EFFICIENCY ENHANCEMENT OF HYBRID PHOTOVOLTAIC-THERMOELECTRIC GENERATOR FOR GREENHOUSE BASED ON TEMPERATURE DISTRIBUTION

By

MOHD RUZAIMI BIN MOHD ARIFFIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Doctor of Philosophy

June 2024

ITMA 2024 5

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Doctor of Philosophy

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Chairman : Suhaidi bin Shafie, PhD
Institute : Nanoscience and Nanotechnology

Food security is a pressing global issue, prompting the search for sustainable agricultural solutions. Agricultural greenhouses present a viable option by providing controlled environments for crop cultivation. This research focuses on enhancing the efficiency of photovoltaic (PV) systems in greenhouse applications through the integration of thermoelectric generators (TEG). The main goal is to convert residual heat from PV panels into additional electricity using TEGs, thereby optimizing energy utilization. The study tackles critical challenges in greenhouse energy management, such as high energy consumption, excessive solar radiation, and the limitations of conventional PV systems. A hybrid PV-TEG system was developed to capitalize on the temperature difference between the heated surface of solar panels and a controlled cooling mechanism where circulating aquaponic water used as a liquid cooler to enhance power generation. The methodology involved designing a small-scale PV greenhouse system, analyzing the temperature

distribution across the PV panels, and developing a power logger for real-time performance monitoring. Feasibility and temperature distribution analyses were conducted through both experimental setups and simulations to optimize the positioning and orientation of TEG modules. In a PV-TEG hybrid system, the temperature distribution significantly affects the performance of both PV panels and TEG modules. Non-uniform temperature distribution can lead to uneven heating, creating "hot spots" that reduce the overall efficiency of the PV panels. Conversely, a uniform temperature distribution helps maintain consistent performance across the panel, minimizing thermal stress and enhancing efficiency and lifespan. Similarly, TEG performance is adversely impacted by non-uniform temperatures, as they generate power based on temperature differentials; cooler areas on the PV panel can lead to suboptimal TEG operation, reducing overall system efficiency. Achieving uniform temperature distribution ensures TEGs are consistently exposed to a reliable heat source, maximizing energy conversion capabilities. To achieve this in this study, the PV panels were installed at an optimal tilt angle of 3° facing South, maximizing solar exposure at average direct normal irradiance of 314.9 W/m^2 in Serdang, Malaysia. The hybrid system demonstrated significant energy efficiency improvements, with a 33% reduction in power loss due to temperature mismatches across TEG modules. Strategies employed included selecting the highest performance TEG cell models, implementing controlled thermal management through liquid cooling systems, optimizing TEG placement based on temperature analysis, and designing effective heat sinks. This study also introduces a novel analytical model for PV-TEG integration, the PV-TEG Integrated Module (PV-TEGIM), aimed at optimizing heat

distribution and passive cooling techniques. The power output of the PV-TEG hybrid system increased with solar radiation, peaking at 31.05 W at noon. The total electrical energy output of the hybrid system was 31% greater than that of a standalone 100 Wp photovoltaic panel. The findings suggest that this hybrid system can reduce energy consumption in greenhouse applications, lower greenhouse gas emissions, and provide a sustainable energy solution for agricultural production. Future work should focus on expanding the system for larger-scale applications and investigating advanced materials to enhance performance further.

Keywords: Greenhouse System, PV-TEG Hybrid, Solar Photovoltaic (PV), Thermoelectric (TE), Thermoelectric Generator (TEG)

SDG: GOAL 2: Zero Hunger, GOAL 7: Affordable and Clean Energy

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENAMBAHBAIKAN KEBERKESANAN KUASA SOLAR BAGI PENJANA HIBRID FOTOVOLTAIK - TERMOELEKTRIK BAGI RUMAH HIJAU BERDASARAKAN AGIHAN SUHU

