

T.C
BAHCESEHIR UNIVERSITY
GRADUATE SCHOOL
THE DEPARTMENT OF ELECTRICAL AND ELECTRONIC
ENGINEERING

“SUSTAINABILITY AND THERMODYNAMIC ASSESSMENTS OF
THERMOELECTRIC GENERATORS”

Z. Masalha

MASTER’S THESIS

ZAID MASALHA

ISTANBUL 2024

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THESIS SUPERVISOR:

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ABSTRACT

“SUSTAINABILITY AND THERMODYNAMIC ASSESSMENTS OF THERMOELECTRIC GENERATORS”

Zaid S H Masalha

Master’s Program in Electrical and Electronic Engineering (English)

Supervisor: Assist. Prof. Dr. Hüseyin Günhan Özcan

06/ 2024, 99 pages

In this thesis, the performances of four different kinds of solar collectors (flat plate (FP), parabolic dish (PD), and parabolic trough (PT)) working in conjunction with three different physical types of bismuth telluride thermoelectric generators (TEGs) in four different sites (Istanbul, Jerusalem, Casablanca, and Sydney) are evaluated. Therefore, the thesis gives insight into the aspects of TEG and solar collector integration that have huge potential for sustainable energy solutions and global efforts toward carbon neutrality. The objective of the thesis is to assess the energy, exergy, economic, and environmental performances of the created systems. From this research, it was discovered that distributed TEG systems combined with PT collectors had an outstanding efficiency that increased up to 6.31% in Jerusalem when the TEG number 199-150-2 was used. Economic analysis and assessment revealed that the PT collector is the most cost-effective again in Jerusalem, having a specific cost of \$0.02/kWh. Environmental evaluation highlighted that high greenhouse gas reductions are occurring in Jerusalem and Casablanca due to their high solar radiation potential, among selected other sites. The second law of thermodynamic analysis indicated that PT collectors attain higher energy efficiencies than FP and PD collectors. In the meantime, the highest efficiency amounts were gathered in Jerusalem.

Keywords: Thermoelectric Generators, Solar Collector, Sustainability, Thermodynamic Evaluation, Environmental Impact.

ÖZ

“TERMOELEKTRİK JENERATÖRLERİN SÜRDÜRÜLEBİLİRLİĞİ VE Termodinamik Değerlendirmeleri”

Zaid S H Masalha

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Bu tez çalışmasında, üç farklı fiziksel tip bizmut tellür termoelektrik jeneratör ile birlikte çalışan dört farklı türde güneş kollektörünün (düz plaka, parabolik çanak ve parabolik oluk) performansları dört farklı lokasyon için (İstanbul, Kudüs, Kazablanka ve Sidney) incelenmiştir. Bu nedenle tez çalışması, sürdürülebilir enerji çözümleri ve karbon nötrlüğe yönelik küresel çabalar açısından büyük potansiyele sahip olan TEG ve güneş kollektörü entegrasyonunun yönleri hakkında fikir vermektedir. Tezin amacı oluşturulan sistemlerin enerji, ekserji, ekonomik ve çevresel performanslarını değerlendirmektir. Bu araştırmadan, düz plaka kollektörünün farklı TEG Sistemleri ile birlikte kullanılması durumunda, 199-150-2 numaralı TEG kullanıldığında Kudüs'te %6,31'e kadar çıkan bir verime sahip olduğu bulunmuştur. Ekonomik analiz değerlendirmesi, düz plaka kollektörünün Kudüs'te yine 0,02 \$/kWh'lik spesifik maliyetiyle en uygun maliyeti verdiği ortaya çıkarılmıştır. Çevresel değerlendirme sonucunda ise seçilen diğer bölgeler arasında yüksek güneş radyasyonu potansiyeli nedeniyle Kudüs ve Kazablanka'da yüksek sera gazı azaltımlarının meydana geldiği belirlenmiştir. Termodinamiğin ikinci yasası uygulandığında ise, düz plaka kollektörünün parabolik çanak ve parabolik oluk tipine göre daha yüksek ekserji verimliliğine ulaştığını göstermiştir. Bu arada en yüksek verim miktarları yine Kudüs lokasyonunda elde edilmiştir.

Anahtar kelimeler: Termoelektrik Jeneratörler, Güneş Kollektörü, Sürdürülebilirlik, Termodinamik Değerlendirme, Çevresel Etki.

I dedicate this thesis to my family and friends, whose unwavering support and encouragement have been my guiding light. I am deeply grateful to my parents, whose unwavering love and sacrifices have shaped me into the person I am today. I express my gratitude for my teachers and lecturers, whose counsel and sagacity have been of immeasurable use along this journey. To all those who believed in me, this work is a testament to your faith and support.

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TABLE OF CONTENTS

ETHICAL CONDUCT	III
ABSTRACT	II
ÖZ	III
ACKNOWLEDGEMENTS	V
TABLE OF CONTENTS	VI
LIST OF FIGURES	IX
LIST OF TABLES	XI
LIST OF ABBREVIATIONS	XIII
Chapter 1: INTRODUCTION	1
1.1 Statement of the Problem	2
1.2 Purpose of the Study:	3
1.3 Research Questions:	4
1.4 Significance of the Study	4
1.5 Definitions:	5
Chapter 2 :Theory and Literary reviews	7
2.1 Thermoelectric generator:	7
2.1.1 Capacity of the thermoelectric	9
2.1.2 Applications of TEG	9
2.2 Solar collectors:	15
2.2.1 The operational mechanism of solar energy collectors:	17

2.2.3 Solar collector equations:.....	20
2.3 Literary reviews	25
Chapter 3: Methodology	30
3.1 Research Design:	30
3.2 Data Collection:.....	32
3.2.1 Data Collection Procedures:.....	32
3.2.2 Data Analysis Procedures:.....	35
3.3 Parametric Investigation	36
3.3.1 Factors Considered	36
3.3.2 Parametric Study Methodology	36
Chapter 4:Results and Discussion	38
4.1 Results	40
4.1.1 Efficiency.....	40
4.2 Discussion	52
4.2.1 Energy Efficiency	53
4.2.1.1 Comparative analysis with previous literary research	53
4.3 Finding of the Parametric Study	60
4.4 Second law of thermodynamics Analysis:	64
4.5 Economy Aspects	65
4.6 Environmental Impact	69
4.7 Limitations:	71
Chapter 5: Conclusion	72
Future Research	73

References 74

Appendix **Error! Bookmark not defined.**

Appendix A: Unit Conversions **Error! Bookmark not defined.**



LIST OF FIGURES

FIGURE 1: THE WORKING PRINCIPLE OF TEG.	7
FIGURE 2. ILLUSTRATION OF THE SCHEMATIC DIAGRAM OF A TEG.	10
FIGURE 3. THE TEG OPERATES BASED ON THE CONCEPT OF THERMOELECTRICITY.....	11
FIGURE 4. TEG WITH AN EQUAL ELECTRICAL CIRCUIT.	11
FIGURE 5. SOLAR ENERGY IS CONVERTED INTO DIFFERENT FORMS OF ENERGY.....	15
FIGURE 6. SCHEMATIC DIAGRAM OF A DISH-SHAPED PARABOLIC CONCENTRATOR WITH A FRONTAL VIEW OF A CONICAL HOLLOW TUBE SOLAR RECEIVER.	18
FIGURE 7. DIAGRAM ILLUSTRATING THE STRUCTURE AND COMPONENTS OF A PTC (HE, XIAO, CHENG, & TAO, 2011).	19
FIGURE 8. A CONVENTIONAL LIQUID FLAT PLATE COLLECTOR.	19
FIGURE 9. EFFICIENCY FOR FPC WITH TEG (ISTANBUL/TÜRKIYE).	40
FIGURE 10. EFFICIENCY FOR FPC WITH TEG (JERUSALEM/PALESTINE).	41
FIGURE 11. EFFICIENCY FOR FPC WITH TEG (CASABLANCA/MOROCCO).	42
FIGURE 12. EFFICIENCY FOR FPC WITH TEG (SYDNEY/AUSTRALIA).	43
FIGURE 13. EFFICIENCY FOR PDC WITH TEG (ISTANBUL/TÜRKIYE).	44
FIGURE 14. EFFICIENCY FOR PDC WITH TEG (JERUSALEM/PALESTINE).	45
FIGURE 15. EFFICIENCY FOR PDC WITH TEG (CASABLANCA/MOROCCO).	46
FIGURE 16. EFFICIENCY FOR PDC WITH TEG (SYDNEY/AUSTRALIA).	47
FIGURE 17. EFFICIENCY FOR PTC WITH TEG (ISTANBUL/TÜRKIYE)	48
FIGURE 18. EFFICIENCY FOR PTC WITH TEG (JERUSALEM/PALESTINE)	49
FIGURE 19. EFFICIENCY FOR PTC WITH TEG (CASABLANCA/MOROCCO).	50
FIGURE 20. EFFICIENCY FOR PTC WITH TEG (SYDNEY/AUSTRALIA).	51

FIGURE 21.EFFICIENCY TEG1 WITH PTCs/PM=30 °C.....55

FIGURE 22. EFFICIENCY COMPARISON OF TEGs WITH PDCs IN VARIOUS LOCATIONS.....60

FIGURE 23. SEEBECK COEFFICIENT AND THERMAL CONDUCTIVITY OF MATERIALS61

FIGURE 24.'EFFICIENCY COMPARISON OF TEGs WITH FPCs IN VARIOUS LOCATIONS'.....62

FIGURE 25. EFFICIENCY COMPARISON OF TEGs WITH PTCs IN VARIOUS LOCATIONS63

FIGURE 26.EXERGY EFFICIENCY COMPARISON FOR DIFFERENT LOCATIONS AND CONFIGURATIONS65



LIST OF TABLES

TABLE 1.GLOBAL HORIZONTAL IRRADIATION AND AIR TEMPERATURE WAS MEASURED BY THE “SOLCAST PROGRAM”.....	32
TABLE 2:TABLE 1 (CONT'D)"	33
TABLE 3.THE SPECIFICATION OF SFPCs (ALGARNI & KASHIF , 2023).....	34
TABLE 4.TEG DATA.....	35
TABLE 5.CASES OF STUDY	39
TABLE 6.EFFICIENCY FOR FPC WITH TEG (ISTANBUL/TÜRKIYE, LATITUDE 40.97)...	40
TABLE 7.EFFICIENCY FOR FPC WITH TEG (JERUSALEM/PALESTINE, LATITUDE 31)..	41
TABLE 8.EFFICIENCY FOR FPC WITH TEG (CASABLANCA/MOROCCO, LATITUDE 33.57)	42
TABLE 9.EFFICIENCY FOR FPC WITH TEG (SYDNEY/AUSTRALIA, LATITUDE -33.89)	43
TABLE 10.EFFICIENCY FOR PDC WITH TEG (ISTANBUL/TÜRKIYE, LATITUDE 40.97)	44
TABLE 11.EFFICIENCY FOR PDC WITH TEG (JERUSALEM/PALESTINE, LATITUDE 31)	45
TABLE 12.EFFICIENCY FOR PDC WITH TEG (CASABLANCA/MOROCCO, LATITUDE 33.57)	46
TABLE 13.EFFICIENCY FOR PDC WITH TEG (SYDNEY/AUSTRALIA, LATITUDE -33.89)	47
TABLE 14.EFFICIENCY FOR PTC WITH TEG (ISTANBUL/TÜRKIYE, LATITUDE 40.97).	48
TABLE 15.EFFICIENCY FOR PTC WITH TEG (JERUSALEM/PALESTINE, LATITUDE 31)	49
TABLE 16.EFFICIENCY FOR PTC WITH TEG (CASABLANCA/MOROCCO, LATITUDE 33.57)	50
TABLE 17.EFFICIENCY FOR PTC WITH TEG (SYDNEY/AUSTRALIA, LATITUDE -33.89)	51
TABLE 18.ANALYSIS OF THE ECONOMIC ASPECTS OF A PARABOLIC TROUGH COLLECTOR	66

TABLE 19. ANALYSIS OF THE ECONOMIC ASPECTS OF A PARABOLIC DISH COLLECTOR 66

TABLE 20. ANALYSIS OF THE ECONOMIC ASPECTS OF A FLAT-PLATE COLLECTOR 66

TABLE 21. ECONOMIC ASSESSMENT OF THERMOELECTRIC GENERATORS COMBINED WITH SOLAR COLLECTORS 68

TABLE 22. GREENHOUSE GASES (GHGs) FACTOR WAS MEASURED BY THE “RET SCREEN” PROGRAM 69

TABLE 23. CARBON EMISSION GREENHOUSE GASES (GHGs) [KGCO₂/KWH] 69



LIST OF ABBREVIATIONS

NOMENCLATURE

I) Thermoelectric generator.

V_{oc} : open circuit voltage (V)

ZT: figure of merit.

ΔT : different between the TEG sides temperature (K).

T_h : hot side temperature of TEG (K).

T_c : cold side temperature of TEG (K)

Q_h : heat current of hot side (W).

Q_c : heat current of cold side (W)

II) Solar collector

Q_s : absorbed solar radiation (W).

Q_u : useful energy (W).

Q_i : solar irradiance incident on the collector (W).

Q_o : heat loss coefficient (W).

I: solar irradiation (W/m^2).

U_L : heat transfer coefficient (W/m^2K).

T_a : ambient temperature (K).

T_{pm} : absorber plate temperatures (K).

T_r : receiver temperature (K).

T_{in} : input fluid temperature (K).

T_{out} : output fluid temperature (K).

A: collector area (m^2).

A_{ap} : aperture area (m^2).

A_{abs} : absorber surface area (m^2).

GREEK SYMBOLS

η_{TEG} : efficiency thermoelectric generator (%).

η_{Th} : thermal efficiency of collector (%).

η_{OP} : optical efficiency (%).

α : seebeck coefficient (V/K).

ρ : resistivity of TEG metal (ohm (Ω))

K: Thermal conductance (W/K).

τ : transmittance of collector.

α_{fpsc} : absorptance of collector.

ABBREVIATIONS

TEG: thermoelectric generator

PDC: parabolic dish collector

PTC: parabolic trough collector

FPC: flat-plate collector

HTF: heat transfer fluid.



Chapter 1

INTRODUCTION

Currently, development at present in the field of electrical energy all over this world. With the help of various scientific and technological developments, researchers are looking out for new ways to produce electrical power. Their objective is to reduce complete dependence on non-renewable sources of energy that causes massive environmental degradation. For this reason, renewable energy serves as the best alternative to those non-renewable fossil fuels. Lately, the optimal ways of energy generation that are clean have been sought by scientists and researchers in electric power engineering.

The development of green energy can be considered to start with the utilization of solar energy collectors. These tools were originally adapted to receive sunlight and convert it into thermal energy utilized in the home and industrial complexes, mostly for heating water. One such discovery, and the great potential it bore, was found by energy professionals looking for new ways to generate electricity using photovoltaic panels. The device absorbs a specific part of the solar spectrum and transforms this absorption into electric power (Tian & Zhao, 2013).

Sustainable energy experts dealing with thermic energy issues have proven that huge amounts of unused thermal energy rejected by photovoltaic panels exist. Further investigations were initiated to explore alternative means of generating electrical energy, with the aim of circumventing the consequential dissipation of heat. Among the various approaches considered, thermoelectric engines emerged as a promising option due to the fact that their basis of operation is to produce electrical energy from wasted heat (Hewawasam, Jayasena, Afnan, Ranasinghe, & Wijewardane, 2020).

When we go back in time to the nineteenth century AD, we discover that the scientist Thomas Johann Seebeck was the first to discuss the occurrence of the thermoelectric effect. This phenomenon may be explained by the fact that an electric current will be generated when a temperature gradient is supplied to a closed circuit that consists of two

different metals joined together in a ring. This is the fundamental idea behind the phenomenon. The development of thermoelectric generators could not have occurred without this discovery, which paved the way (Elzalik, Rezk, Mostafa, Thomas, & Shehata, 2020)

1.1 Statement of the Problem

The dependence of all the countries worldwide on non-renewable fossil fuels has led to a variety of problems in environmental, economic, and social aspects. From the way these fossil fuels cause harmful effects that go together—such as greenhouse gases and environmental pollution—and also the fact that they get depleted, it clearly calls for the intense development of alternative forms of energy sources. Among such solutions, that of combining solar collectors with thermoelectric engines has been one of the hot topics. Despite their promise, there are still large knowledge gaps regarding effectiveness, scalability, and barriers to real-world implementation. The current study focuses on assessing the performance effectiveness of thermoelectric engines with respect to solar collectors. The work carried out in this study is expected to give insights into the practicality of the technology and possibly new areas for development.

