array of thousands of sun-tracking reflecting mirrors positioned in a field to concentrate solar radiation to a single point), and
4) Solar dish collectors; Concentrate power by focusing ST energy onto a single point situated above a reflector dish).

2.5 Photovoltaic systems

Electricity can be extracted from solar irradiance via the photovoltaic (PV) system. The PV system converts sunlight into electricity employing the principle of photovoltaic effect. The energy of photons is passed to the charge carriers every time sunlight reaches the solar module. Due to the electric field around the junction, the charge carriers split into positively charged holes and negatively charged electrons [36].

As shown in Figure 2.6, a PV system comprises interconnecting electrical components that generate electricity from sunshine and meet our daily energy needs [37].

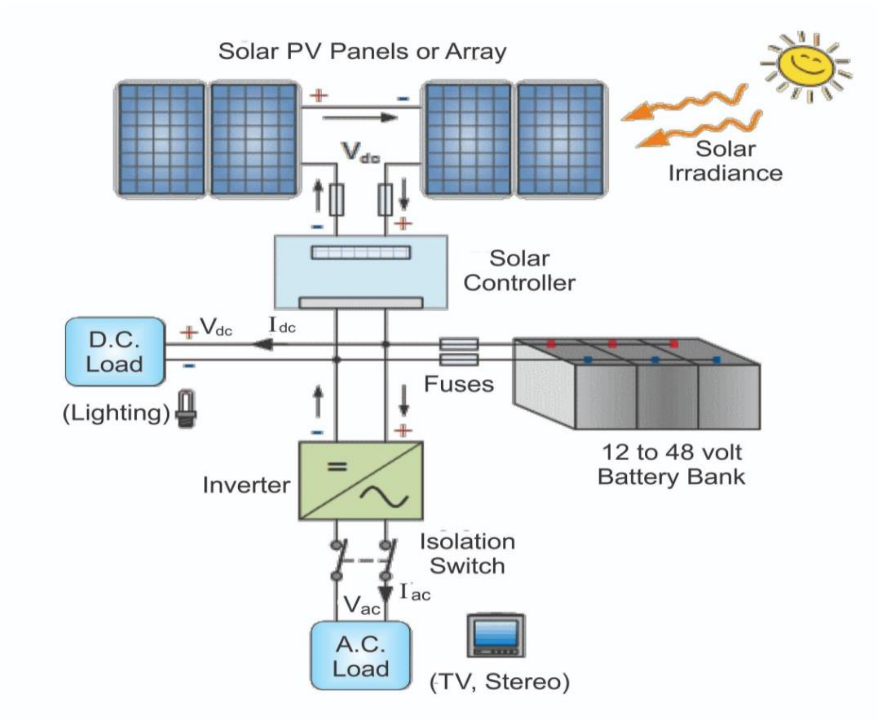

Figure 2.6: Stand-alone Photovoltaic System Components [37].

When a photovoltaic cell is exposed to sunlight, the photovoltaic effect produces a voltage or electric current. This effect makes solar panels worthwhile because it is how the panels' cells convert sunlight into electricity. Edmond Becquerel, a French physicist, first discovered the PV effect. He noticed that the cell's voltage increased when its silver plates were exposed to sunlight [38][39].

2.5.1 Photovoltaic cell

The essential component of a PV system is a photovoltaic cell, which converts sunlight into electricity. The cell is a type of semiconductor diode that converts electromagnetic radiation into direct currents. The following are a few examples of cell silicon, gallium arsenide, cadmium telluride, etc.

When the energy absorption is equivalent to or greater than the band energy, electrons are shifted from the valence band to the conduction bands [40]. This system produces electron-hole pairs, which diffuse and separate at the p-n junction of semiconductors due to the generated electric field. As a result, electrons are attracted to the negative side, whereas holes are pushed to the positive. Finally, as illustrated in Figure 2.7, electrons flow in the external circuit, and current is generated [41]. The maximum conversion efficiency comes from monocrystalline silicon cells[42]. There are two basic types of material with semiconductors, called positive type (p-type) and negative type (n-type). A monocrystalline silicon cell has the best conversion efficiency [43].