Oleh

MOHD RUZAIMI BIN MOHD ARIFFIN

Jun 2024

Pengerusi : Suhaidi bin Shafie, PhD
Institut : Nanosains dan Nanoteknologi

Keterjaminan makanan adalah isu global yang serius, oleh itu mencari penyelesaian pertanian mampan adalah sangat penting. Rumah hijau pertanian adalah satu pilihan yang baik kerana ia boleh menyediakan persekitaran terkawal untuk tanaman. Kajian ini fokus kepada meningkatkan kecekapan sistem fotovoltaik (PV) dalam rumah hijau dengan menggabungkan penjana termoelektrik (TEG). Matlamat utama adalah untuk menukar haba berlebihan daripada panel PV kepada elektrik tambahan menggunakan TEG, menjadikan penggunaan tenaga lebih optimum. Kajian ini menangani cabaran pengurusan tenaga rumah hijau, termasuk penggunaan tenaga yang tinggi, sinaran suria berlebihan, dan batasan sistem PV konvensional. Sistem hibrid PV-TEG direka untuk memanfaatkan perbezaan suhu antara permukaan panel solar yang panas dengan mekanisme penyejukan terkawal, khususnya air baja akuaponik yang beredar sebagai penyejuk cecair bagi meningkatkan penjanaan kuasa. Metodologi kajian

termasuk mereka bentuk sistem rumah hijau PV berskala kecil, menganalisis agihan suhu pada panel PV, dan membangunkan peranti perekod kuasa bagi pemantauan prestasi secara masa nyata. Analisis kebolehlaksanaan dan agihan suhu dijalankan melalui ujian eksperimen dan simulasi untuk mengoptimumkan kedudukan dan orientasi modul TEG. Dalam sistem hibrid PV-TEG, agihan suhu memberi kesan besar kepada prestasi panel PV dan modul TEG. Taburan suhu yang tidak sekata boleh menyebabkan pemanasan tidak rata, mencipta titik panas yang mengurangkan kecekapan keseluruhan panel PV. Sebaliknya, taburan suhu sekata membantu mengekalkan prestasi yang konsisten di seluruh panel, mengurangkan tekanan haba dan meningkatkan kecekapan serta jangka hayat. Prestasi TEG juga terjejas jika suhu tidak sekata kerana TEG menghasilkan kuasa berdasarkan perbezaan suhu. Jika ada bahagian panel PV yang lebih sejuk, TEG di kawasan tersebut tak dapat berfungsi dengan optimum, mengurangkan kecekapan sistem secara keseluruhan. Dengan mencapai agihan suhu yang sekata, TEG mendapat sumber haba yang konsisten, memaksimumkan keupayaan penukaran tenaga. Untuk mencapai matlamat ini, panel PV dipasang pada sudut condong optimum 3° menghadap ke arah Selatan, memaksimumkan pendedahan cahaya matahari dengan purata radiasi normal tahunan matahari sebanyak 314.9 W/m² di Serdang, Malaysia. Sistem hibrid ini menunjukkan peningkatan besar dalam kecekapan tenaga, dengan pengurangan 33% dalam kehilangan kuasa disebabkan ketidakpadanan suhu di antara modul TEG. Strategi yang digunakan termasuk memilih model sel TEG berprestasi tinggi, mengaplikasikan pengurusan haba terkawal melalui sistem penyejukan cecair, mengoptimumkan kedudukan TEG berdasarkan analisis suhu, dan

merekabentuk *heatsink* yang berkesan. Kajian ini juga memperkenalkan model analisis baru untuk integrasi PV-TEG, iaitu Modul Integrasi PV-TEG (PV-TEGIM), yang memberi fokus kepada pengoptimuman agihan haba dan teknik penyejukan pasif. Keputusan menunjukkan output kuasa sistem hibrid PV-TEG meningkat dengan sinaran suria, mencapai maksimum 31.05 W pada tengah hari. Jumlah tenaga elektrik sistem hibrid ini adalah 31% lebih tinggi berbanding panel fotovoltaik 100 Wp sahaja. Hasil kajian menunjukkan sistem hibrid ini boleh mengurangkan penggunaan tenaga dalam aplikasi rumah hijau, mengurangkan pelepasan gas rumah kaca, dan menawarkan penyelesaian tenaga yang mampan untuk pengeluaran pertanian. Cadangan masa depan termasuk memperluas sistem ini untuk aplikasi berskala lebih besar dan meneroka bahan-bahan maju untuk meningkatkan prestasi.