1.2 Purpose of the Study:

The thrust of this thesis is to critically evaluate the efficiency and effectiveness of the combination of the thermoelectric generator and solar collectors as a viable and environmentally friendly energy replacement. The growing demand for power supply around the globe, combined with various negative issues relating to non-renewable energy sources, has made it necessary to quickly explore and develop alternative cost considerations regarding energy. The aim of this study is:

- a. Carry out technical feasibility: adequate knowledge of scientific and technological issues related to thermoelectric generator integration with solar collectors. Determine the critical parameters associated with efficiency.
- b. Consider real-life applications: Analyze the existing examples of this integration in domestic and industrial situations, including an assessment of some of the practical benefits and challenges associated with it.
- c. Models and Model Scenarios: Use computational tools like MATLAB to create scenarios for predicting how such integrated systems would perform under different environmental, geographical, and technical factors.
- d. Suggest Improvements: In the light of the results, possible design, material, or technology changes to enhance efficiency and scalability can be recommended for this proposed energy solution.
- e. This study aims to fill the knowledge void in this field and promote a more in-depth understanding of the potential that thermoelectric engines, combined with solar collectors, have for a sustainable energy future.

1.3 Research Questions:

1. What is the effect of combining thermoelectric generators with solar collectors on the overall energy conversion efficiency?

2. What are the main parameters that impact the performance and efficiency of thermoelectric engines when combined with solar collectors?

3. What is the influence of various solar collector types on the efficiency of integrated thermoelectric engines, and is there an ideal combination?

1.4 Significance of the Study

The pursuit of sustainable and efficient energy solutions is a paramount task in the 21st century. Amidst the global challenges posed by climate change and the constraints of fossil fuels, novel renewable energy options are gaining prominence. This paper explores the effectiveness of thermoelectric engines, coupled with solar collectors, as can be seen from its significance in the following ways:

- **Significance and Contributions:** With the current investigation, the effort has been made to fill out the existing information gap in the concept of renewable energy sources, with particular reference to the fusion of thermoelectric engines in solar collectors. The work at hand would enhance academic literature and basically form the basis for further research initiatives through results, analyses, and simulations.
- **Technological Advancements:** The scientific inquiry can assist the engineer or technician in configuring an advanced function and nature of an energy conversion system, resulting in innovations in this sector.
- **Environmental Impacts:** If this can be proven feasible and it works, the integrated energy system would deplete dependency on high-carbon energy sources, and this alone could drive down emissions of greenhouse gases by a significant margin, which will stop climate change.

- **Economic Effects:** Better systems in renewable energies incur lower costs for production, which result in higher competitiveness with traditional sources. This should stimulate new economic expansion, more employment, and the sustainable establishment of the energy sector.
- **Policy and Decision Making:** Energy policy and investment decisions henceforth will have increasingly valuable insights of energy policies and infrastructural development in totality derived from these studies.

Considering the worldwide trend toward decentralizing energy sources, the study's efficient integrated systems can be used as an example of how to give off-grid and remote communities reliable and long-term access to energy. This can significantly improve their quality of life and socio-economic opportunities.

Essentially, the results of this research have the capacity to make an impact in several areas, ranging from academic settings to residential energy systems. The results of this study could have a big impact on the future of renewable energy because they show how well and if it is possible to combine thermoelectric engines with solar collectors.

1.5 Definitions:

A thermoelectric generator : is a device that utilizes the thermoelectric effect to directly convert heat energy into electrical energy. TEGs consist of thermoelectric materials that produce electrical energy in the presence of a temperature gradient. These devices are highly regarded for their capacity to use waste heat or natural heat differentials without the need for mechanical components, hence providing a sustainable approach to energy production.

The solar collector: is a device designed to gather solar radiation and then convert it into heat that may be used or, in the case of photovoltaic panels, directly into electrical energy. Solar collectors may be classified into two main categories: non-concentrating collectors, which include flat plate and evacuated tube collectors, and concentrating collectors, which include parabolic troughs, dishes, and Fresnel reflectors.

The Parabolic Trough Collector : is a type of solar collector that has been specially designed to absorb and concentrate sunlight on a receiver pipe located at the focal line of a reflector trough having a parabolic shape. The concentrated solar radiation results in thermal energy in a fluid circulating within the conduit, given that it may be used directly or transformed into electrical energy. PTCs are used widely in solar thermal power plants.

Flat Plate Collector : A solar collector designed for converting radiation from the sun into heat. A flat panel is fabricated to absorb energy arriving from the sun; transparent coverings create a way for rays of light to pass through without hindrance. Then there is the frame and insulation. The absorber collects solar energy and heats a working fluid conveyed through tubes attached to the plate. Fiber-Reinforced Composites (FPCs) find popular use in industrial heating applications in both residential and commercial systems, particularly in water heating.

The Parabolic Dish Collector is literally a type of solar collector that uses a parabolic-shaped dish; its task is to focus light onto a central receiver. It works like a satellite dish, though this time it focuses not on radio waves but light. As such, PDCs find application in power generation and industrial heat operations, where high temperatures are created through focused sunlight.

Heat Transfer Coefficient : The rate of heat transfer between a solid surface and a fluid is quantified by this quantity, given as the rate per unit area per unit temperature difference. In fact, thermal conductivity is one of the important factors in design and analysis related to thermal systems, as it takes measure of how much a material or system could conduct heat in support of effective energy flow.

HTF: Heat transfer fluid is a fluid specialized for heating, cooling, and power production systems. Many systems and processes require the efficient transfer of heat in an effective manner. Hydrothermal fluids are selected based on thermal stability and low viscosity and can be performed over a wide range or spectrum of temperatures. They are basically used in solar thermal plants, chemical processes, and HVAC applications.

Chapter 2

Theory and Literary reviews

2.1 Thermoelectric generator:

A full introduction to thermoelectric generators is given in this section of the thesis. It starts with how the idea of making electricity from heat came about, then moves on to look at the factors that affect this process, the basic idea behind it, the different uses, and finally some math calculations. pertaining to thermal power generators.

Utilising the Seebeck effect, cutting-edge technologies known as thermoelectric generators transform heat energy into electrical energy in a straightforward manner. This extraordinary technology has garnered a lot of attention in recent years because of its capacity to collect waste heat and turn it into useable energy, providing a solution that improves energy efficiency and reduces the effect that it has on the environment. the performance of thermoelectric motors is directly proportional to the temperatures at which they are operating open circuit voltage (Elzalik, Rezk, Mostafa, Thomas, & Shehata, 2020):

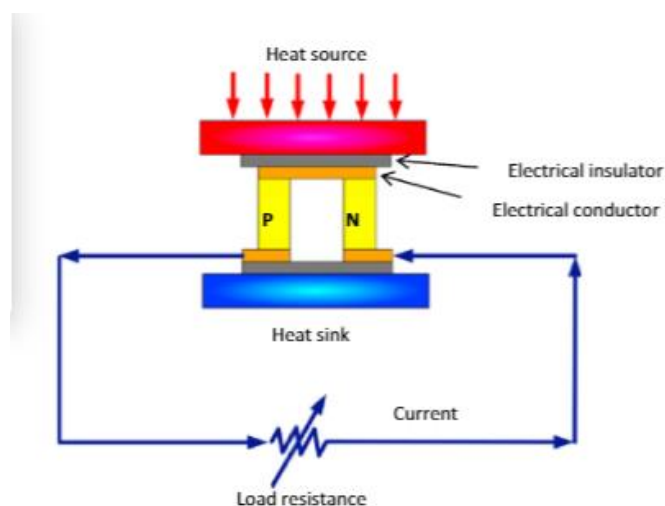


Figure 1: The Working Principle of TEG.

Thermoelectric generators comprise distinct thermoelectric materials that exhibit exceptional characteristics, each of which have their own set of distinguishing characteristics. These are the building blocks of a thermoelectric generator. These characteristics are embodied in three distinct physical qualities known as the Seebeck coefficient, electrical resistance, and thermal conductivity, which provide materials with the ability to produce electricity at a variety of temperatures. These materials include highly efficient semiconductors, such as bismuth telluride and lead telluride, that exhibit remarkable efficacy in electrical energy (Chen & Lin, 2019).

TEGs typically comprise several miniature thermocouples, which are pairs of thermoelectric materials with p-type and n-type properties. These thermocouples are interconnected in either a series or parallel configuration. Subsequently, these components are integrated into modules according to the specified voltage and current requirements. TEGs have a variable capacity that can span from a few milliwatts, which are sufficient for powering tiny sensors, to several hundred watts. By combining many large-scale TEGs, it is possible to generate a significantly higher amount of electricity (Bhuiyan, Mamur, Üstüner, & Dilmaç, 2022).

Thermoelectric Generators There are several advantages to thermoelectric generators compared to conventional methods of power generation. Being solid-state and offering no moving parts, thermoelectric generators are highly reliable once used in applications and entail almost no maintenance services. The only feature of significance to thermoelectric generators is that they can be exploited efficiently over a broad range of temperature differences, making them applicable in different environments and for various uses (Jouhara, et al., 2021).

2.1.1 Capacity of the thermoelectric

Among the attractive characteristics of thermoelectric generators is their ability to convert waste heat into electric power. A variety of industrial processes and power production systems release significant excess heat as a byproduct, which typically gets dumped into the surrounding environment. This wasted heat can be captured by the thermoelectric generator, which in turn converts it into useful energy, thus not only increasing total energy efficiency but also reducing the level of greenhouse gas emissions. Some of the diverse fields of application for thermoelectric generators are cars, aircraft, consumer electronics, and even exploring space. They may be installed in the exhaust systems of vehicles, aviation engines, or portable electronic gadgets to convert the waste heat produced by the equipment into energy (Chen, Saw, Bandala, Wang, & Hoang, 2021).

2.1.2 Applications of TEG

TEGs are used in a range of applications to recover waste heat. These include harvesting thermal energy in low-power situations, generating power for small electronic sensors and devices, producing solar energy, recovering waste heat in industrial settings, managing automotive exhaust heat, enabling IoT applications, and powering medical devices. They play a role in diminishing energy usage and mitigating greenhouse gas emissions within the automobile sector (Bhuiyan, Mamur, Üstüner, & Dilmaç, 2022).

2.1.3 Basic principles of TEGs

The basic principles of TEGs are simple: a semiconductor material is subjected to a thermal gradient, with one side being chilled and the other side being heated, leading to a temperature disparity between the two sides. When a temperature gradient is established, it results in the formation of a potential gradient, which refers to a rise in electrical potential, as seen in Figure 3 below.

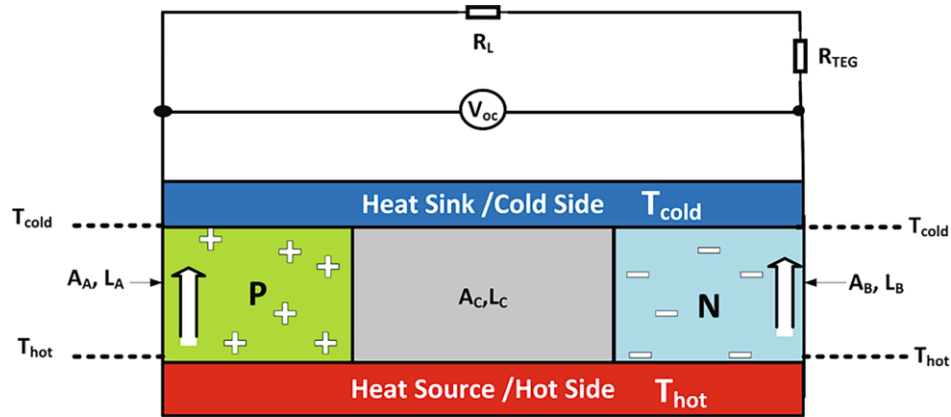


Figure 2. Illustration of the schematic diagram of a TEG.

2.1.4 Seaback Coefficient:

Thomas Seebeck is credited with the discovery of the Seebeck effect in 1821. The Seebeck effect is a phenomenon where a temperature gradient across two dissimilar conductors or semiconductors results in the generation of an electric potential difference between the materials. When heat is supplied to a conductor or a semiconductor, electrons that are heated by the heat travel away from the colder conductor or semiconductor. Direct current (DC) is established in an electrical circuit when a power source is connected to it. The Seebeck effect normally generates just a small number of microvolts per kelvin of temperature variation. Certain Seebeck effect devices have the capability to produce millivolts when there is a substantial change in temperature. A thermocouple is a dual set of metallic conductors employed for the purpose of establishing an electrical circuit (Hantosh, Farag, & Jumaah, 2023).

Thermocouples are employed to approximate temperature fluctuations of a larger magnitude due to the Seebeck effect. As seen in Figure 4, the Seebeck effect influences the functioning of thermocouples, which are utilized for detecting temperature fluctuations or triggering electronic switches that shut down large-scale systems (refer to Figure 5) (Hsu, Huang, Chu, Yu, & Yao, 2011).

Seebeck is unable to precisely identify the origin of the magnetic field. The magnetic field is generated by two metal strips with equal and opposite currents flowing through their legs. The temperature gradient between the materials generates a potential difference across the connection, which in turn induces these currents. If the connection is unobstructed but the temperature difference stays consistent, no electric current will pass through the branch. However, it is possible to measure the voltage across the open circuit (Hantosh, Farag, & Jumaah, 2023).

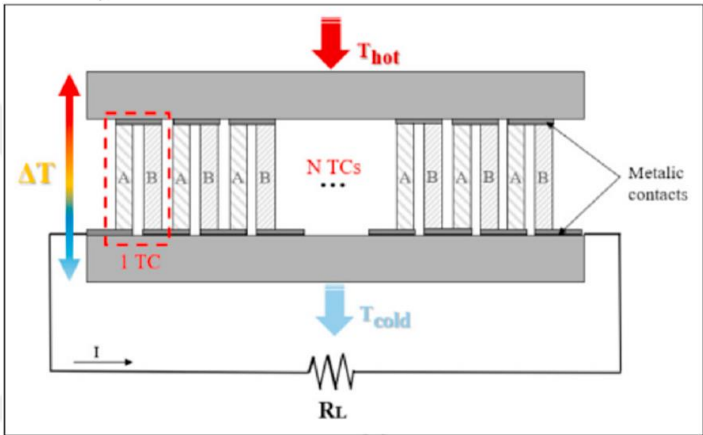


Figure 3. The TEG operates based on the concept of thermoelectricity.

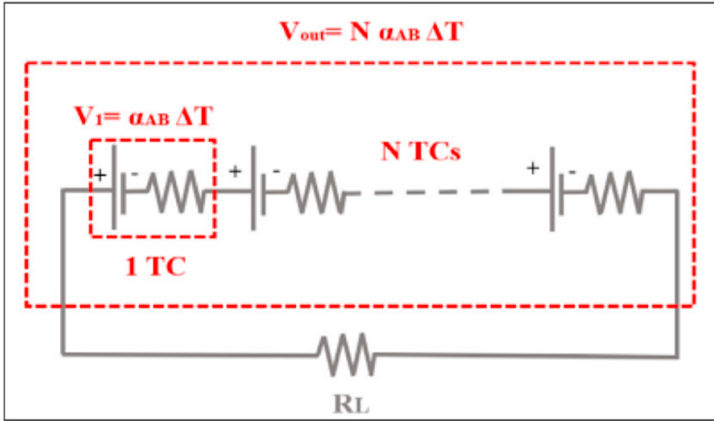


Figure 4. TEG with an equal electrical circuit.

2.1.5 Equations specifically designed for TEG:

This section will elucidate the equations used for the computation of voltage, current, power, and efficiency in thermoelectric generators.