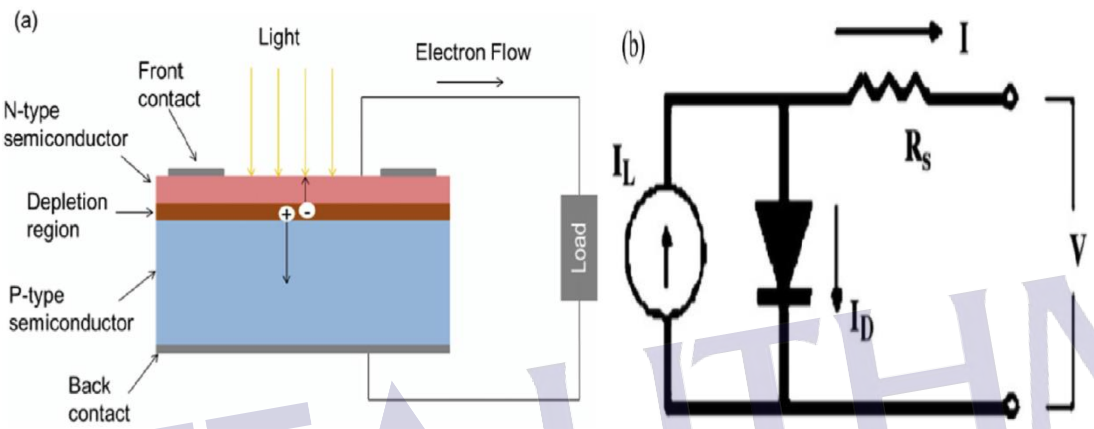

Figure 2.7: Photovoltaic cell (a) p-n junction structure and (b) simplified equivalent circuit [43].

Modelling photovoltaic cells and simulating their operation with software is relevant since it allows for simultaneous modelling of photoelectric and peripheral electronics. The equations below show that a solar cell with a parallel diode can be modelled as a current source [43].

$$I_D = I_o \left[exp\left(\frac{q(V+IR_S)}{\gamma KT_C}\right) - 1\right] \quad (2.1)$$

$$I_O = DT_{ab}^3 exp\frac{q\mathcal{E}G}{AKT_{ab}} \quad (2.2)$$

where D is the diode diffusion factor, $T_{ab}$is absolute temperature, I_OIs Reverse saturation current is q is the electron charge, $\mathcal{E}G$is material bandgap energy, K is Boltzmann constant, and A is the cross-sectional area. Depending on required voltage and current levels, solar cells are connected in series and parallel, respectively. The solar cell generator voltage and current can be obtained as,

$$V_g = I_g R_s \frac{N_S}{N_P} l_n \left(1 + \frac{N_P I_{Ph} - 1}{N_P I_O}\right) \quad (2.3)$$

where $R_S$is the series resistance, $N_S$is the number of cells in series, $N_P$is the number of cells in parallel and $I_{Ph}$is the cell photocurrent proportional to solar irradiance.

$$I_g = I_{Ph} - I_O exp\left(\frac{qV_g}{K_T} - 1\right) \quad (2.4)$$

where T is the cell temperature. Also, the PV cell short circuit current (I_{SC}) can be obtained by letting V_g= 0 and I_{SC}= I_{Ph}. this value varies with cell irradiance and the PV cell open-circuit voltage (V_{OC}) can be obtained by setting Ig = 0 thus,

$$V_O = \frac{K_T}{q} l_n \left[\frac{I_{Ph}}{I_O}\right] \quad (2.5)$$

The maximum output power of the PV is expressed as

$$\frac{d(V_g x I_g)}{dt} \quad (2.6)$$

$$V_{mp} = V_{OC} - \frac{KT}{q}\left[\frac{V_{mp}}{\frac{kt}{q}} + 1\right] \quad (2.7)$$

Fill factor (FF) can be expressed as

$$FF = \frac{V_{mp} x I_{mp}}{V_{OC} x I_{SC}} \quad (2.8)$$

The efficiency of the PV can be expressed as

$$\eta_{PV} = \frac{FF x V_{OC} x I_{SC}}{P_{in}} \quad (2.9)$$

where P_{in} is the incident power on the PV cell.