Kata Kunci: Hibrid PV-TEG, Penjana Termoelektrik (TEG), Solar PV, Sistem Rumah Hijau Fotovoltaik (PV), Termoelektrik (TE),

SDG: MATLAMAT 2: Sifar Kebuluran, MATLAMAT 7: Tenaga Bersih dan Berpatutan

ACKNOWLEDGEMENTS

In recognition of the boundless love, support, and encouragement bestowed upon me by my parents, wife, and children, I dedicate this thesis to them. My deepest gratitude also goes out to my brother, sister, in-laws, and supervisors. To everyone who has encouraged me to dream big and follow my heart, I am eternally grateful.

I certify that a Thesis Examination Committee has met on 24 July 2024 to conduct the final examination of Mohd Ruzaimi bin Mohd Ariffin on his thesis entitled “Efficiency Enhancement of Hybrid Photovoltaic - Thermoelectric Generator for Greenhouse Based on Temperature Distribution” in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Mohd Nizar bin Hamidon, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Izhal bin Abdul Halin, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Mohd Zainal Abidin bin Ab. Kadir, PhD
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Nattha Jindapetch, PhD
Associate Professor
Faculty of Electrical Engineering
Prince of Songkla University
Thailand
(External Examiner)

RUSMAWATI BINTI SAID, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 2 January 2025

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Suhaidi bin Shafie, PhD
Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Wan Zuha bin Wan Hasan, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Norhafiz bin Azis, PhD
Associate Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohammad Effendy bin Ya'acob, PhD
Senior Lecturer, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Eris Elianddy bin Supeni, PhD
Associate Professor,
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 13 January 2025

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LIST OF ABBREVIATIONS

PV	photovoltaic
TEG	thermoelectric generator
TEC	thermoelectric cooler
CPV	concentrated photovoltaic
PCM	phase change materials
CO_2	carbon dioxide
mono-Si	monocrystalline silicon
poly-Si	polycrystalline silicon
TF	thin film
TE	thermoelectric
DC	direct current
V	voltage (V)
I	current (A)
T	temperature
η	efficiency
P	power
Q	radiation
FEM	finite element modelling
AC	alternating current
CdTe	cadmium telluride
CIGS	copper indium gallium selenide
CPV	concentrated photovoltaic
c-Si	crystalline silicone
a-Si	amorphous silicone

L	length of TEG leg (m)
K	thermal conductivity (W/mK)
S	Seebeck coefficient
X	exergy (W)
zT	figure of merit of TEG material
α	reflectivity
β	Peltier coefficient
γ	electrical resistivity (Ω m−1)
σ	Boltzmann constant 5.67 × 10−8 W/m2K4
λ	shape factor (measure of PV imperfection)
μ	micro (10−6)
ϖ	Thomson coefficient (V/K)
ξ	electrical resistivity (Ω m)
φ	exergy efficiency
η	conversion efficiency
ε	emissivity coefficient
ϑ	volume of PV (m3)
ρ	density (kg/m3)
PGEC	phonon glass-electron crystal
RES	renewable energy sources
c	specific heat capacity (J/kgK)
C	concentration factor
D	electrical flux density
f	fill factor of TEG
G	solar radiation (W/m2)

J	current density (A/m)

CHAPTER 1

INTRODUCTION

This section provides a summary of the research setting, objectives, aims, approach, and innovation. It outlines the background of the study, encompassing energy consumption, demand, and global targets for carbon emissions. Furthermore, it delves into the advantages of sustainable energy, specifically emphasizing solar power as the primary focus of investigation. Furthermore, the chapter provides a brief explanation of the principles underlying photovoltaic systems, thermoelectric generators, and hybrid photovoltaic-thermoelectric systems.