Thermoelectric generators operate by using the temperature differential between the hot and cold sides, as well as the Seebeck coefficient. By connecting these two factors, the thermoelectric generators generate an electrical voltage, which is mathematically represented by Equation (1) as given below (Bjørk & Nielsen, 2015).

$$V_{oc} = \alpha \cdot \Delta T \dots \dots (1)$$

Where, ΔT the difference between the hot and cold sides TEG sides temperature as represented by Equation (1.1) :

$$\Delta T = T_h - T_c \dots \dots \dots (1.1)$$

Using the given mathematical expressions, the thermoelectric properties of Bismuth telluride alloys are measured, which are dependent on the operating temperature (Sahu, K, & Natarajan, 2021).

$$\text{Seebeck coefficient, } \alpha = (22224 + 930.6 \cdot T_{av} - 0.9905 \cdot T_{av}^2)10^{-9} \dots \dots (1.2)$$

$$\text{Electrical resistivity, } \rho = (5112 + 163.4 \cdot T_{av} - 0.6279 \cdot T_{av}^2)10^{-10} \dots \dots (1.3)$$

$$\text{Thermal conductivity, } K = (62605 - 277.7 \cdot T_{av} + 0.4131 \cdot T_{av}^2)10^{-4} \dots \dots (1.4)$$

Equation (1.5) represents the division of the sum between the hot and cold sides of the TEG by 2.

$$T_{av} = \frac{T_h + T_c}{2} \dots \dots \dots (1.6)$$

Equation (2) provides the thermal-electric figure of merit. We divide the Seebeck coefficient square (α^2) of TEG by the multiplied resistivity of the TEG metal ρ and the thermal conductance K to find the amount of ZT . All these factors multiply the temperature T . (Li, et al., 2023):

$$ZT = \frac{\alpha^2}{\rho \cdot K} \cdot T \dots \dots \dots (2)$$

By utilizing equations (1.1, 2) in sequence, the maximum current I_{\max} for the thermoelectric motors can be calculated using Equation No.(3) (Zhang & Zhao, 2015):

$$I_{\max} = \frac{\sqrt{1 + ZT_{\text{avg.}}}}{\sqrt{1 + ZT_{\text{avg.}} + \frac{T_c}{T_h}}} \cdot \frac{-1}{T_h} (T_h - T_c) \dots \dots \dots (3)$$

Apply the first law of thermodynamics to transfer heat from a region of high temperature, as shown in Equation (4), to a region of low temperature using the following Equation (5) (Sahu, K., & Natarajan, 2021):

$$Q_h = \alpha \cdot I_{\text{teg}} \cdot T_h + K \cdot \Delta T - \frac{1}{2} I_{\text{TEG}}^2 \cdot R_{\text{int}} \dots \dots \dots (4)$$

$$Q_c = \alpha \cdot I_{\text{teg}} \cdot T_c + K \cdot \Delta T + \frac{1}{2} I_{\text{teg}}^2 \cdot R_{\text{int}} \dots \dots \dots (5)$$

Where R_{int} total pellets internal resistance

For the calculation of the TEG power, we can subtract Equation No. 4 from Equation No. 5, resulting in Equation (6.3). (Edvin Risseh, Goupil, & Nee, 2018)

$$P = Q_h - Q_c \dots \dots \dots (6)$$

$$P = \alpha \cdot \Delta T \cdot I_{\text{teg}} - I_{\text{teg}}^2 \cdot R_{\text{int}} \dots \dots \dots (6.1)$$

$$P = (\alpha \cdot \Delta T - I_{\text{teg}} \cdot R_{\text{int}}) \cdot I_{\text{teg}} \dots \dots \dots (6.2)$$

$$P_{TEG} = V_{teg} \cdot I_{teg} \dots \dots \dots (6.3)$$

Utilize Ohm's law to analyze the TEG module-comparable circuit as show in fig 5. The output voltage (V_{teg}) of a TEG may be derived from the following relation when it is connected to a load resistance (R_l) (Elzalik, Rezk, Mostafa, Thomas, & Shehata, 2020):

$$V_{teg} = \alpha \cdot \Delta T - I_{teg} \cdot R_{int.} = V_{oc} - I_{teg} \cdot R_{int.} = I_{teg} \cdot R_l \dots \dots \dots (7)$$

$$P_{teg} = I_{teg}^2 \cdot R_l \dots \dots \dots (7.1)$$

The efficiency (η) of the TEG can be found from Equation (8). To determine the amount of η , the electrical power output of TEG (P_{teg}) is divided by the heat flow rate on the hot side of the TEG (Q_h) (Cheng, 2016):

$$\eta_{TEG} = \frac{P_{teg}}{Q_h} \dots \dots \dots (8)$$

The equation provided may be used to determine the voltage, current, and power at the maximum power point (MPP) (Ashraf, 2020).

$$V_{mpp} = \frac{\alpha \cdot \Delta T}{2} = \frac{1}{2} V_{oc} \dots \dots \dots (9)$$

$$I_{mpp} = \frac{\alpha \cdot \Delta T}{2 \cdot R_{int.}} = \frac{V_{oc}}{2 \cdot R_{int.}} \dots \dots \dots (10)$$

$$P_{mpp} = V_{mpp} \cdot I_{mpp} = \frac{\alpha^2 \cdot \Delta T^2}{4R_{int.}} = \frac{V_{oc}^2}{4R_{int.}} \dots \dots \dots (11)$$

$$P_{max} = \frac{V_{out.}^2}{4R_{teg}} \dots \dots \dots (12)$$

2.2 Solar collectors:

This portion of the thesis presents an introductory overview of solar collectors. The discussion commences by categorizing solar collectors based on the concentration of solar radiation. It then proceeds to examine the factors that influence solar collectors, followed by an explanation of the operational principles for each of the three types that will be utilized in this thesis. Lastly, mathematical calculations are presented. Pertaining to each of the three chosen intricate categories.

Solar collectors are one of the methods that may be used for the purpose of harvesting solar energy and transforming it into either electrical or thermal energy show to Figure 5. Unconcentrated solar collectors are on one end of the spectrum, while concentrated solar collectors are on the other. Solar collectors are divided into these two groups based on the concentration of their collected sunlight.

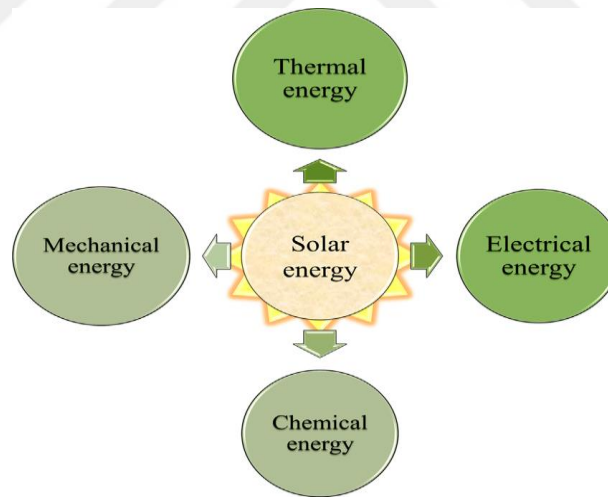


Figure 5. Solar energy is converted into different forms of energy.

Solar energy collectors are devices that are designed to capture and convert solar radiation into usable energy. The initial classification pertains to unconcentrated collectors. This category is stationary and lacks the ability to effectively monitor the movement of solar radiation. Illustrative instances comprise a flat plate (Struckmann, 2008). Regarding the second classification, the concentrative collectors can be bifurcated into two segments: the initial segment tracks a singular axis of the sun's beams. One instance that can be cited is a parabolic trough (Mwesigye & Meyer, 2017).

The second mechanism has the capability to monitor the movement of the sun's rays along two axes. An instance of such a mechanism is a parabolic dish reflector (Hantosh, Farag, & Jumaah, 2023).

Solar collectors possess a significant benefit in their capacity to produce electricity without releasing any detrimental pollutants or greenhouse gases. Renewable energy sources offer a viable and eco-friendly substitute for conventional energy sources, thereby playing a crucial role in mitigating carbon emissions and environmental degradation. In light of the global challenges posed by climate change, solar collectors have garnered significant attention and have emerged as a crucial component of the worldwide shift towards renewable energy (Tian & Zhao, 2013).

2.2.1 The operational mechanism of solar energy collectors:

A solar collector is a device that, in its most basic form, acts to collect the sunlight that is received from the sun. In concentrated solar power technology, for example, the amassed solar energy may be transformed into thermal energy for the working fluid; in photovoltaic technology, however, the solar can be converted into electrical energy (Bellos & Tzivanidis, 2018).

I) Parabolic dish solar collector:

A parabolic dish is comprised of a meticulously designed arrangement of mirrors shaped in the form of parabolic dishes. The precise shape closely resembles a round paraboloid, similar to that of a satellite dish as shown in Figure 6. The design of the shape aims to convert the incoming plane wave, which propagates down the axis, into a converging spherical wave that is directed towards the focal point. These gadgets ensure a consistent focus, while the reflectors are designed to shift. Attaining accurate focus requires a significant degree of accuracy and is not easily achievable (Abbas, et al., 2023).

A solar collecting dish functions by gathering heat radiation and concentrating it at a certain focal point where the receiver is positioned. The receiver contains a substantial amount of transmission fluid. The fluid undergoes heating, resulting in an increase in both its temperature and pressure. At the receiver outlet, a motor is present which transforms thermal energy into electrical energy. The thermoelectric generator will serve as the engine in this context (Ahmad, et al., 2024).

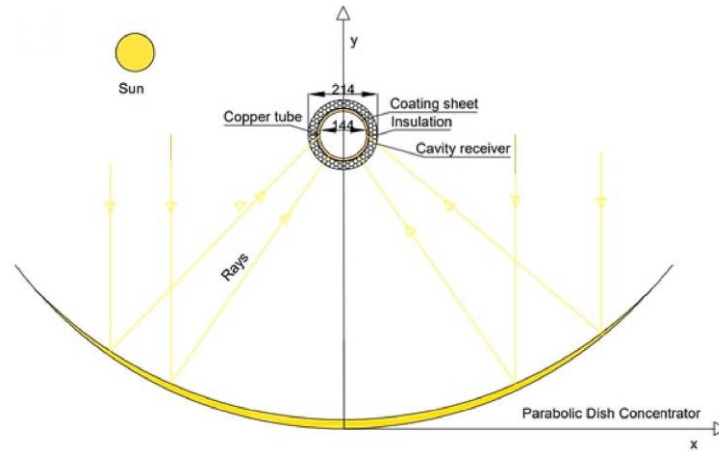


Figure 6. Schematic diagram of a dish-shaped parabolic concentrator with a frontal view of a conical hollow tube solar receiver.

II) Parabolic trough solar collector (PTC):

The initial configuration and fundamental operations are largely analogous to those of a parabolic dish, with the exception that there is no Stirling dish connected at the end stage of the dish. A parabolic trough is characterized by a linear form in one dimension and curved shapes in the other two dimensions, as shown in Figure 7 (Ahmad, et al., 2024). The purpose of the trough is to enable the sun's rays to enter in a parallel manner to its axis of symmetry and then focus them along the focal line. The recipient, in this instance, is a charred cylinder positioned just above the midpoint of the paraboloid. The tube contains a thermal fluid, typically a blend of water and thermal oil. The reflective surface is often composed of reflective silver-coated metal or polished aluminum, or alternatively, mirrors are utilized (He, Xiao, Cheng, & Tao, 2011).

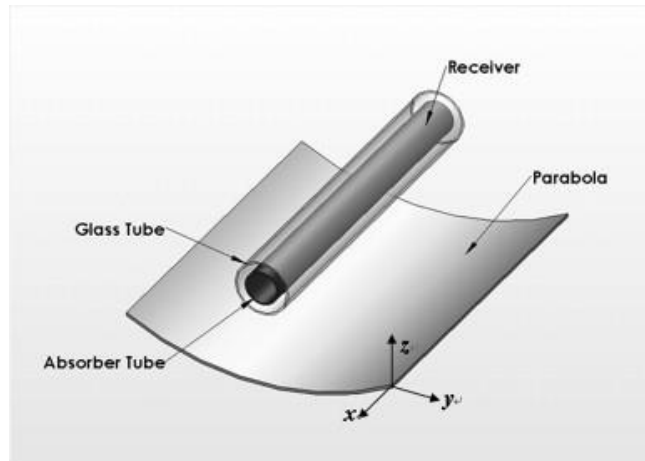


Figure 7. Diagram illustrating the structure and components of a PTC (He, Xiao, Cheng, & Tao, 2011).

III) Flat plate solar collector:

Flat-plate collectors are widely used as sun collectors in residential solar water-heating systems and solar space heating. A standard flat-plate collector consists of an insulated metal enclosure with glazing made of glass or plastic, together with a dark-colored absorber plate. These collectors raise the temperature of liquid or air to levels below 80°C, show in Figure (8) (Struckmann, 2008).

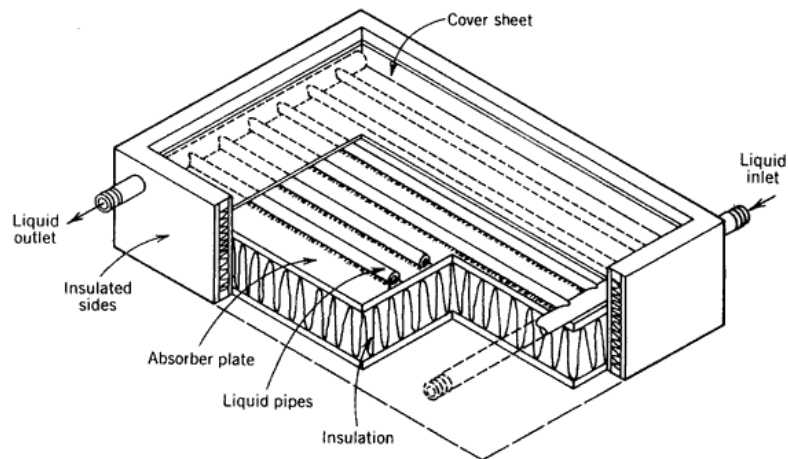


Figure 8. A conventional liquid flat plate collector.

2.2.3 Solar collector equations:

I. Energy Calculations

This part provides an overview of the equations related to each of the three categories of solar energy collectors discussed in the preceding chapters of the thesis.

I) parabolic dish solar collector equations (Abbas, et al., 2023) (Hantosh, Farag, & Jumaah, 2023) (Shanmugam, Eswaramoorthy, & Veerappan , 2011) , (Hussain & Hasanuzzaman, 2022) :

The amount of solar energy Q_s that can be acquired or accessed is defined as the product of solar radiation I multiplied by the collector's area A as show in Equation (13)

$$Q_s = A \times I \dots \dots \dots (13)$$

Where A is the area of the collector can calculate as follows in Equation (13.1):

$$A = \pi \times (D/2)^2 \dots \dots \dots (13.1)$$

D is the diameter of dish.

We use the energy balance in the fluid's volume (in this case, water) to calculate the effective heat production Q_u . This involves multiplying the mass m of the liquid by the specific heat capacity c times the temperature as shown in Equation (14):

$$Q_u = m \cdot c \cdot \Delta T \dots \dots \dots (14)$$

Where: c is the specific heat capacity of water around $4186 \text{ J/Kg}^\circ\text{C}$,

The thermal efficiency (η_{th}) of the collector in Equation 15 can be calculated by dividing Equation (13) by Equation (14).

$$\eta_{th} = \frac{Q_U}{Q_s} \dots \dots \dots (15)$$

Power output from the collector is calculated as the product of multiplying thermal efficiency (η_{th}) by absorbed solar radiation Q_s as show in Equation (16):

$$P_{DC} = Q_s \times \eta_{th} \dots \dots \dots (16)$$

II) flat -plat solar collector, parabolic trough collector (Yousefi, Veisy, Shojaeizadeh, & Zinadin, 2012) (Struckmann, 2008) (Faddouli, et al., 2020), (Jebasingh & Joselin Herbert, 2016) , (Rosen & Farsi, 2022) :

Solar irradiance incident Q_i on the collector in Equation (17) can be calculation involves multiplying the solar radiation I by the transmittance τ , absorption α_{fpSC} , and area of the collector A :

$$Q_i = I \cdot (\tau \cdot \alpha_{fpSC}) \cdot A \dots \dots \dots (17)$$

The following calculation, which multiplies the heat transfer coefficient (U_1) by the temperature difference between the collector's sides ΔT and area A , determines the heat loss coefficient in Equation (18):

$$Q_o = U_1 \cdot A \cdot (\Delta T) \dots \dots \dots (18)$$

Calculate the rate of useful energy gained as shown in Equation 19 by subtracting Equation (17) from Equation (18):

$$Q_u = Q_i - Q_o = (I \cdot \tau \cdot \alpha_{fpSC}) \cdot A - U_1 \cdot A \cdot (T_{pm} - T_a) \dots \dots \dots (19)$$

The value Heat transfer coefficient (U_L) is calculated by multiplying the optical efficiency (η_{op}), aperture area (A_{ap}), and solar irradiation (I), and then dividing it by the product of the absorber surface area (A_{abs}) and the difference between the receiver temperature (A_{abs}) and the ambient temperature (T_a). as shown in Equation (20):

$$U_L = \frac{\eta_{op} \cdot A_{ap} \cdot I}{A_{abs} \cdot (T_r - T_a)} \dots \dots \dots (20)$$

To calculate the input temperature as shown in Equation (21)

$$T_{IN} = T_a + \frac{Q_s}{m \cdot c} \dots \dots \dots (21)$$

Efficiency of collector in Equation (22) can be calculated by dividing useful energy gained Q_u by absorbed solar radiation Q_s ..:

$$\eta = \frac{Q_u}{A \cdot I} \dots \dots \dots (22)$$

These equations represent the second law of thermodynamics.