The temperature has a severe influence on photovoltaic cells [43]; as a result, many studies on PV systems have focused on improving efficiency through effective thermal management strategies. The efficiency of the solar cell is excellent under standard test conditions using Eq. (2.2). However, as given in Eq. (2.4) and in Figure 2.8, once the cell temperature rises above the STC, the efficiency of the solar cell drops. Figure 2.8 shows that the short circuit current I_{sc} increases repetitively with temperature and then saturates to a maximum before decreasing at high temperatures due to the cell's high temperature, which affects system performance. The open circuit voltage V_{oc}, on the other hand, increases linearly with temperature. The fill factor and efficiency, which are directly related to I_{sc} and V_{oc}, follow the letter variations. The trend can be explained by the mobility's behaviour, which is a temperature-activated process. According to the graph, the highest efficiency (9.7 %) occurred at I_{sc} 0.63 and V_{oc} 0.58 [44]. Figure 2.9 depicts the variation of the photovoltaic (PV) cell's current voltage (I-V) characteristic with temperature change. The effect is explained using solid state theory. The lower the open-circuit voltage and the higher the short-circuit current, the higher the temperature. This trend can be explained using band theory from solid state physics. As the temperature rises, the proscribed gap narrows and the Fermi energy level shifts toward the proscribed gap's centre. Both of these effects result in a lower potential barrier in the PN junction's band figure, and thus a lower photovoltaic voltage. Furthermore, narrowing the proscribed gap causes an increase in the generation of electron-hole pairs in the PN junction, as well as an increase in short-circuit current [45].

PVs operate better at reduced cell temperatures in general. The temperature coefficient is a property that describes how PV efficiency is affected by temperature. It is being used to measure how sensitive PV cells are to temperature changes. The temperature coefficient is commonly expressed as a normalized value of 25 °C or 298.15 K [46] to compare different PV cells.

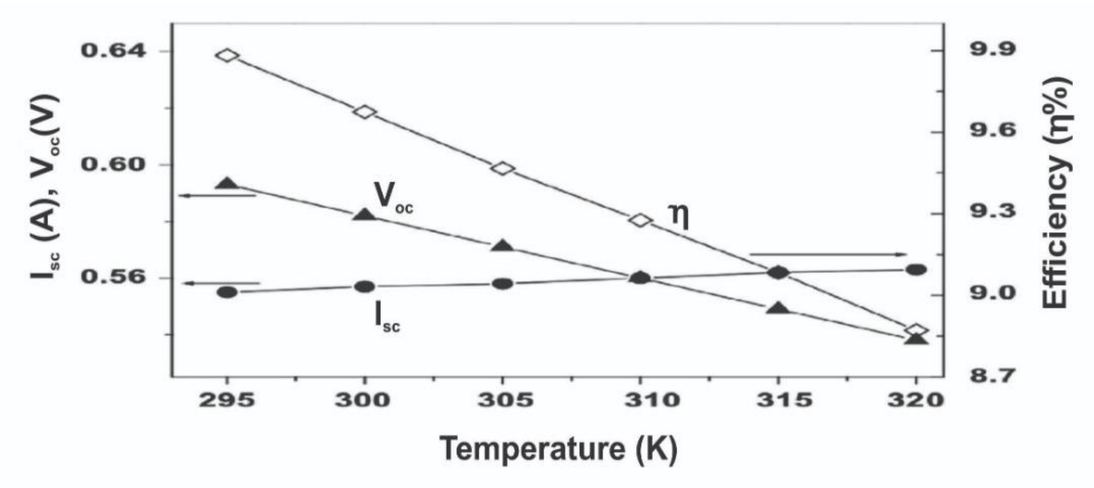

Figure 2.8: Effect of cell temperature on efficiency, open-circuit voltage and short circuit current of a monocrystalline silicon cell [42][47].