1.1 Background and Motivation

Since the industrial revolution, fossil fuels including natural gas, coal, and oil have been a major source of energy generation. This is mainly because they have a far higher power density than renewable energy sources. As a result, fossil fuels have several downsides, including environmental degradation and unpredictable pricing and restricted supply. Figure 1 shows that renewable energy sources (RES) generated an estimated 29.9% of global electricity in 2022, increased by 9% since from 21.3% in 2012 [1]. Wind, biopower, solar, and geothermal are all renewable sources of energy that can be easily supplied. Because of this, current research efforts have been devoted to developing and upgrading solar energy systems and other renewable energy systems. Thermal energy and electrical energy are the two most common methods of converting solar energy. In addition to photovoltaic (PV) converters, thermoelectric generators (TEG) also provide a reliable method of converting solar thermal energy into electrical energy. Low operating and maintenance costs and no hazardous gas emissions characterize thermoelectric devices. They can be scaled up and down easily, and they don't pollute the environment when they're in use. It is thus possible to increase solar PV system efficiency at the same time as decreasing the amount of waste heat that is emitted from it.

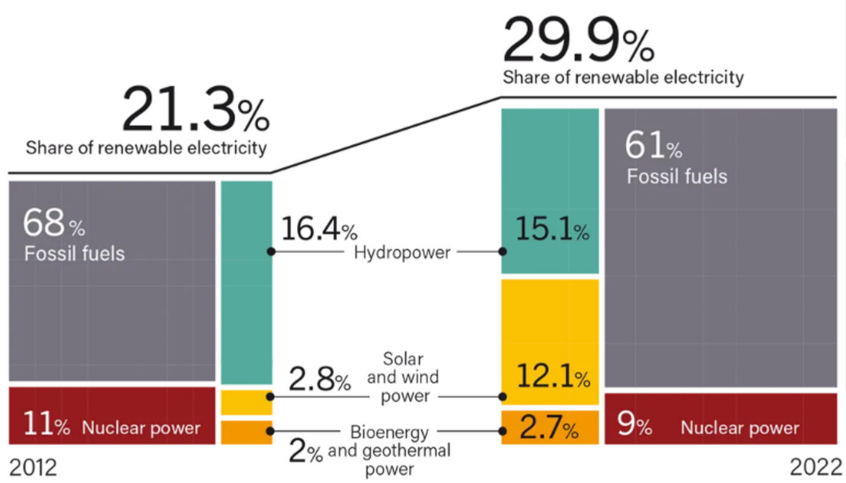

Figure 1.1: Percentage of renewable energy sources in the world's electrical supply by the end of 2022
(Source: Renewables 2023 - Global Status Report)

The efficient utilization and conversion of solar energy into electricity is the focus of a considerable deal of research due to increased environmental awareness and concern. Concentrated PV (CPV) systems are plagued by a decrease in conversion efficiency due to the rise in cell temperature and the associated waste heat [2]. The utilization of thermoelectric modules to recycle waste heat from solar PV cells has been a major driving force behind the development of combined Photovoltaic-Thermoelectric Generator (PV-TEG) systems. PV cells can be used alone, however, when they are combined with TEG modules, they create a more sophisticated system. PV cells and TEG modules are adversely affected by rising temperatures in an integrated PV-TEG system. Higher concentration results in a higher temperature gradient, which enhances the TEG module's efficiency, but it also reduces the PV cell's efficiency and longevity. Research in recent years has focused on the use of phase change materials (PCM) and nanotechnology in an integrated PV-TEG system to improve heat transfer and efficiency [3]. As a result of the intricate relationships and trade-offs introduced by PV cell and TEG module integration, system optimization is critical.