I. Exergy Calculations (Ahmad, et al., 2024) (Ashraf, 2020) (Björk & Nielsen, 2015) (Cai, et al., 2020)

a. Exergy of Solar Radiation

The following equation can be used to calculate the exergy of solar radiation (Ex_{solar}):

$$E_{x,solar} = I \times A \times \left(1 - \frac{T_a}{T_{sun}}\right) \dots \dots \dots (23)$$

Where: T_{sun} is the temperature of the sun, typically approximated as 5778 K.

b. Exergy Destruction in Solar Collectors

The exergy destruction in the solar collector ($E_{x,d, collector}$) is represented by:

$$E_{x,d,collector} = E_{x,solar} - E_{x,usful} \dots \dots \dots (24)$$

The useful exergy output from the solar collector can be calculated using the thermal efficiency (η_{th}):

$$E_{x,usful} = \eta_{th} \times E_{x,solar} \dots \dots \dots (25)$$

c. Exergy degradation in Thermoelectric Generators (TEGs)

The exergy destruction in the TEG can be calculated by comparing the exergy input to the TEG with the electrical exergy output.

$$E_{x,d,TEG} = E_{x,input,TEG} - E_{x,output,TEG} \dots \dots \dots (26)$$

The input exergy to the TEG is derived from the thermal exergy of the hot side.

$$E_{x,input,TEG} = Q_h \left(1 - \frac{T_c}{T_h}\right) \dots \dots \dots (26.1)$$

The electrical power generated is the output exergy from the TEG.

$$E_{x,output,TEG} = P_{TEG} \dots \dots \dots (26.2)$$

d. Exergy Efficiency

The system's overall exergy efficiency (η_{ex}) can be calculated by

$$\eta_{ex} = \frac{E_{x,output,TEG}}{E_{x,solar}} \dots \dots \dots (27)$$

Earlier works have used variable costs of 0.3F and 1.3F annually (Kabeel, 2009) (Tawfik, ELTohamy, Metwally, Khallaf & Abd Allah, 2022), respectively. The current thesis takes the system's variable cost, V, as being 0.8F per year. The aggregate expenditure (TC) may be computed as:

$$TC = F + V \dots \dots \dots (28)$$

Total productivity (P_L) can be calculated as:

$$P_L = \text{minimum daily productivity} \times \text{working days per years} \\ \times \text{still life time} \dots \dots (29)$$

Assume a lifespan of 10 years and 320 working days per year.

The specific cost (C_S) of 1\$/KW

$$C_S = \frac{TC}{P_L} \dots \dots \dots (30)$$

To calculate the GHG carbon emissions, as shown in the equation:

$$\text{carbon emission savings} = \text{Total productivity } (P_L) * (\text{GHGs}) \text{ factor}$$

Note: Tabla24 shows the Greenhouse gases (GHG) factor.

2.3 Literary reviews

(Bjørk & Nielsen, 2015) The article examines the performance of a combined solar photovoltaic and thermoelectric generator system using an analytical model. Results show that the degradation of PV performance with temperature dominates the increase in power produced by the TEG. Previous experimental results have demonstrated an increase in performance of more than 50%.

(Ruzaimi, et al., 2021) This study investigated the performance of TEGs under non-uniform temperature conditions and suggested approaches for improving efficiency. Results showed a slight difference in power extracted at each area, with the highest power produced at the center of the PV backside surface. The present article, as well as its predecessor, have addressed the correlation between PV-TEGs. The presidents of temperature While the preceding article employed a uniform temperature, the present article employs a non-uniform temperature.

(Hewawasam, Jayasena, Afnan, Ranasinghe, & Wijewardane, 2020) investigates the feasibility of waste heat recovery from TEGs integrated with the muffler of internal combustion engines (ICEs). Simulations were used to predict the electrical power output by the TEMs, and the power generation increased as the exhaust gas temperature increased. The pressure drop across the muffler was found to be 28 kPa.

(Eldesoukey & Hassan, 2019) investigated a new three-dimensional model of TEGs using CFD modeling to study the impact of flow regimes on TEG performance when mounted on a chimney wall. It found that installing the TEG at the inlet position of coolant flow and hot gases achieved the maximum power output. In this and the previous article, TEGs were designed using the same simulation programming (ANSYS).

(Elzalik, Rezk, Mostafa, Thomas, & Shehata, 2020) proposes and implements a TEG system with an INC-MPPT algorithm to maximize the output power of the TEG module. Results show that the efficiency of the INC-MPPT techniques has increased from 96.9% to 98.6% and the harvested power has been duplicated by more than six times.

(Owoyele, Ferguson, & O'Connor, 2015) analyzes the performance of a thermoelectric cooler with a corrugated architecture and optimizes its geometry and materials to improve efficiency and reduce cost. Results show that the corrugated cooler has higher cooling power density and lower required input power compared to a conventional bulk thermoelectric cooler.

(Wu, et al., 2014) This article discusses the use of thermoelectric generators to generate electric power, but high temperatures or heat flux can negatively impact the device's lifespan. A numerical analysis of the thermodynamics and thermal stress performance of the device found that thermal stress has a decisive effect on the device's lifespan. Different geometrical configurations were tested to improve the module's working condition.

(Chen, Saw, Bandala, Wang, & Hoang, 2021) The article discusses the importance of improving the performance of thermoelectric generators to recover waste heat and convert it into green power. Results show that installing plate fins or square pin fins can significantly increase waste heat harvest.

(Jouhara, et al., 2021) TEGs are a promising alternative for green power production due to their unique advantages such as being environmentally safe, quiet, position independent, and ideal for bulk and compact applications.

(Sahin & Yilbas, 2013)The study investigates the influence of thermoelectric leg geometry on the efficiency and power generation of a thermoelectric power generator. It finds that increasing or decreasing the shape parameter has a favorable effect on efficiency, but an adverse effect on power generation.

(Erturun, Erermis, & Mossi, 2014) The article discusses the effect of different Leg geometries significantly affect thermal stresses in thermoelectric devices, with smaller thermal stresses in cylindrical and trapezoidal prism legs.

(Sahin & Yilbas, 2013), (Erturun, Erermis, & Mossi, 2014) Both this article and another article explored the same concept. The initial scholarly publication employed leg geometries in a theoretical context, while a subsequent article employed the same methodology in an experimental setting. Both articles present identical findings.

(Chen & Lin, 2019) The article discusses the use of thermoelectric generators TEGs to generate power from waste heat, but their performance changes with temperature. Simulations show that the output power of TEGs deviates from the formula when their properties are temperature-dependent and that different materials have different performances.

(Li, et al., 2023)The text discusses a new technology for generating electricity from waste heat using high-efficiency solid-state conversion achieves superior zT of 1.47 at 973 K. This work has a transformative impact on the design and development of next-generation thermoelectric generators for any thermoelectric material family.

(Cai, et al., 2020) This study examines the impact of solar irradiance, quantity of thermoelectric generators, and ambient air temperatures on the power output of CPV-TEG. Results show that the system's energy and exergy efficiencies during winter heating mode are significantly greater than those observed during summer cooling mode.

(Tian & Zhao, 2013) The text discusses the increasing interest in thermal applications in solar energy research due to their high performance in energy storage density and conversion efficiency. Solar collectors and thermal energy storage systems are essential components of solar energy research due to their high energy storage density and conversion efficiency.

(Struckmann, 2008) The paper is an analysis of active systems of solar energy and solar collectors in such systems. The report limits its scope to an analysis of a flat-plate solar collector and the difficulties associated with analyzing thermal performance. An attempt was made to suggest a mathematical model to describe the performance of the thermal collector in a computationally efficient manner.

(Suman, Kaleem Khan, & Pathak, 2015) The paper primarily reviews progress in solar thermal technology, with special references to the methods adopted for improving performance. It contains different types of solar collectors and modifications done in each category to develop the use of solar energy. Also, it mentions a few techniques for enhancement of performances, like geometrical modifications, solar selective coatings, and nanofluids.

(Hantosh, Farag, & Jumaah, 2023) The focused proposal study is on the design, fabrication, and testing of the thermoelectric generator powered by solar energy and looks into exploring a concentrator. It is made from a Peltier 12706 module, heatsink, antenna dish, and a programmed temperature difference monitor unit. From the paper's results, the generated voltage of the thermoelectric generator depends on the temperature difference of its surfaces; an increase in the difference thus generates a more external voltage.

(Mwesigye & Meyer, 2017) It researched on the best performance of a parabolic trough solar energy system with various nanofluids. The best thermal performance was signified by Silver-Terminal VP-1, whereas aloe vera VP-1 showed the least thermal performance.

(Zehui, et al., 2023) The article had a solar-collector system which detects compounds and parabolic concentrations. This system was used for soil disinfection without pollution with the use of energy from the sun. It was tested in a greenhouse and found to suppress weed growth and kill pests and pathogenic bacteria.

(Abbas, et al., 2023) The article discusses the importance of designing a parabolic dish concentrator system and the selection of proper operating parameters in the conversion of solar energy. The average efficiency of exergy found for the conical receiver is 8.16%, and the average energy efficiency is 65.81% at the higher concentration ratio.

(Hsu, Huang, Chu, Yu, & Yao, 2011) The requirement of the effective Seebeck coefficient concept occurs in the paper to talk about the difference that appears between the theoretically predicted and experimentally measured Seebeck coefficients. This difference relates itself to the contact effect and the thermal resistor network effect. It has been concluded from the work that the thermal contact effect is the key parameter of TEG module performance. A thermal resistor network is developed to get a detailed measure of the temperature difference across the TE ingot. Effective Seebeck coefficient ideas will be introduced in order to make sense of module performance for different situations

(Cheng, 2016) The model proposed is briefly described, for which mean forecasts for the performance of thermoelectric generator are developed at the device level. The developed model considered effects of Seebeck, Peltier, Thomson and Joule conduction heat. It alternates the analysis of TEG performance by shedding light on the effects of its main factors, thermal and electrical variables, while omitting the Thomson effect. Some details of an experimental setup are given. The design idea on which the book and a previous article's basis was the same—details of how to calculate the Seebeck coefficient—but the approach of the article is from an experimental point of view, whereas that of the book is through simulation software.

Chapter 3

Methodology

In this section, a fully comprehensive strategy is taken to evaluate the working efficiency of the thermoelectric generator when combined with solar collectors. The approach was developed with the goal of answering the research questions that were established in the previous sections of this study. This ranged from the choice of some of the materials to be used to experimental setup design, data collection, and its interpretation by analysis. Of focal interest are replication, validation, and dependency on the investigation results.

Note on Units: "In this thesis, all measurements have been converted to the International System of Units (SI) for consistency." The conversion factors used can be found in Appendix A.

3.1 Research Design:

The research approach used in this work is a quasi-experimental one, and it involves the modeling of the operation of a thermoelectric engine in controlled settings by making use of solar collector apparatus. Using this method, it is possible to manipulate important factors in order to examine the influence that they have on the effectiveness, economic aspects, and environmental impact of the system.

In general, solar collectors primarily depend on solar radiation to generate thermal energy, which is then converted into electrical energy using engines. In this case, these engines will serve as thermoelectric generators that function based on the concept of temperature differentiation.

This thesis examined nine distinct examples. The nine instances included three variations of bismuth telluride thermoelectric engines, which were linked to three different kinds of solar energy collectors. The selection of these solar energy collectors was based on sun tracking, as elucidated in the preceding chapters of the thesis.

Solar collectors depend on solar radiation to raise the temperature of the liquid inside them, and thus thermal energy is produced according to their operating principle, as mentioned in the previous chapter. The thermal energy in this position will serve as an input for thermoelectric generators that rely on the temperature difference to generate electrical energy.

Based on the information presented in the previous chapters of this thesis, in which the basic principles behind the operation of thermoelectric generators and solar collectors were discussed, we can understand the methodology that we will use in this thesis.

The methodology used in this thesis is a semi-experimental approach using the MATLAB software to assess the effectiveness, economic aspects, and environmental impact of solar power systems and thermoelectric generators.

The objective of this experiment is to use the MATLAB software to replicate the solar system by inputting the values of solar radiation, temperature differentials, and other factors that are crucial for both solar collectors and thermal generators. This portion of the thesis will provide an explanation.

Simulated manufacturing requires data entry and calculations to provide a comprehensive comparison between the different situations. This is to answer the research questions that were clarified in the previous parts of the thesis. We thus have the information required to address the queries presented in the later parts of the thesis.

3.2 Data Collection:

Data collection is a critical step on which all parts of this chapter depend.

3.2.1 Data Collection Procedures:

Data collection was shown in many sections. The data gathering process was conducted in three distinct parts, which are outlined as follows:

Section I: The values of solar radiation and temperature used to represent this section.

These numbers were obtained through the use of software specifically designed for that purpose.

Section II: This section encompasses the many factors that solar power complexes and thermoelectric generators rely on, as determined by prior research.

Section III: This section presents the findings from prior research about the effectiveness of the system. It is through these findings that the outcomes of this thesis will be compared with the results of past research in order to provide answers to the research issues that were indicated previously.

Section 1:

This dataset depicts the climatic conditions for the month of June 2023 in four cities in many different nations.

Table 1: Global horizontal irradiation and Air temperature was measured by the “Solcast program”.

Country/city	Latitude	GHI (W/m ²)
Türkiye, Istanbul	40.97	273.06
Palestine, Jerusalem	31.00	329.00
Morocco, Casablanca	33.57	313.54
Australia, Sydney	-33.89	112.11

Table 2:Table 1 (cont'd)"

Country/city	Latitude	T _a (K)
Türkiye, Istanbul	40.97	294.50
Palestine, Jerusalem	31.00	298.42
Morocco, Casablanca	33.57	296.81
Australia, Sydney	-33.89	287.29

Section II: Two categories of data are represented in this section; their explanations are as follows:

Data on solar energy collectors comes first. The subsequent three tables, in that order, detail the various configurations of parabolic dish solar collectors, parabolic trough solar collectors, and flat panel solar collectors.

Table 3.Parameters for a SPDCs (*Abbas, et al., 2023*)

Parameters	Values
Diameter of parabolic dish	0.9 m
Aperture area of single reflector	0.71 m ²
Parabola depth (h)	0.05m
Dish concentrator focal length	1.02 m
Refractive index of glass	1.50
Class reflectivity	8%
Glass transmittance	2%
AgNO ₃ reflectivity	97.50
Rim angle	45°

Table 4. Typical trough collector segment specification (*Chafie, et al., 2016*).

Description	Values
Length	4m
Aperture	2.70m
Focal distance	0.84m
Aperture area	10.8m ²
Concentration ratio	11.77
Rim angle	76.30°
Reflected surface reflectivity	0.9300.93
Dimeter inner tube	0.07m
Dimeter outer tube	0.12m
Absorptivity	93%
Emittance	8 %
Glass transmissivity	0.95

Table 5. The specification of SFPCs (*Algarni & Kashif, 2023*).

Description	Values
Surface area	2.86 m ²
Absorber surface area	2.68 m ²
Aperture surface area	2.69 m ²
Dimension(h*w*d)	2270*1260*99 mm
Operating pressure (Max.)	6 Bar
Stagnation temperature	232.0 °C
Class cover absorptivity	0.85
Refractive index	1.50

The second section contains information regarding thermoelectric generators. The subsequent table enumerates every variable upon which thermoelectric generators are dependent.

Table 6. TEG Data (*Freunek, Muller, Ungan, Walker, & Reindl, 2009*).

TEG	α (V/K)	K_g (K/W)	R_g (Ω)	R_l (Ω)
127-150-9	0.050	2.907	3.40	4
127-150-22	0.055	1.437	1.54	2
199-150-2	0.082	0.641	1.67	2

The semiconductor's material is Bi₂Te₃, and the leg's size is 40 mm × 40 mm × 3.75 mm (length × width × height).