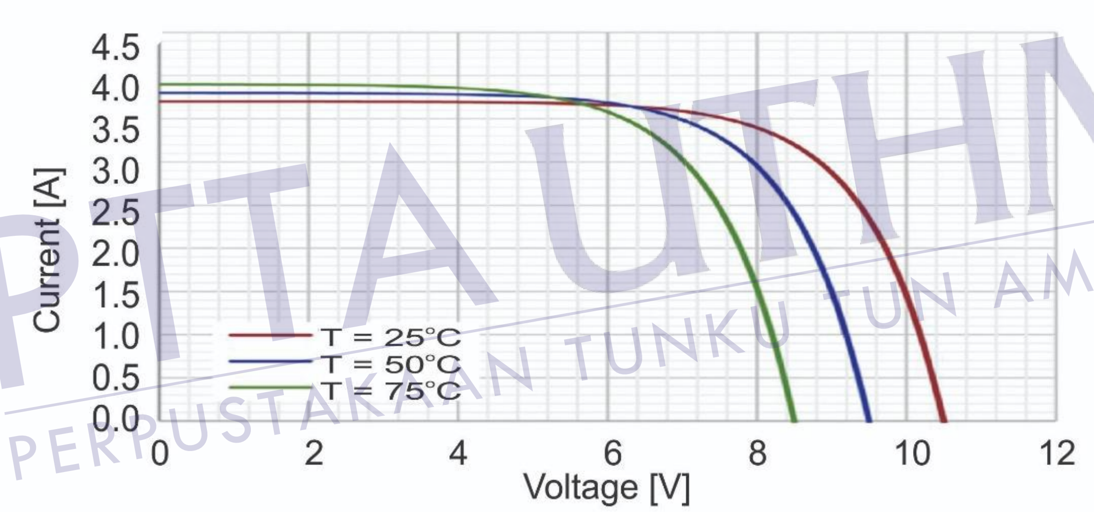

Figure 2.9: Temperature Influence on the I-V characteristics of a photovoltaic cell [48].

Photovoltaic electrical efficiency can be improved by minimizing and adequately utilizing the heat accumulated on the covered PV surface [49]. Various technologies have been developed for such a purpose, including Photovoltaic-Thermal (PV-T) and Photovoltaic-Thermoelectric Generator (PV-TEG) [50]. On the other hand, the PV-TEG can only accomplish this if the TEG is in physical contact with the PV (i.e. direct coupling method). Nonetheless, the TEG will have to function more significantly than the ambient temperature to generate electricity. If the solar cell is not adequately cooled, it would most likely overheat [50].

2.5.2 Solar photovoltaic panel

A solar panel comprises several solar cells with interconnected semiconductor qualities in a support structure, resulting in a higher output. These characteristics allow the cell to catch sunlight or photons and convert their energy into useable electricity [51].

The current and voltage generated by a PV cell are proportional to its size. A solar cell with a 13.5 m x 13.5 m can generate 0.55 V and a current density of 30 to 35 mA/cm^2 [52]. Several panels are connected in the following way to meet the power requirements of a specific system;

i. Series connection to increase a voltage
ii. Parallel connection to improve a current

For series connection, the number of panel modules in series (N_s) is obtained by dividing the system dc voltage (DC) by the rated voltage of one panel (V_r) as expressed as system dc voltage divided by the voltage rated of one panel as [53]

$$N_s = \frac{System\ Voltage\ (DC)}{Rated\ valve\ of\ Voltage\ of\ one\ PV\ Module} = \frac{V_{dc}}{V_r} \tag{2.10}$$

While for the numbers of the parallel of panel module in parallel (N_p) can be obtained by dividing the system's total DC by the rated current of one module as below [53].

$$N_p = \frac{Total\ Current\ of\ the\ PV\ Module}{Rated\ Current\ of\ one\ PV\ Module} = \frac{I_{dc}}{I_r} \tag{2.11}$$

Solar Photovoltaic Array combines multiple solar panels electrically connected to form a large photovoltaic system known as an array with a large surface area to generate more electricity.