The overall efficiency of a PV roof system can be improved by integrating TEG devices and PV solar cells. However, the additional costs of this integration must be considered when determining if it is economically feasible [4]. The cost of the integrated system is increased by the additional equipment, such as TEG devices and reflectors. Consequently, it is vital to study the economic viability of PV-TEG systems as a first step. The integration of TEG modules into PV-TEG systems has resulted in a significant increase in efficiency. The combined use of PV converters and TEGs for power generation in integrated PV-TEG systems provides a solution to the problem of wide-spectrum solar radiation consumption [5]. As a result, PV-TEG systems are currently receiving more attention and research efforts aimed at improving their reliability and efficiency [6, 7]. Integrated PV-TEG system performance improvement has been studied experimentally and computationally in the current study.

Presented were the characteristics and models of solar PV converters, along with the operating principles of TEG devices. An in-depth discussion of several modeling methodologies for the integrated PV-TEG system ware discussed. The effect of temperature distribution and relationship with the optimization of solar angle has also been explored. It was also discussed how PV cells can be integrated with TEG devices and what the future may hold.

1.2 Problem Statement

Current PV greenhouse systems face several challenges, including high energy consumption for heating, cooling, and lighting, which impacts overall efficiency. Additionally, excess solar radiation can lead to overheating, negatively affecting plant growth and energy use. The limited space on greenhouse roofs restricts the number of solar panels that can be installed, thereby capping energy generation. Moreover, current technology does not fully utilize both light and heat energy effectively, resulting in underutilize energy. These issues highlight the need for innovative hybrid solutions and optimized designs to improve energy efficiency and productivity in PV greenhouse systems.

The utilization of electrical energy is essential for environmental control in greenhouse operations. Among the significant expenses in greenhouse production are the heating and cooling systems. Typically, heating is accomplished through the combustion of fossil fuels (diesel, fuel oil, liquid petroleum, gas), contributing to increased CO_2 emissions. Alternatively, electric heaters are employed, resulting in **higher energy consumption**. Therefore, a key challenge for agricultural greenhouses is to explore methods that enhance energy efficiency while simultaneously reducing overall energy consumption and associated CO_2 emissions within the greenhouse industry [8].

Excessive solar radiation has a significant impact on crop production. With a 1% decrease in light, yield loss is anticipated to be over 1% [9]. Solar radiation is frequently too strong for certain crop species, especially in summer or in areas with high levels of irradiation. To reduce the amount of radiation reaching plants in a greenhouse, one way is to employ screens and coatings [10]. This finding suggests PV modules could be a practical way to harness the abundant sunlight that reaches greenhouses, transforming it into electricity that can power environmental control devices. Optimizing one plot of land is possible with the help of solar PV systems installed on rooftops or integrated into greenhouse structures; this makes use of the abundant surfaces available in greenhouses, allowing for the cultivation of crop yield products below and the production of self-consumed energy above.

In earlier PV greenhouse systems, flexible PV modules made from monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si), or thin-film materials were commonly used. However, due to **space and area limitations on the greenhouse roof**, including specific power consumption requirements, these types of PV modules often reduced overall power output [11–14]. To address this issue, improving PV cell technology or finding alternatives has become a priority. One promising solution is the integration of TEGs with photovoltaic cells, which has shown to enhance performance beyond what either technology can achieve alone. A hybrid system combining solar and thermal technologies offers a viable option for utilizing residual heat and improving efficiency.

In the **current progress of PV-TEG hybrid system** point of view, the system can be configured in various ways, either with the components functioning independently or in direct combination. To optimize the system's performance, additional elements such as a PV module, a TEG, and a cooling system can be integrated or fabricated. When both the PV module and the TEG contribute to the power output, the total energy produced is the combined result of both components. Previous studies have shown that the efficiency of hybrid systems varies depending on the configuration and approach used [15]. In greenhouse systems, the cold side of the TEG is influenced by the lower internal temperature of the greenhouse, while the hot side—corresponding to the temperature of the photovoltaic panels—fluctuates based on the amount of sunlight received and the time of day.