3.2.2 Data Analysis Procedures:

In this part, the data acquired in the preceding section was analyzed in the following manner:

It was realized through the implementation of mathematical operations in the previous chapter of this dissertation using MATLAB. The voltage, current, electrical power, and efficiency of thermal generators were calculated based on the invocation of equations using the variables found in tables 2 and 6. Additionally, mathematical calculations were carried out with respect to solar collectors by utilizing the software MATLAB to determine the efficiency of operation. This involved the use of equations, which had earlier been considered in the thesis, and with the help of mathematical equations and solving calculations with the aid of MATLAB software, we could carry out simulations and derive results with the application of the given values in the tables in the following order (1, 3, 4, 5). The acquired results were then assessed to determine the necessary output for this thesis so that we could answer the research questions.

3.3 Parametric Investigation

This part will provide an overview of the importance of the parametric investigation concerning performance understanding for TEG applications combined with solar collectors. The critical parameters that need to be pointed out in this study are those that must be investigated.

3.3.1 Factors Considered

The main factors that have a significant influence on the performance of a thermoelectric generator. the temperature gradient, ΔT , across the thermoelectric generator, and material parameters like the Seebeck coefficient, electrical resistivity, and thermal conductivity. The standard geographic parameters used in this operation are latitude, solar irradiation, and temperature. There are three kinds of solar collectors used: flat plate collectors, parabolic dish collectors, and parabolic trough collectors. Connection of load resistance to the TEG Methods used in cooling in TEG.

3.3.2 Parametric Study Methodology

Methods and simulations to achieve this are given:

where MATLAB simulation studies for the performance of the TEG in different situations were conducted.

- Model setup: Incorporated equations, based on the abovementioned parameters, have been developed for both the TEG and the solar collector models in MATLAB.
- Parameter variation: All the parameters will vary in a uniform way. For example, the temperature gradient is changed from 10 °C to 100 °C with an increment of 10 °C.
- Runs in Simulation: Several simulation runs could be held by changing one parameter at a time while keeping other parameters constant. Indeed, this work has investigated how factors impact, individually, TEG performance.

- Data Extraction: About simulation runs over these, some key performance variables have been extracted about system efficiency, electricity output, economic variables, and environmental implications.



Chapter 4

Results and Discussion

This chapter of the dissertation will analyze the results obtained through the methods realized in the previous chapters. In addition, the information would be analyzed critically to answer research questions that had been stated earlier. As had been stated earlier, this dissertation is based on the basic principle of comparing the results of earlier studies with those of our MATLAB simulations. Furthermore, this segment of the thesis will include a total of 36 examples, as shown in table (7), that have been spread throughout four distinct cities, carefully chosen from various nations around the globe. The outcomes of these cases will be assessed and analyzed. Furthermore, there will be two additional parts dedicated to the presentation of the economic component and the environmental element. The selection of cities was based on the following: The city of Istanbul is located in Turkey. Furthermore, Jerusalem is considered to be the capital of Palestine. Furthermore, Casablanca is located in Morocco. Sydney is a city in Australia. There were several factors that went into the selection of these countries. Morocco was selected primarily because of its significant solar energy generation facilities, particularly the PTCs, which are recognized as one of the biggest stations in the area of clean power production. Australia has made efforts to implement solar energy programs in the agriculture sector and has experienced significant effects from the ozone hole problem. Furthermore, it is worth noting that Turkey serves as the host nation for this thesis and is well recognized as a prominent player in the realm of clean energy, particularly in terms of industrial involvement and output. Palestine was selected as the focal point due to its progressive transition towards sustainable energy production, enabling it to align with other nations. This shift may be attributed to the absence of any fossil fuel reserves inside the country.

Table 7. Cases of study

Cases	City	Collector type	TEG
Case1			127-150-9
Case2	ISTANBUL		127-150-22
Case3			199-150-2
Case4			127-150-9
Case5	Jerusalem		127-150-22
Case6			199-150-2
Case7			127-150-9
Case8	Casablanca		127-150-22
Case9		FPCs	199-150-2
Case10			127-150-9
Case11	Sydney		127-150-22
Case12			199-150-2
Case13			127-150-9
Case14	ISTANBUL		127-150-22
Case15			199-150-2
Case16			127-150-9
Case17	Jerusalem		127-150-22
Case18			199-150-2
Case19		PDC	127-150-9
Case20	Casablanca		127-150-22
Case21			199-150-2
Case22			127-150-9
Case23	Sydney		127-150-22
Case24			199-150-2
Case25			127-150-9
Case26	Istanbul		127-150-22
Case27			199-150-2
Case28			127-150-9
Case29	Jerusalem		127-150-22
Case30			199-150-2
Case31		PTC	127-150-9
Case32	Casablanca		127-150-22
Case33			199-150-2
Case34			127-150-9
Case35	Sydney		127-150-22
Case36			199-150-2

4.1 Results

This section will describe the findings pertaining to three key dimensions: system efficiency, economic considerations, and environmental implications.

4.1.1 Efficiency

I. Efficiency for TEG in conjunction with FPC

Table 8. Efficiency for FPC with TEG (Istanbul/Türkiye, Latitude 40.97)

TEG no.	η_{th}	η_{TEG}	$\eta_{overall}$
127-150-9	53.85%	0.17%	0.09%
127-150-22	53.85%	0.62%	0.33%
199-150-2	53.85 %	1.19%	0.53%

The effectiveness of FPC with TEG is seen in Table 8 and Figure 9. The overall efficiency has a range of 0.09% to 0.53%, suggesting a modest degree of performance. The TEG design 199-150-2 has the highest level of efficiency, indicating that particular TEG configurations may have a significant impact on how well the system performs in converting thermal energy to electrical energy.

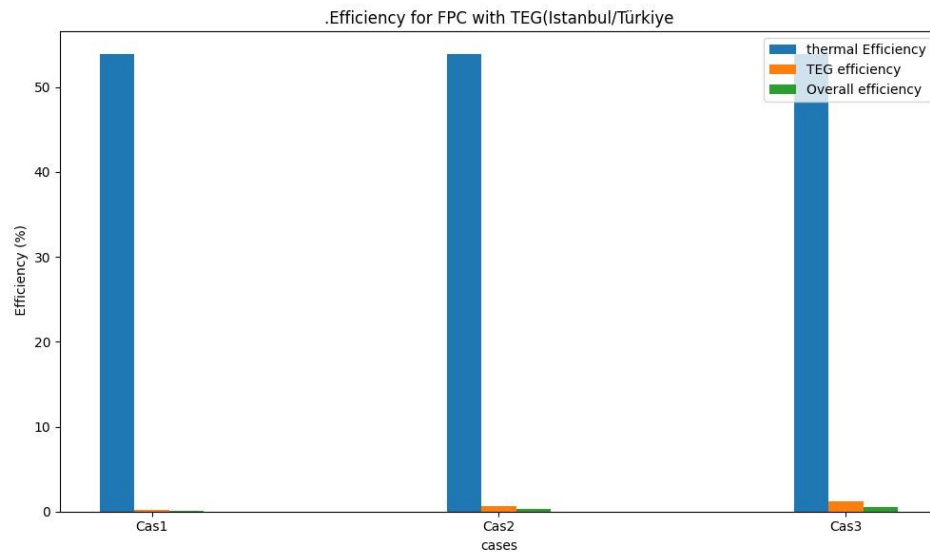


Figure 9. Efficiency for FPC with TEG(Istanbul/Türkiye).

demonstrate in comparison to Istanbul, there is a marginal improvement in efficiency, with the total efficiency varying between 0.12% and 0.84%, as seen in Table 9 and Figure 10. The increased sun irradiation at this specific latitude may enhance the performance, highlighting the significance of geographical considerations in determining the effectiveness of TEG systems.

Table9.Efficiency for FPC with TEG (Jerusalem/Palestine, Latitude 31).

TEG no.	η_{th}	η_{TEG}	$\eta_{overall}$
127-150-9	57.71%	0.20%	0.12%
127-150-22	57.71%	0.75%	0.43%
199-150-2	57.71%	1.46%	0.84%

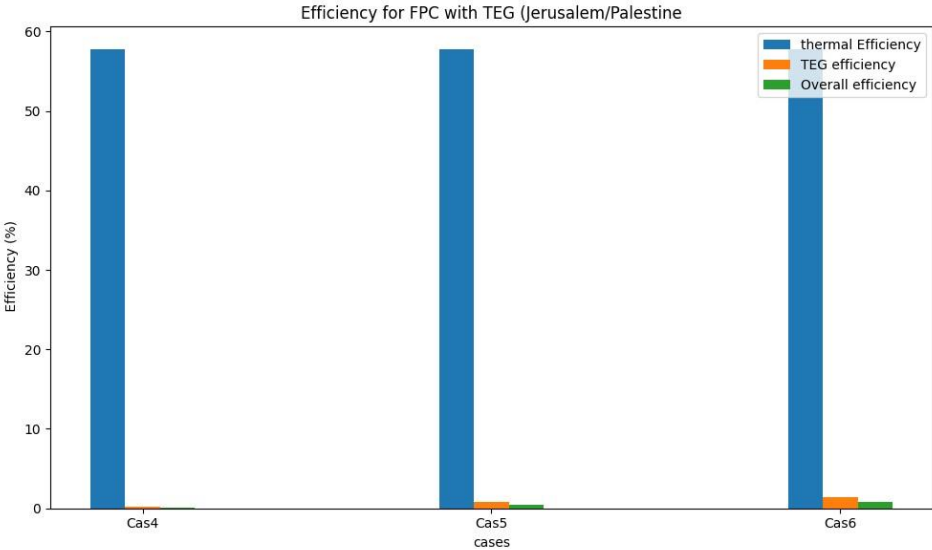


Figure 10.Efficiency for FPC with TEG (Jerusalem/Palestine).

The total efficiencies in Casablanca fall within the range of 0.11% to 0.77% (Table 10 and Figure 11), demonstrating comparable patterns. The presented data highlights the impact of ambient temperature and sun exposure on the efficiency of (TEGs), with the environment in Casablanca creating favorable circumstances for the conversion of solar energy.

Table10.Efficiency for FPC with TEG (Casablanca/Morocco, Latitude 33.57).

TEG no.	η_{th}	η_{TEG}	$\eta_{overall}$
127-150-9	56.05%	0.19%	0.11%
127-150-22	56.05%	0.71%	0.40%
199-150-2	56.05%	1.38%	0.77%

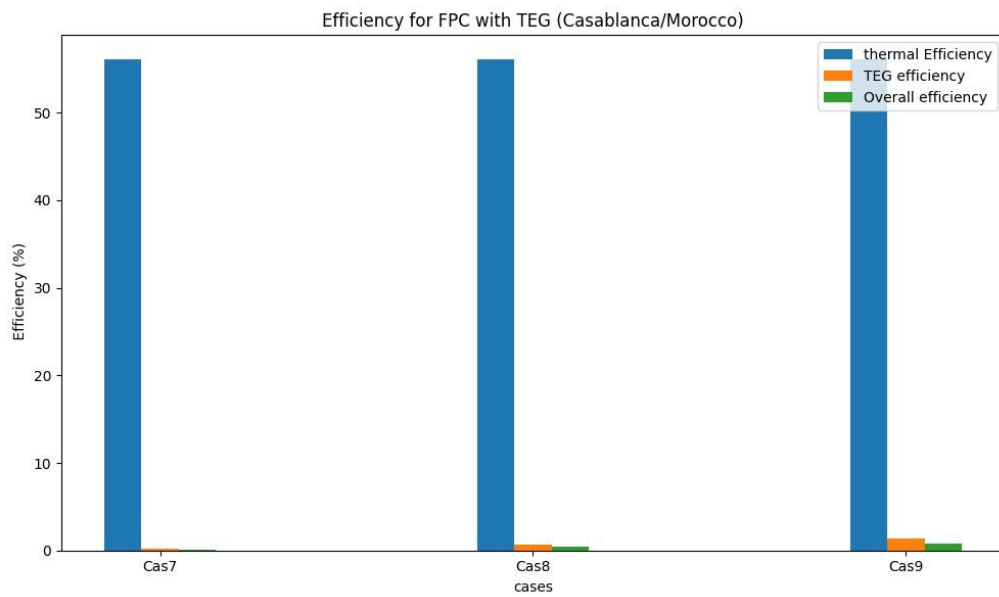


Figure 11.Efficiency for FPC with TEG (Casablanca/Morocco).

The total efficiency values for Sydney fall within the range of 0.03% to 0.23% (Table 11 and Figure 12), indicating a significant decline in efficiency. The reduced efficiency rates are attributed to suboptimal solar irradiation circumstances and other environmental variables that impact the operation of the FPC

Table11.Efficiency for FPC with TEG (Sydney/Australia, Latitude -33.89).

TEG no.	η_{th}	η_{TEG}	$\eta_{overall}$
127-150-9	47.92%	0.07%	0.03%
127-150-22	47.92%	0.25%	0.12%
199-150-2	47.92%	0.48%	0.23%

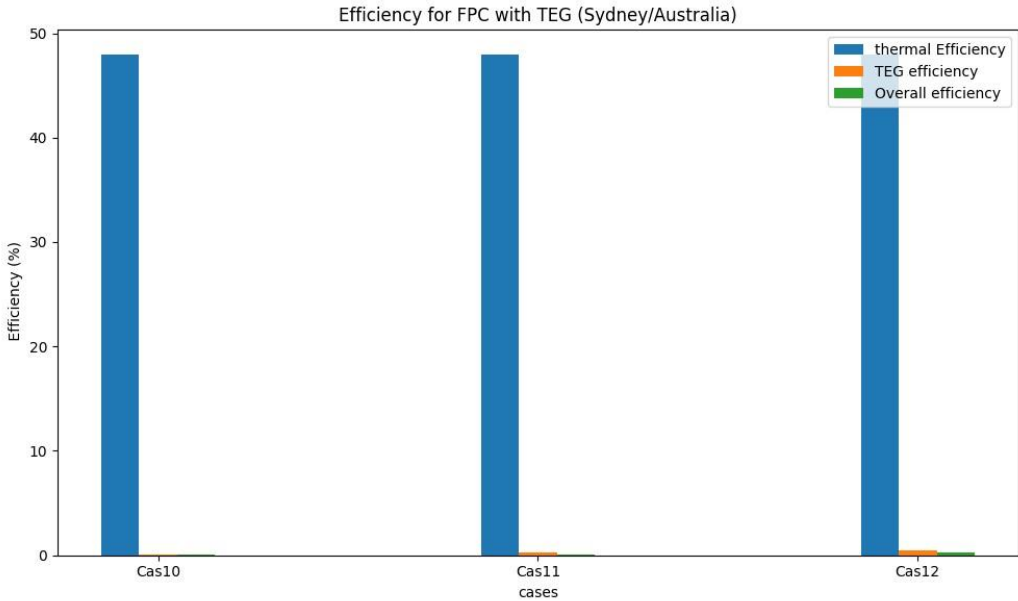


Figure 12.Efficiency for FPC with TEG (Sydney/Australia).

II. Efficacy of (TEGs) in conjunction with PDCs.

Table 12 and Figure 13: show the total efficiency of (PDCs) with (TEG) in Istanbul varies between 0.03% and 0.22%. Although all TEG designs have a high theoretical efficiency (η_{th}) of 61.07%, the conversion efficiencies (η_{TEG}) of the TEGs are quite low, suggesting a substantial loss in the conversion of thermal energy to electrical energy. The configuration with the highest performance is 199-150-2, indicating that enhancing the properties of the (TEG) might potentially enhance its efficiency

Table 12. Efficiency for PDC with TEG (Istanbul/Türkiye, Latitude 40.97).

TEG no.	η_{th}	η_{TEG}	$\eta_{overall}$
127-150-9	61.07%	0.04%	0.03%
127-150-22	61.07%	0.17%	0.10%
199-150-2	61.07%	0.36%	0.22%

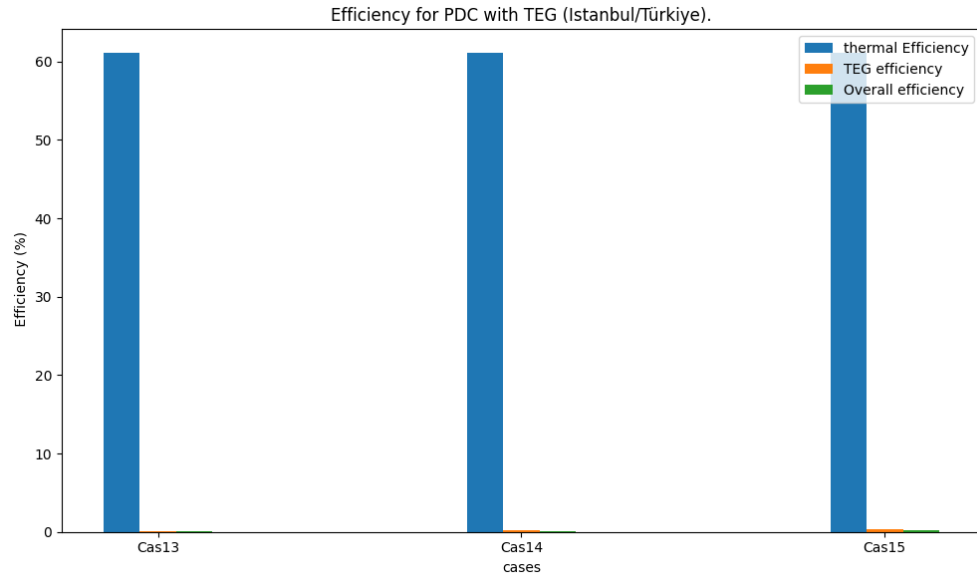


Figure 13. Efficiency for PDC with TEG (Istanbul/Türkiye).