The main challenge in using solar photovoltaic source with multiple cells in series is dealing with its nonlinear internal resistance. When the array receives nonuniform irradiance or is partially shaded, the problem becomes more complicated.

Partial shading is common in larger solar photovoltaic arrays due to tree leaves falling on it, birds or bird litter on the array, shade from a neighboring structure, and so on. All the cells in a string of connected cells carry the same amount of current. Although some cells in the shade produce less photon current than the other fully illuminated cell, these cells are still required to carry the same amount of current

The current and voltage generated depend on the area of the cell. A photovoltaic cell with size 13.5 m x 13.5 m can generate 0.55 V and 30 to 35 mA/cm^2 of current density [54].

2.6 Thermoelectric Generator

Figure 2.10 illustrates the schematic of TEG under generator mode and cooler mode. In Figure 2.10(a), the Seebeck effect allows thermoelectric generators to generate electrical energy from heat energy when a temperature gradient (T) is provided to a thermoelectric couple made up of p and n-type semiconductor materials. The mobile charge carriers at the hot end (heat source) diffuse to the cold end (heat sink), resulting in an electrostatic potential (ΔV) at the cold end [55]. Thomas Seebeck discovered the Seebeck effect, which creates potential differences due to temperature gradients given in equation 2.11. The Seebeck coefficient is a material feature that is intrinsically thermoelectric [56].

$$\alpha = \frac{\Delta V}{\Delta T} \tag{2.11}$$

Applying a current via the two junctions of a thermoelectric couple, on the other hand, results in a temperature difference. This process, known as the Peltier effect, was discovered by Jean Charles Peltier depicted in Figure 2.10(b) [55][57]. Although the Thomson effect is not primarily significant in thermoelectric devices, detailed calculations are still essential to influence device performance [58].

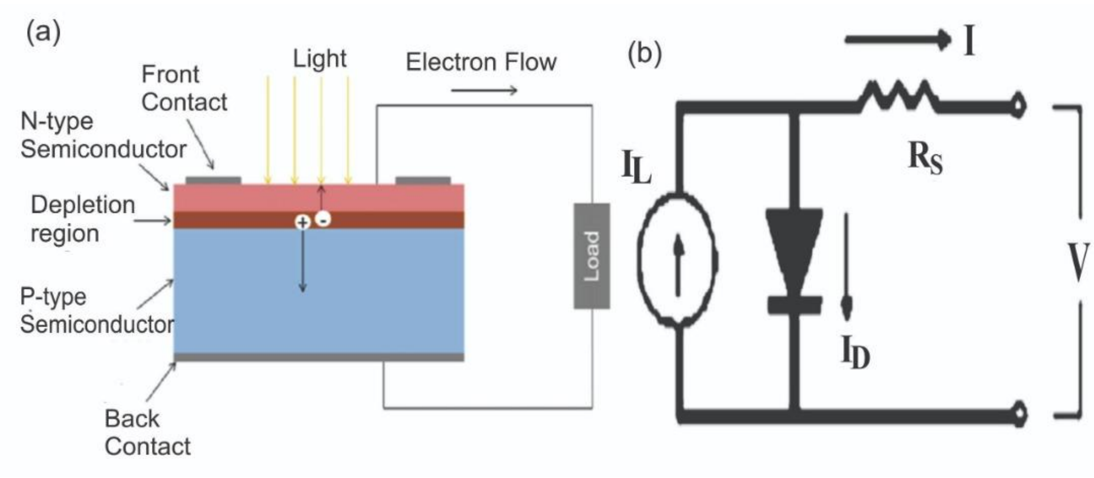

Figure 2.10: Schematic of a thermoelectric (a) generator and (b) cooler [55].