Previous research on PV-TEG hybrid systems has predominantly operated under the **assumption of constant incident solar radiation**. However, in actual environment conditions, solar radiation, along with temperature distribution, undergoes continuous fluctuations in actual applications. Uneven TEG cell power generation, when analyzed through Kirchhoff's Laws, highlights how individual cells' lower performance affects the entire system's current and voltage, leading to significant energy losses. [16, 17].

1.3 Research Objectives

A hybrid photovoltaic system that incorporates a thermoelectric generator (TEG) in an agriculture greenhouse application is the goal of this research, which intends to improve overall efficiency, generate more electricity, and harvest more energy from the sun. The thermoelectric generator's electrical performance can be improved by optimizing the PV panel temperature distribution, which is the focus of this study. To accomplish this purpose, the following objectives have been laid out:

a) To build a small-scale PV greenhouse system tailored to specific crops and standard environmental controls at minimum loads. Simultaneously, enhance the energy output of PV panels by integrating TEG modules. This integration aims to utilize the limited backside surface area of PV panels, adhere to power consumption requirements, and align with greenhouse environmental control parameters. The goal is to harness both light and thermal energy from solar radiation for increased overall efficiency.
b) To develop and analyze novel PV-TEG Integrated Module (PV-TEGIM) power output based on uniform heat of optimized angle of PV panels to enhance PV greenhouse roof system efficiency.

c) To develop a working model of a DC energy power logger that uses microcontroller to track and monitor the DC voltage and current of a TEG integrated module array circuit.
d) To verify the results between simulation and developed hardware by comparing th PV-TEGIM with a conventional PV system, i.e; *I-V-t, I-V-T, η, P-Q,* etc.

1.4 Scope and Limitation of the Study

The study of PV-TEG hybrid systems in greenhouse environments covers several important aspects, particularly the integration of photovoltaic (PV) panels with thermoelectric generators (TEGs) to boost energy efficiency. This research focuses on assessing how waste heat from PV panels can be converted into additional electrical power through TEGs, enhancing energy output while supporting optimal microclimate conditions essential for plant growth. However, this research was conducted on a small scale due to the lower costs and manageable complexity of these systems, which may limit the applicability of findings to larger setups. Larger systems can face different challenges, such as increased infrastructure demands and more complex energy management issues.

Additionally, the cost of integrating TEGs with PV systems can be significant, as the initial investment for TEG technology is often higher than that of conventional PV systems alone. This can deter large-scale adoption, particularly in budget-sensitive agricultural operations. Although TEGs can improve energy output, the return on investment may not be immediately evident, as the efficiency gains from the added technology can be marginal compared to the higher setup costs. Hence, in this study, the PV-TEG Integrated module developed applied only on one PV panel for data collection and analysis.

Furthermore, small-scale studies may not fully capture the fluctuating power consumption dynamics typical of commercial-scale greenhouses, where energy demands vary significantly based on factors like crop type and local climate conditions. The management of heat distribution from TEGs in smaller installations may not accurately reflect the thermal dynamics encountered in larger systems, potentially affecting the overall efficiency and operational effectiveness of the hybrid approach. Overall, while small-scale PV-TEG hybrid systems provide valuable insights into optimizing energy efficiency in greenhouses, further research is needed to address these limitations and validate their effectiveness in larger commercial applications.

1.5 Research Novelty

During the investigation of PV-TEG hybrid system technologies, the following innovations were identified in relation to the existing literature:

Structural Innovation - In a greenhouse hydroponic system, circulating nutrient-enriched or fertilized water facilitates thermal energy transfer between the hot backside surface of the PV panel and the cold side of the TEG. The process optimizes the temperature difference between the hot and cold sides of the TEG, improving heat extraction from the solar panel, minimizing heat loss, and reducing geometric constraints. Water cooling, which is more efficient than air cooling, has become the preferred method for cooling the TEG's cold side, resulting in enhanced overall performance of the hybrid system.