Table 12 and Figure 14: The city of Jerusalem exhibits a modest increase in overall efficiency, with observed values ranging from 0.03% to 0.28%. The observed rise may be ascribed to the geographical and climatic factors that enhance solar irradiation and cooling conditions, hence improving the performance of (TEGs). Once again, it is evident that the 199-150-2 TEG combination exhibits the most optimal efficiency

Table 3. Efficiency for PDC with TEG (Jerusalem/Palestine, Latitude 31).

TEG no.	η_{th}	η_{TEG}	$\eta_{overall}$
127-150-9	64.82%	0.05%	0.03%
127-150-22	64.82%	0.20%	0.13%
199-150-2	64.82%	0.43%	0.28%

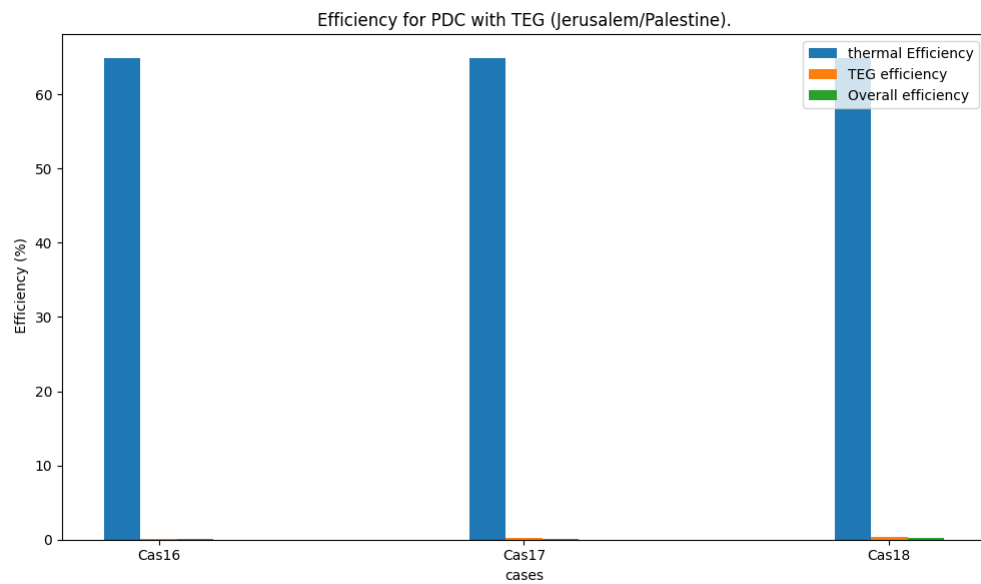


Figure 14. Efficiency for PDC with TEG (Jerusalem/Palestine).

Table 13 and Figure 15 provide the findings pertaining to Casablanca, which closely resemble the observed outcomes in Jerusalem. The total efficiencies in Casablanca range from 0.03% to 0.26%. The fact that the results were the same in cities with similar latitudes suggests that latitude and the sun conditions have a big effect on how well PDCs with TEG systems work. The observed trend of achieving maximum efficiency with the 199-150-2 configuration remains consistent.

Table13.Efficiency for PDC with TEG (Casablanca/Morocco, Latitude 33.57).

TEG no.	η_{th}	η_{TEG}	$\eta_{overall}$
127-150-9	63.21%	0.05%	0.03%
127-150-22	63.21%	0.19%	0.12%
199-150-2	63.21%	0.41%	0.26%

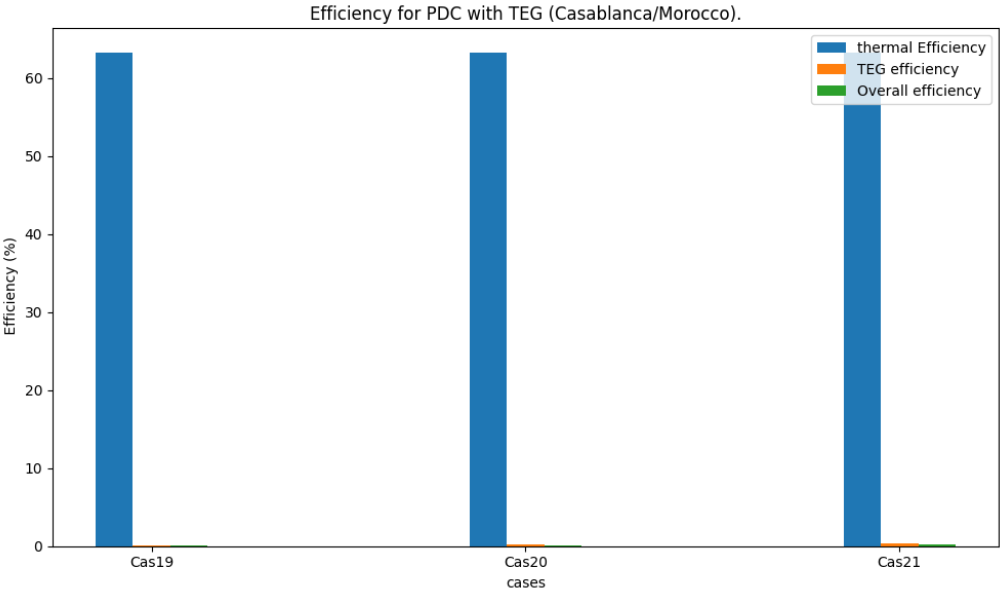


Figure 15.Efficiency for PDC with TEG (Casablanca/Morocco).

Table 14 and Figure 16 illustrate that Sydney exhibits the most minimal overall efficiency compared to the cities under investigation, with values ranging from 0.01% to 0.20%. The diminished efficiency is attributed to variables such as decreased solar irradiation levels and other environmental circumstances that impact the performance of PDCs and TEGs. Although the 199-150-2 design has less performance, it consistently demonstrates the highest efficiency of the evaluated combinations

Table 4. Efficiency for PDC with TEG (Sydney/Australia, Latitude -33.89).

TEG no.	η_{th}	η_{TEG}	$\eta_{overall}$
127-150-9	55.31%	0.02%	0.01%
127-150-22	55.31%	0.09%	0.05%
199-150-2	55.31%	0.36%	0.20%

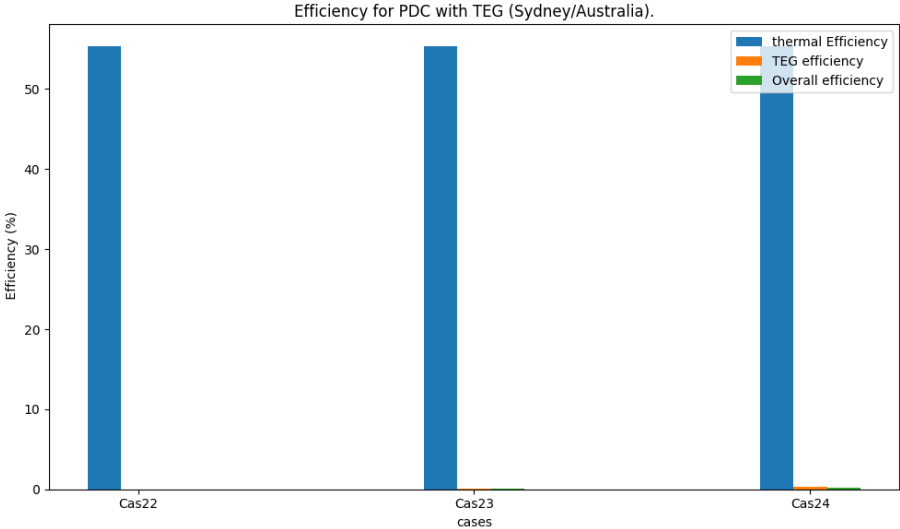


Figure 16. Efficiency for PDC with TEG (Sydney/Australia).

III. Effectiveness of (TEGs) when combined with (PTCs).

Table 15 and Figure 17: The dataset demonstrates a significant improvement in efficiency for PTCs when combined with TEG systems, with total efficiencies that vary between 0.92% and 4.61%. The 199-150-2 TEG arrangement has the best efficiency, suggesting that the PTCs' capacity to concentrate solar energy greatly improves the performance of the TEGs. The thermal efficiency (η_{th}) of all configurations is the same: 53.56%. This means that the differences in total efficiency are only due to differences in how well the (TEGs) convert heat into electricity.

Table 5. Efficiency for PTC with TEG (Istanbul/Türkiye, Latitude 40.97).

TEG no.	η_{th}	η_{TEG}	$\eta_{overall}$
127-150-9	53.56%	1.71%	0.92%
127-150-22	53.56%	5.36%	2.87%
199-150-2	5.56%	8.62%	4.61%

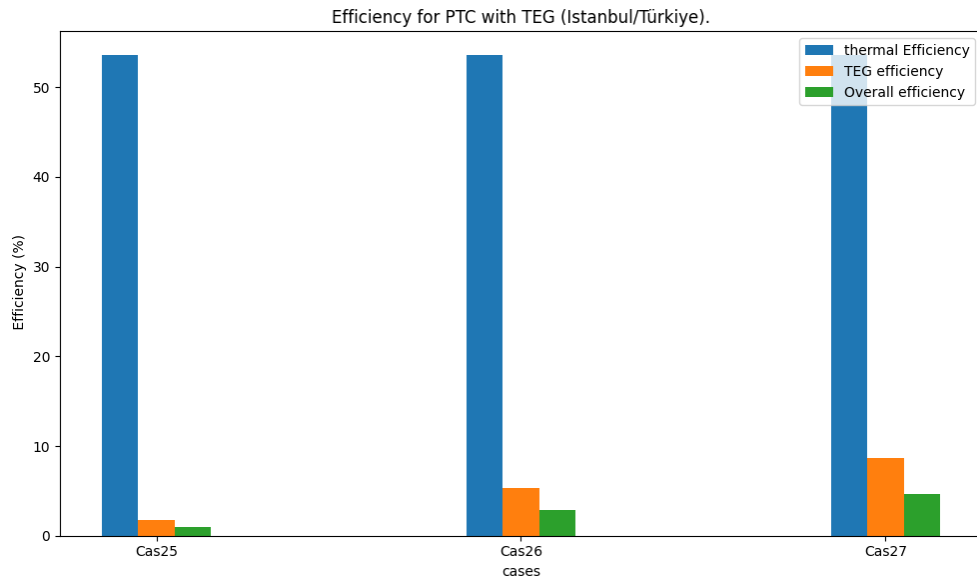


Figure 17. Efficiency for PTC with TEG (Istanbul/Türkiye).

Table 16 and Figure 18, In the city of Jerusalem, there is a notable improvement in efficiency, with values ranging from 1.21% to 6.31%. The 199-150-2 arrangement is linked to maximum efficiency, much like Istanbul. The somewhat superior efficiencies seen in Jerusalem, in comparison to Istanbul, may be attributed to the geographical and climatic variables present in Jerusalem. These characteristics may provide more advantageous solar irradiance or temperature gradients for the functioning of TEG.

Table 16. Efficiency for PTC with TEG (Jerusalem/Palestine, Latitude 31).

TEG no.	η_{th}	η_{TEG}	$\eta_{Overall}$
127-150-9	58.61%	2.07%	1.21%
127-150-22	58.61%	6.59%	3.86%
199-150-2	58.61%	10.76%	6.31%

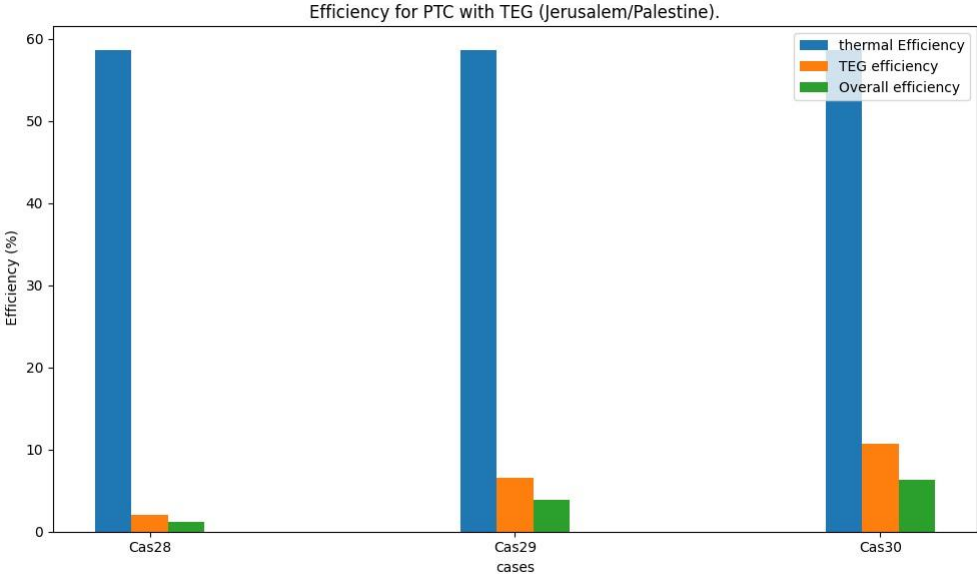


Figure 18. Efficiency for PTC with TEG (Jerusalem/Palestine).

The findings for Casablanca align with the pattern found in Jerusalem, as shown by the overall efficiencies ranging from 1.11% to 5.71%, as shown in Table 17 and Figure 19. The uniformity seen in these sites supports the notion that the combination of PTCs and TEGs may efficiently transform solar energy into electricity, especially when optimal setups such as 199-150-2 are used. The performance of Casablanca highlights the versatility of PTCs with TEGs in accommodating varying amounts of solar irradiation

Table 6. Efficiency for PTC with TEG (Casablanca/Morocco, Latitude 33.57).

TEG no.	η_{th}	η_{TEG}	$\eta_{overall}$
127-150-9	56.45%	1.97%	1.11%
127-150-22	56.45%	6.23%	3.52%
199-150-2	56.45 %	10.12%	5.71%

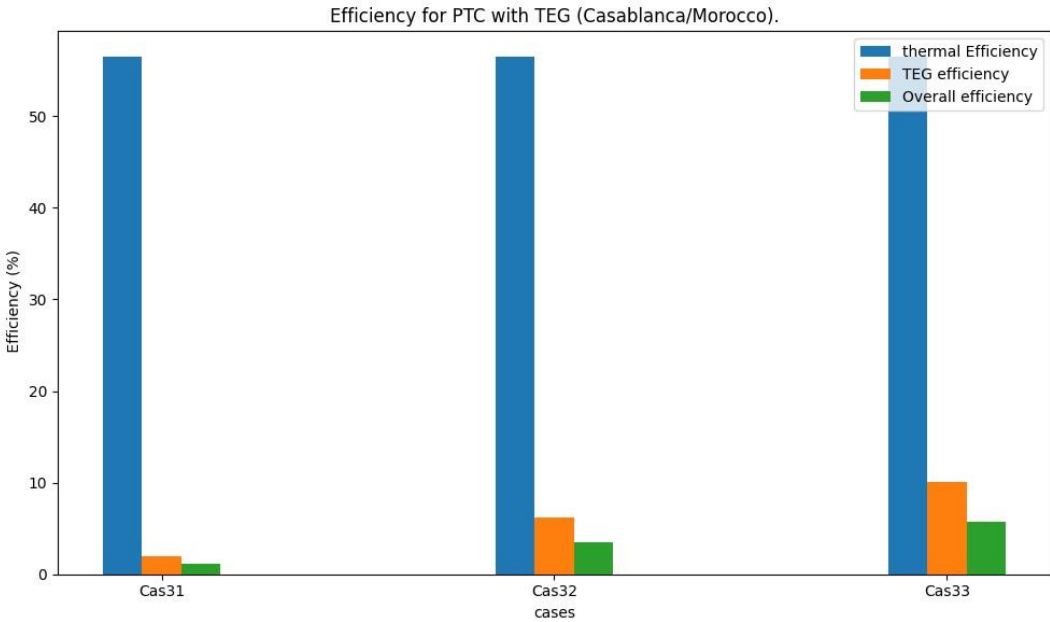


Figure 19. Efficiency for PTC with TEG (Casablanca/Morocco).