Akashah et al. [59] and Wan Jamaluddin et al. [60] investigated the viability of employing a TEG as a renewable energy source. The experiment was conducted using a TEC1-12706 with dimensions of 40 x 40 x 3.5 mm. The voltage, current, and temperature data were taken with a National Instrument (NI-CRIO 9014). The TEG was heated with halogen lamps, and the data was shown using LabView software. When the two TEGs were connected in series across 200 Ω resistance, they generated 41.82 W of power, whereas when connected in parallel, they generated 100 megawatts (MW) at a temperature of 70°C. Another research examined the possibilities of developing sustainable thermal energy from shingles using a TEG for domestic applications [61]. A test ring was employed for TEG, and the shingle was attached to the NI-CRIO 9014 for data acquisition. At a load of 138 Ω, the four TEG modules in series generated a total of 0.003 V, producing 65.22 uW of energy.

Ding et al. [62] investigated a unit TEG for exhaust thermal heat recovery using modelling and simulation. The TEG tit angle, hot side temperature, and output power were all evaluated. The results show that the TEG generated 0.21 W at 1.75 °C. Furthermore, the findings of this study shows that the design, theoretical investigation, and optimization of systems with multiple thermoelectric generators will yield higher performance. The study validated the research conducted by [63] which indicates that as the number of TEG is increase, the delta T increases for more power generation.

2.6.1 Thermoelectric Materials

Electrical conductivity, thermal conductivity and Seebeck coefficient are the three inherent material qualities that govern the performance of thermoelectric materials used to produce electric power using the Seebeck effect or to cool using the Peltier effect as shown in Eq. (2.12). Electrical current is passed in power generating and cooling mode; hence materials with high electrical conductivity are desirable. Furthermore, a significant Seebeck coefficient is needed because a considerable produced voltage per unit temperature gradient is required. Finally, TE materials require a low thermal conductivity since temperature variations must be sustained across the material [64]. The thermoelectric figure of merit, *ZT* is a dimensionless parameter commonly used to evaluate thermoelectric efficiency in equation (2.12) [65].

$$ZT = \frac{\alpha^2 \sigma T}{K} \tag{2.12}$$

where α is the Seebeck coefficient, σ is the electrical conductivity, K is the thermal conductivity, and T is the absolute temperature.

In general, materials with a high ZT are preferred; however, because the inherent material qualities that determine the ZT are co-dependent and reciprocal, optimizing all of them at the same time is complicated. Through optimization, the TEG resulted in having the highest ZT with $Z\approx 1$ [66]. Nevertheless, due to extensive material research, successive advancement has been reported in overcoming limitations and significantly improving the thermoelectric figure of merit.

Modifying the material microstructure to enhance photon scattering and reducing thermal conductivity are two approaches that have been investigated. This method has been used to optimize materials such as chalcogenides, clathrates and skutterudites. The other process is to reduce the material dimensionality for quantum size effects to change electrical and thermal conductivity [67]. Additionally, attempts were made to increase the ZT of materials by incorporating other semiconductor or nanostructured materials. At 300 °C, the figure of merit for nanostructural materials was three, and it ranged from 0.4 to 1.1 at a low-temperature difference of 27 ° C. [68][69]. This is much higher than the typical ZT value (0.8) of commercial materials like n-type Bi2Te3 and p-type Sb2Te3 at temperatures below 150 °C as affirmed by ref [40]. Other methods for developing high-efficiency thermoelectric materials include plasma treatment, material segmentation and super-lattice structure [70].

Based on the classification, bismuth telluride (Bi2Te3) is used for low-temperature (<500K) electricity production in the category of thermoelectric materials based on the operating temperature range. For mid-temperature (500–900 K) electricity production, materials found on group-IV tellurides such as PbTe, GeTe, and SnTe are used. Finally, silicon-germanium alloys are used to generate high-temperature (> 900 K) [71]. High-quality ZT materials with low prices must be produced to provide thermoelectric devices with more proper applications. Because of the tremendous study being done in this field, this is an attainable future goal.