Theoretical Innovation - Building and validating theoretical models for thermoelectric generators and photovoltaic-thermoelectric hybrid systems opens up new possibilities for performance prediction in both steady-state and dynamic conditions. These models serve as powerful tools, allowing for the fine-tuning of design parameters to maximize system efficiency. In PV solar systems, for instance, how heat is distributed across the panels is closely linked to the angle at which the panels are tilted, an adjustment that plays a crucial role in balancing temperatures and avoiding hotspots. Improper angles can lead to uneven heating, known as thermal hotspots, where certain parts of the panel become significantly hotter than others. Simulations are also conducted using the finite element method (FEM) approach with ANSYS software. Experimental study has been done to identify the optimum angle. By optimizing the tilt angle for a specific location (UPM Serdang), the temperature distribution becomes more uniform, optimizing temperature differences across the panel surface and TEG cells of TEG integrated module circuit. Simulations analysis also conducted using the finite element method (FEM) approach with ANSYS software.

Conceptual innovation – Building upon the optimization strategies discussed, this study proposes a new method to enhance the performance of PV-TEG hybrid systems by addressing the issue of uneven temperature distribution. By refining panel tilt angles, strategically positioning TEG modules, and implementing advanced thermal management techniques, the proposed system is designed to significantly boost energy output and efficiency in hybrid configurations. PV-TEG integrated module has been developed and applied in the PV Greenhous system roof, taking advantage of the fertilization water as the TEG cold side cooling medium. This project has the potential to significantly enhance renewable energy generation in applications such as greenhouses, where both solar energy and heat management are critical for sustainability and productivity.

1.6 Thesis Structure

Chapter 1 situates this research within its historical context, highlighting the key motivations for reassessing energy usage in greenhouse systems. The study aims to explore the feasibility, methodology, and benefits of transitioning from a traditional alternating current (AC) electrical supply to a direct current (DC) supply through a PV-TEG hybrid system, aiming to improve energy efficiency in greenhouse applications. The chapter delves into the limitations inherent in a conventional PV greenhouse system and explores the potential benefits of integrating thermoelectricity into the standard PV system. This integration is intended to enhance energy output efficiency and address the management of excess heat generated by PV panels. Referred to as the 'global objective,' these aspects serve as the driving force behind the ongoing discourse.

In **Chapter** 2, summary and comparison of all of the prior work is presented. This research, which is theoretically constructed and goes through the parameters that affect the greenhouse, is compared, and contrasted with the work that they have done. In order to serve as a foundation for further research, it evaluates the efforts that they have made in the past. Several critical analyses are included in this article, as well as a discussion of the various ways in which this research differs in terms of methodology and analysis.

Chapter 3 outlines the methodology, focusing on the identification and understanding of key parameters. These parameters include electrical loads, PV energy generation, heat dissipation from PV panels, and the equations governing these elements. The analysis examines how each parameter impacts the design process of the PV-TEG hybrid system. A selection of DC appliances is made for the lab-scale PV-TEG model, and relevant equations are applied to accurately size the energy storage system. A set of example calculations using two types of TEG modules is presented. These equations were used to collect and display graphically data for a variety of loads and currents at different voltages.

In **chapter 4**, the results of the experiment are discussed. Details of the experimental test rig and technique are given. The outcomes of several case studies conducted in the laboratory, as well as the validation of the simulation model through experimental findings and previously published data, are discussed. This chapter also covers the outcomes of optimization research on hybrid photovoltaic-thermoelectric systems based on a verified simulation model.

Chapter 5 serves as a wrap-up for the study, outlining the steps taken to meet the study's stated goals. In addition, the research's primary findings and limitations are discussed in this section. Finally, suggestions for further research are provided as a point of reference.

The earlier chapters have been thoughtfully arranged and interconnected to provide a cohesive view of how the research goals and objectives were achieved. This structure enhances understanding and offers a clear summary of the study’s overall research process and findings.

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