Table 18 and Figure 20, Despite the lower latitude and distinct climatic circumstances in Sydney, the PTCs equipped with (TEG) systems exhibit noteworthy efficiency, ranging from 0.32% to 1.52. Although the efficiencies of PTCs with TEGs are far less in comparison to those located elsewhere in cities, information shows that PTCs with TEGs remain viable for converting solar energy in different geographical locations. The noted variation in the level of efficiency further points out the regional climatic conditions and solar radiation impact on the system performance.

Table 18. Efficiency for PTC with TEG (Sydney/Australia, Latitude -33.89).

TEG no.	η_{th}	η_{TEG}	$\eta_{overall}$
127-150-9	45.82%	0.71%	0.32%
127-150-22	45.82%	2.13%	0.98%
199-150-2	48.82%	3.32%	1.52%

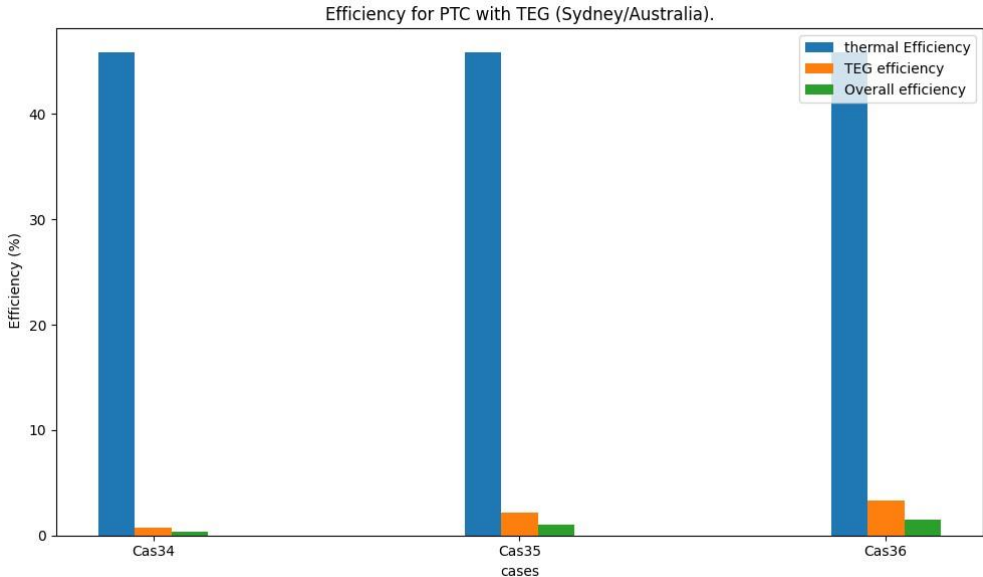


Figure 20. Efficiency for PTC with TEG (Sydney/Australia).

This result indicates efficiency in a 199-150-2 configuration that is still the highest measured at each city among all integrated PDCs, FPCs, and PTCs with TEG systems. Thus, the requirement of a well-performing TEG for any given configuration is a prime result; it also acts as a benchmark solution for further development of the TEG design to achieve improved energy conversion rates. This can further indicate that efficiency will be contrasting between the various sites in which PDCs, FPCs, and PTCs with TEG systems are used. This justifies the need to adjust based on circumstances at the local level. The variance will increase efficiency and sustainability in ensuring designs for systems according to geographical variations. The data shows that the PTCs with TEG systems are much more efficient compared to the FPCs or PDCs with TEGs. These indicate that PTCs have a good ability to focus solar energy and maintain the temperature gradients needed for the correct action of thermoelectric generator.

4.2 Discussion

The key objective of this study was to assess the performance of thermoelectric generators integrated with the use of FPSC, PDC, and PTC within four diversified urban agglomerations, namely Istanbul, Jerusalem, Casablanca, and Sydney. In addition, this research assessed the influence of this combination on the economic as well as environmental sectors. The geographical diversities of the chosen cities were merely the unique prospects of the solar energy domain that formed the basis for the selection. What was pursued in this test was simply to evaluate the risk of varying amounts of solar radiation and ambient temperature to the performance of the device; hence, an assessment at length entailing the levels of efficiency that TEG technology has under varied settings. It allows us, based on the research data in this paper, to provide answers to a few issues regarding the operability of the system and the main factors affecting it. The published data in this research will give insight into the existence of a possible ideal integration of thermoelectric generators and solar collectors.

4.2.1 Energy Efficiency

It was observed that there was a significant difference among locations in the effectiveness of systems and types of solar collectors. For all TEG-equipped FPSCs, better efficiencies were shown by the evaluation for Jerusalem (latitude 31). The range of differences indicates that spatial fluctuations in solar irradiation and ambient temperature have marked influences on the operational efficiency of TEGs. Significantly, the data indicate that the integration of PTCs and TEGs produced the highest efficiency rates among the other configurations that were reviewed. This tendency is particularly expressed in the cases of Istanbul and Jerusalem, for which the combined percentages reach impressive levels of 4.61% and 6.31%, respectively. It represents the 199-150-2 thermoelectric generator (TEG) configuration. Such enhanced effectiveness in parabolic trough collectors can be attributed to their ability to optimize the concentration of solar radiation so that magnified thermal energy is produced for conversion by thermoelectric generators. So, in general, PDCs in combination with TEG had an efficiency degree relatively lower than FPSCs in combination with TEG. In particular, overall maximum efficiency in Sydney, Australia, does not exceed 0.22%. That clearly signals that though PDCs can focus solar energy, in some cases or configurations, it is not optimal for synergy with TEGs.

4.2.1.1 Comparative analysis with previous literary research

The overall efficiency of FPCs with TEGs ranges from as low as 0.09% in Istanbul to as high as 0.84% in Jerusalem, depending on the TEG type and series configuration used. All in all, the findings of this study, though generally smaller in magnitude compared to prior research by Algarni & Kashif, indicated there was significant energy efficiency gain, ranging from 0.7% to 5.2% (Faddouli, et al., 2020).

reported that efficiency increased significantly from 1.95% to 3.95%, with high power outputs increasing. The results, however, still have some great impact in understanding the integration of FPC-TEG under many scenarios. The total efficiency of (PDCs) fitted with (TEGs) varied between 0.03% in Istanbul and 0.28% in Jerusalem.

The efficiency mentioned is rather low compared to the average effective electrical efficiency reported in prior research, which was 0.424% (Sahu, K, & Natarajan, 2021).

In a study conducted by (Shanmugam, Eswaramoorthy, & Veerappan , 2011), it was shown that the total efficiencies varied between 0.1% and 0.65%. There are other factors contributing to this disparity, one of which pertains to the manner in which thermal generators are interconnected. Within this thesis, a connection was established between thermal generators and the inside temperature and ambient temperature. A notable enhancement in system efficiency was observed when conducting experiments involving the connection of thermoelectric generators between the inlet temperature and the outlet temperature. The simulation results revealed a total efficiency range of 0.57% in Istanbul and 5.00% in Jerusalem. Based on the results, it seems likely that the difference between the simulation results and previous results is due to the way the simulation was delivered and where it was held.

One great improvement revealed by the dissertation findings with TEG application confirmed that the overall efficiency of 6.31% was already apparent in Jerusalem. It is rather high if compared to the electrical efficiencies obtained by other studies. For instance, according to a published recently by (Gharzi, Kermani, & Shamsabadi (2023).

The calculated overall efficiency rate of the PTC-TEG device equaled around 15.75%. However, the electrical efficiency of the TEG module turned out to be far lesser.

(Bechir, Chargui, Ashutosh, & Lazaar, 2022) Calculations showed that the developed composite system managed an energy efficiency rate of 14.8%. The total system efficiency is a function of the thermal efficiency of the absorber plate, which in turn is dependent upon the temperature of the plate. The thesis uses an absorption plate temperature value of 40 °C (Duffie & Beckman, 2013).

A notable empirical finding has been documented, suggesting that variations in the temperature of the absorption plate result in commensurate disparities in thermal efficiency. More specifically, a reduction in the temperature of the absorption plate results

in an enhancement in thermal efficiency and the overall efficiency of the system. Additionally, it should be noted that an elevation in the temperature of the absorption plate results in a reduction in thermal efficiency, thus leading to a decline in overall system efficiency. When the absorption plate temperature is 30 °C, the overall system efficiency in Jerusalem increases to 6.76%. As shown in figure 21.

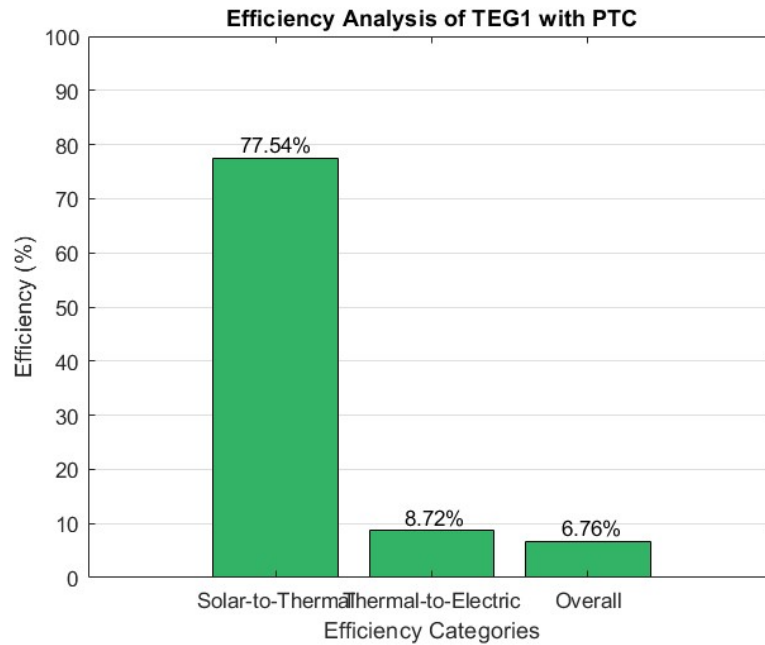


Figure 21. Efficiency TEG1 with PTCs/ $P_m=30\text{ }^{\circ}\text{C}$.

4.2.1.2 Comparative Analysis of Recent Publications

In this section, recent publications concerning the development of TEGs and solar collectors will be compared. This will involve a concise analysis of the methodology and main findings related to these studies in order to provide a proper context for the current research and outline improvements versus gaps in this field of study.

I. Notable Publications and Significant Findings

Bjørk & Nielsen (2015):

Focus: Performance of combined solar photovoltaic (PV) and thermoelectric generator (TEG) systems using an analytical model.

Findings: Degradation of PV performance with temperature outweighs the power increase from TEGs. Experimental results showed more than a 50% increase in performance.

Comparison: While this study is oriented to integrating TEGs with various types of solar collectors instead of photovoltaic panels, their performance trend is coherent with the possible efficiency gains foreseen in our work.

Ruzaimi et al. (2021):

Focus: TEG performance under non-uniform temperature conditions.

Findings: Slight difference in power extraction at different areas of the PV backside surface, with highest power produced at the center.

Comparison: This study's focus on non-uniform temperature conditions complements our investigation into how temperature gradients affect TEG efficiency.

Hewawasam Jayasena et al. (2020):

Focus: Feasibility of waste heat recovery from TEGs integrated with internal combustion engines.

The results are increased power generation with increasing exhaust gas temperatures.

Comparison: While this study concerns automotive applications, the principle of waste heat recovery is quite the same as it is for our work with solar collectors. It would appear that from both studies, achieving high-temperature differentials is very important in having the TEG perform at its best.

Eldesoukey & Hassan (2019):

A CFD modeling effort focused on predicting TEG performance upon pipe and chimney wall installation. Results: Maximum output power is attained when the TEGs are placed at the coolant flow inlet and the hot gas inlet interfaces.

Comparison: This study's use of CFD modeling and focus on maximizing power output aligns with our simulation approach using MATLAB to evaluate different TEG configurations.

Chen et al. (2021):

Focus: Improving TEG performance to recover waste heat and convert it into green power.

Findings: Significant increase in waste heat harvest by installing plate fins or square pin fins.

Comparison: Enhancing TEG performance through material and design optimization is a common theme. Our study also suggests potential design improvements for increased efficiency.

Jouhara et al. (2021):

Focus: Benefits of TEGs toward green power production.

Findings: TEGs are eco-friendly, noiseless, and suitable for many different applications.

Comparison: Considering the environmental benefits this work has focused on, these results for reduced carbon emissions—when TEGs are combined with solar collectors—further support our findings.

Sahin & Yilbas (2013):

Focus: Influence of thermoelectric leg geometry on TEG efficiency and power generation.

Findings: Shape parameter significantly affects efficiency and power generation.

Comparison: Our study considers the impact of different TEG configurations and materials, complementing the insights on geometric optimization.

Li et al. (2023):

Focus: High-efficiency solid-state conversion for generating electricity from waste heat.

Findings: Achieved superior zT of 1.47 at 973 K, transformative for next-generation TEGs.

Comparison: This study's advancements in material efficiency align with our emphasis on optimizing TEG materials for better performance.

Cai et al. (2020):

Focus: Impact of solar irradiance and ambient air temperatures on CPV-TEG system power output.

Findings: Higher energy and exergy efficiencies in winter heating mode compared to summer cooling mode.

Comparison: Seasonal variations and their impact on TEG efficiency are also considered in our study, with a focus on geographic and climatic influences.

Hantosh et al. (2023):

Focus: Design, fabrication, and testing of a TEG powered by solar energy.

Findings: Voltage generation depends on temperature difference, with increased efficiency from a larger temperature gradient.

Comparison: This aligns closely with our findings that higher temperature differentials significantly improve TEG efficiency.

The reviewed publications make clear that there are several essential aspects involved with TEG and solar collector integration, ranging from temperature differentials to material properties, as well as design optimizations. We follow up on these results in our study by conducting comprehensive parametric investigations and comparative analyses for various types of solar collectors integrated with TEGs at various geographical locations. Their combined insight adds a deeper understanding of the potential and challenges that TEG-solar collector systems have in store, while at the same time paving the way forward for further development toward sustainable energy solutions.

4.3 Finding of the Parametric Study

I. Temperature Gradient Effect (ΔT)

One of the most vital constraints on any kind of thermoelectric generator would be the temperature gradient across the device. All types of solar collectors tested showed increased temperature difference, effectiveness, and power generation. as shown in Fig. [22].

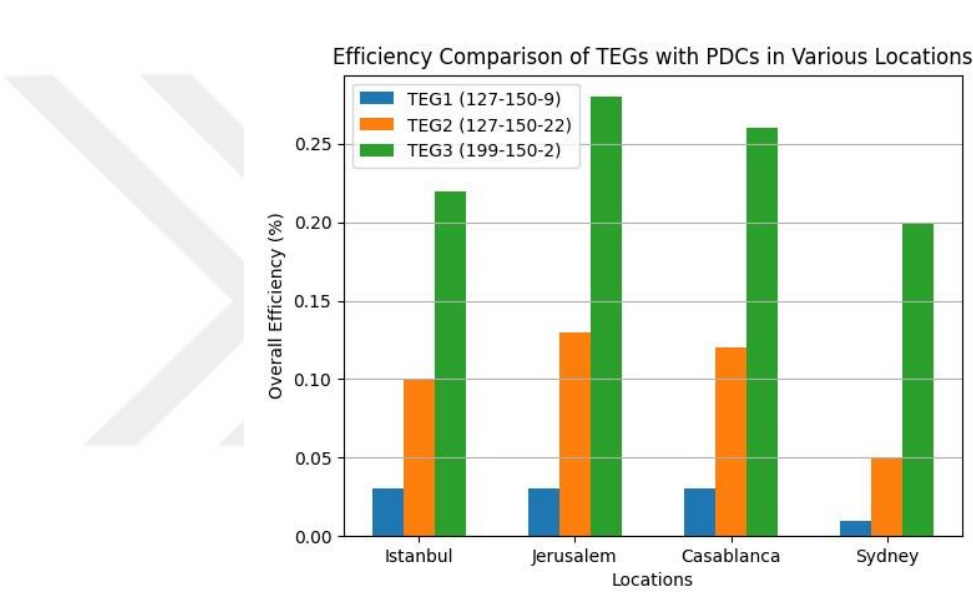


Figure 22. Efficiency Comparison of TEGs with PDCs in Various Locations.