2.6.2 Modelling of Thermoelectric Generator and Cooler

Thermoelectric generator efficiency is given in Equation (2.13) [72],

$$\eta = \frac{Energy\ supply\ to\ the\ load}{Heat\ energy\ absorbed\ at\ the\ hot\ juction} \tag{2.13}$$

For having good thermoelectric material qualities with minimal contact resistances, the efficiency can be expressed as follows in Equation (2.14)

$$\eta_{teg} = \frac{I^2R}{\alpha I T_H} = \frac{T^2R}{K(T_H - T_C) - \frac{1}{2}I^2R} \tag{2.14}$$

where I, R,$T_{H,and}$ T_C represent the TEG current, series resistance, hot and cold side temperatures respectively.

The maximum conversion efficiency is given in Equation (2.15),

$$\eta_{max} = \eta_C = \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}} \tag{2.15}$$

where η_C represents the Carnot efficiency expressed in Equation (2.16)

$$\eta_C = \frac{T_H - T_C}{T_H} \tag{2.16}$$

Thermoelectric cooler efficiency is expressed as its coefficient of performance (COP) given in Equation (2.17) [66][72],

$$COP = \frac{Heat\ absorbed}{Electrical\ power\ input} = \frac{\alpha I T_C - K(T_H - T_C)}{\alpha I(T_H - T_C) + I^2 R} \tag{2.17}$$

The maximum cooling power current *I* is given in Equation (2.18)

$$I = \frac{\alpha T_C}{R} \tag{2.18}$$

The maximum coefficient of performance is given in Equation (2.19),

$$COP_{max} = \frac{T_C[(1+ZT)^2] - \frac{T_C}{T_H}}{(T_H - T_C)[(1+ZT)^2] + 1} \tag{2.19}$$

As with the thermoelectric generator, the merit figure (ZT) also determines the maximum performance coefficient that can be achieved.

2.6.3 Application of Thermal Electric Generators

Thermoelectric generators are applied for a variety of purposes, including heat recovery for automobiles. One of the significant issues currently being faced is reducing the amount of energy wasted in the form of heat energy. TEGs are used extensively in the automotive sector. According to the study, nearly 65% of the heat generated in internal combustion engines is wasted [71]. The department of energy (DOE) and the Ford Group conducted research on the v6 engine fitted with TEGs with the objective of making 500 W, but the result obtained [72] in 2019 revealed that the generated output was only 250 W. Volvo and Renault trucks collaborated on the recovery of energy from exhaust of an engine from 2015 to 2020. According to this project, TEG can generate up to 130 W from a passenger car exhaust [73].

Next, TEG are used in wearable sensors network, since human body heat is both natural and reliable, it can be used to provide some electricity in specific uses, like those in medicine. At rest, the human body generates about 100 W of heat, and when exercising, 525 W. [74]. Since 2001, several studies on wearable thermoelectric generators (WTEGs) have been carried out. with the target of replacing lithium ion batteries, as portable device power sources, provided that the international market for portable technologies is rapidly expanding and is predicted to surpass USD 34 billion by 2025 and USD 78 billion by 2023. WTEGs are categorized as rigid or flexible architectures in either 2D or 3D configurations, or as inorganic, organic, or hybrid TEG component materials [75].

The heat from the sun is used as a heat source in these generators. The total efficiency achieved by using TEGs is approximately 5-10%, as such, TEG can be used in micro-power generation, [76] performed a research and demonstrated that with a temperature difference of 1000^{o}C and a concentration of solar intensity of 100, an efficiency of 14.1 percent can be achieved using the available thermoelectric device. Similarly in paper [77] has been working on thermoelectric generation by people since the 2000s with the aim of powering electronic health care systems. IMEC and the Holst Centre have produced a number of wireless sensors, including the body powered electroencephalogram acquisition system, which generates 2-2.5 mW of power and is worn as a headband wireless sensor network. They also invented a wireless pulse oximeter (2006) that is powered completely by a TEG-style watch which uses commercial Bi2Te3 thermopiles and generates around 89 □W of power.

Space power, production of electricity in some of the harsh environments must adhere to exacting standards. Extreme weather can include very hot or cold temperatures, among other things. Additionally, maintenance should be kept to a minimum because it is challenging in these kinds of settings. TEGs are used in space applications due to their low weight, high reliability, and ability to operate for extended periods of time [56][78]. The voyager I and II, which were launched in 1997, were

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