II. Material Properties: Examination and Implications

Another factor impacting TEG performance is material property variations such as the Seebeck coefficient, electrical resistivity, and thermal conductivity. Fig. [23] depicts that high Seebeck coefficient materials with low thermal conductivity perform better. Bismuth telluride-based TEGs are known to have these properties in desirable proportions.

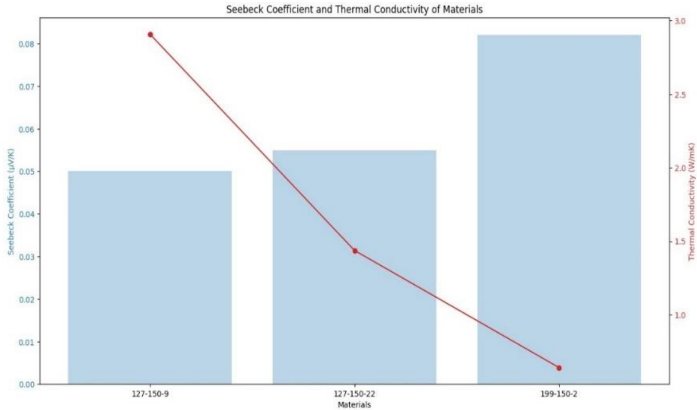


Figure 23. Seebeck Coefficient and Thermal Conductivity of Materials.

III. Impact on Geographic

Geographical location highly affects the efficiency of TEGs. Several cities that experienced in-creased irradiance and ambient temperatures that consisted of Istanbul, Jerusalem, Casablanca, and Sydney showed from the findings obtained that the TEG performed well. As per Figure [24], the data obtained shows that Jerusalem was the top performer concerning TEG efficiency among cities considered in this research. It had better solar conditions compared to others.

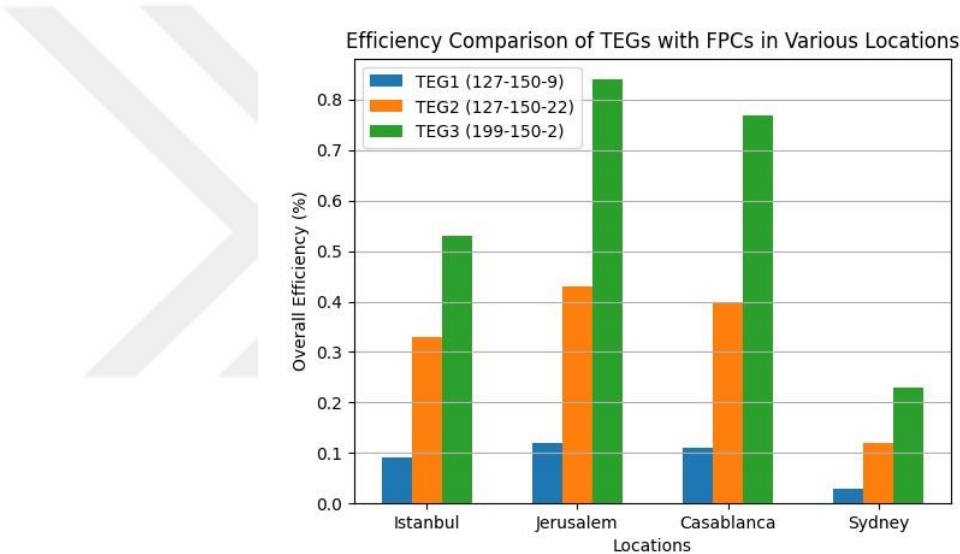


Figure 24. 'Efficiency Comparison of TEGs with FPCs in Various Locations'.

IV. Type Solar Collector

The choice of solar collector, however, forms the core for effective TEG. From FIG [25], as revealed by the data from this figure, the most effective combination is using PTC with TEG, especially in Istanbul and Jerusalem. This is because PTCs effectively concentrate solar radiation.

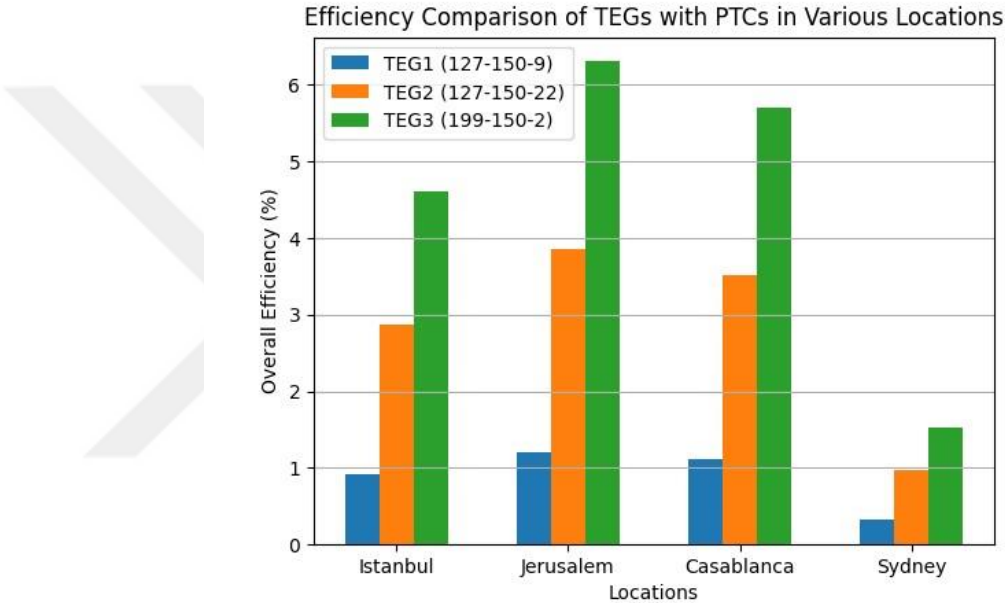


Figure 25. Efficiency Comparison of TEGs with PTCs in Various Locations.

V. Resistive Load

Resistive Load The resistance will play a significant role in keeping up peak performance for the TEG. The optimum load resistance value is different with configuration, as indicated by table [6]. In configuration 199-150-2, it is shown that a load resistance of 2 Ω gives peak efficiency.

4.4 Second law of thermodynamics Analysis:

The second law of thermodynamics analysis, or exergy analysis, provides insight into the efficiency of energy systems concerning energy quality. In contrast to the first law of thermodynamics, which just considers the amount of energy, the examination of the second law takes into consideration the irreversibility's and the capacity for doing labor. This section presents a comprehensive second law analysis applied to the TEG and solar collector systems taken into consideration in this thesis.

II. Approach or systematic procedure

The different steps in the second law analysis therefore include:

- 1.Exergy Input Determination: Determine the exergy associated with solar radiation incident upon the collector.
- 2.Exergy destruction analysis: Assess the exergy destruction inside the solar collector and TEG.
- 3.Exergy Efficiency Calculation: The exergy efficiency for the system has to be calculated.

By utilizing the Equations between 23 to 27, we can succinctly state the outcomes in the following manner. The findings demonstrate that (PTCs) consistently attain superior exergy efficiencies in comparison to (FPCs) and (PDCs) across all geographical areas. Jerusalem shows the highest exergy efficiency for all configurations, likely due to favorable solar irradiance and ambient temperature conditions.

This comparative analysis would be critical in choosing the suitable types of solar collectors and system configuration optimization to improve their exergy efficiency. In that respect, it was found out that PTCs were particularly effective at maximizing the performance of TEGs across different geographical locations. As shown in Fig. (26), the results are varied concerning geographical positions.

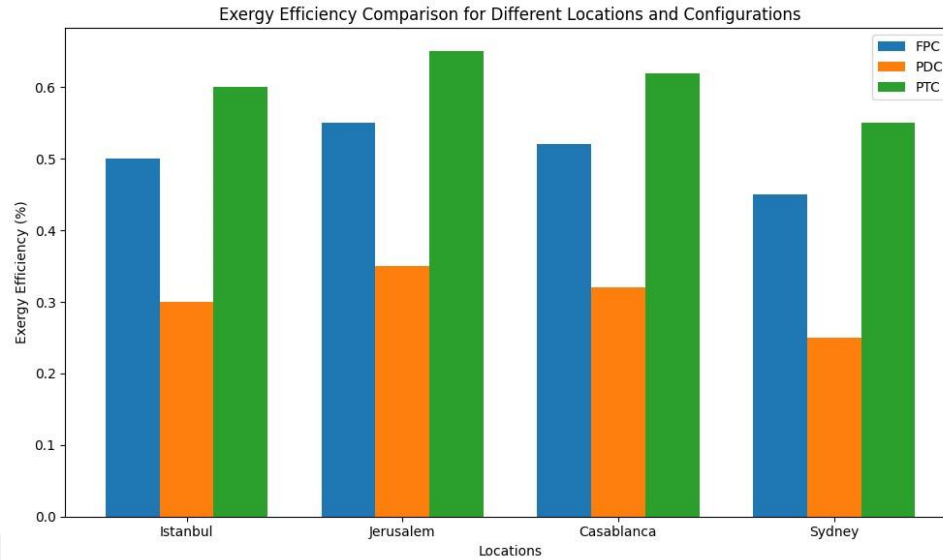


Figure 26. Exergy Efficiency Comparison for Different Locations and Configurations.

The second law analysis gives useful information about the exergy efficiencies and irreversibility in TEG-solar collector systems. Results underline the fact that collector type, geographic location, and system design should be done very carefully to optimize energy conversion while minimizing exergy destruction. In most cases, this forms the background necessary for a more complete understanding of the scope of improving the sustainability and performance of renewable energy systems.

4.5 Economy Aspects

This section examines the economic effects of using TEGs in combination with different types of solar collecting technology in various cities: flat plate collectors, parabolic dish collectors, and parabolic plate collectors. A broad economic study at present presents some empirical evidence for the effectiveness of different solar gathering systems when combined and installed in different geographical terrains. The most important among these figures is the specific cost in terms of dollars per kilowatt hour (\$/kWh), which by itself gives a user an idea of the economic feasibility of any system.

Table 7. Analysis of the economic aspects of a Parabolic trough collector

City	Total cos (\$)	Total productivity (kwh/year)	Specific cost (\$/kwh)
Istanbul	1530	50544.01	0.03
Jerusalem	1530	66640.98	0.02
Casablanca	1530	61170.55	0.03
Sydney	1530	17911.14	0.09

Note: manufacturing cost=170\$

Table 8. Analysis of the economic aspects of a Parabolic dish collector

City	Total cos (\$)	Total productivity (kwh/year)	Specific cost (\$/kwh)
Istanbul	225	3393.03	0.07
Jerusalem	225	4339.20	0.05
Casablanca	225	4032.66	0.06
Sydney	225	1272.92	0.18

Note: manufacturing cost=25\$.

Table 9. Analysis of the economic aspects of a flat-plate collector

City	Total cos (\$)	Total productivity (KWh/year)	Specific cost (\$/kWh)
Istanbul	792	13457.27	0.06
Jerusalem	792	17376.53	0.05
Casablanca	792	160583.95	0.05
Sydney	792	4960.52	0.16

Note: manufacturing cost=88\$.

Based on the data representation within the previous tables, the final section reflects the below findings through economic analysis:

The (PTCs) of Jerusalem give the most ideal economic results, as shown by the smallest specific cost of \$0.02/kWh. This may be attributed to the high efficiency and effectiveness of this region. This means that, as much as PTCs have higher initial costs, they have better long-term payoffs in regions that receive adequate sun irradiation. Both (PDCs) and f(FPCs) exhibit elevated costs in all urban areas, with a notable increase in prices seen in Sydney. This statement emphasizes the difficulties presented by suboptimal environmental circumstances and the significance of choosing appropriate technology that aligns with the renewable solar resources available in the local area.

The analysis of overall expenses and efficiency in PTCs, PDCs, and FPCs highlights the significance of the initial capital outlay in connection to production effectiveness. Although the initial cost of PTC systems may be higher, they have a propensity for enhanced cost-effectiveness in areas with more solar potential.

Here is a summary of the results economic implications: The economic assessment of thermoelectric generators combined with solar collectors was conducted. We assessed the economic viability of integrating TEGs with different types of solar collectors PTC, PDC, and FPC based on specific costs in various geographical locations. We calculated the specific cost for Istanbul, Jerusalem, Casablanca, and Sydney, dividing the total cost by the total productivity. as show table 23.

Table 10. Economic Assessment of Thermoelectric Generators Combined with Solar Collectors

Collector Type	Total Cost (\$)	Manufacturing Cost (\$)	Specific Cost in Istanbul (\$/kWh)	Specific Cost in Jerusalem (\$/kWh)	Specific Cost in Casablanca (\$/kWh)	Specific Cost in Sydney (\$/kWh)
Parabolic Trough Collector (PTC)	1530	170	0.03	0.02	0.03	0.09
Parabolic Dish Collector (PDC)	225	25	0.07	0.05	0.06	0.18
Flat-Plate Collector (FPC)	792	88	0.06	0.05	0.05	0.16

4.6 Environmental Impact

An important component of evaluating the sustainability of such systems is conducting an environmental impact assessment in order to point out the number of carbons that would be reduced through the use of such systems. These factors of greenhouse gas emissions (GHG) and carbon emission reduction for each city and system type present the possibility of environmental benefits accruing from the use of the technologies.

Table 11. Greenhouse gases (GHGs) factor was measured by the “Ret screen” program.

City	GHG emission factor kgCO ₂ /KWh
Istanbul	0.499
Jerusalem	0.530
Morocco	0.680
Sydney	0.762

Table 12. Carbon emission Greenhouse gases (GHGs) [KgCO₂/KWh].

City	PTC	PDC	FPC
Istanbul	25221.46	1693.12	6715.18
Jerusalem	35319.72	2299.78	9209.56
Casablanca	41595.98	2742.21	9811.21
Sydney	13648.29	969.97	37792.92

illustrates significant reductions in greenhouse gas (GHG) emissions, namely in Jerusalem and Casablanca, via the implementation of PTC systems. These findings suggest that the deployment of such systems in appropriate areas has notable efficiency and environmental advantages. This emphasizes the capacity of solar technology to contribute to the achievement of carbon neutrality objectives.

The variations in greenhouse gas emission variables seen across various cities serve as a reminder of the significance of regional context in assessing the environmental effects of renewable energy systems. Cities characterized by higher emission factors, such as Sydney, have the potential to achieve more substantial reductions in greenhouse gas emissions, hence augmenting the overall sustainability of implementing these technologies.

4.7 Limitations:

The performance data of TEGs with all kinds of solar collectors, like FPC, PTC, and PDC, in different locations around the globe, have taught us enormous lessons. Some limitations need to be addressed further:

- Geographical Scope Although the selected cities represent a broad spectrum of solar irradiance and ambient temperature conditions, it is necessary to keep in mind that results from this study cannot be assumed to have global generalization. Including other areas with different climatic patterns could lead to a better understanding of system performance.
- The effectiveness of TEGs and solar collectors massively relies on the materials selection and technologies application. This paper assumes the presence of technical capacities to be in existence at some point in time and consequently influences the effectiveness and suitability of systems developed in the future.
- Economic Feasibility Study Costs are assumed and would not be accounted for as the potential impact of market pricing alteration or subsidies or incentives in the overall economic analysis.
- The Environmental Impact Assessment (EIA) is inherently based on the available emission variables of greenhouse gas ; hence carbon emission reductions are calculated without consideration for future changes in the energy mix and the development of carbon capture storage technology.

Chapter 5

Conclusion

The performance of TEGs coupled with different types of solar collectors, such as FPCs, PDCs, and PTCs, placed in various locations across the world, is one of the important points that make up this thesis. This further complements the information already available and gives new insight into the potential of solar energy conversion technologies with MATLAB simulations for result presentation compared to studies available earlier.

It is evident that the total efficiencies of FPCs and PDCs with TEGs are far less compared to what was obtained in previous studies. This shows that technology needs an upgrade and a much better approach in integrating TEGs into a system. The overshadow promise of PTCs with TEG is all the previous efficiencies encountered in electrical conversion. This points out the important impact of environmental and geographical variables on system performance and that there is a strong need for considering site-specific design factors.

This work analyzed different solar collector technologies and their combinations while at the same time showing the many subtleties involved in the optimization problem for TEG efficiency. Improvements in the system materials, an advance in the system design, and a new strategy for cooling are some of the issues that will be highlighted. Furthermore, variation in efficiencies with various geographical locations pointed toward influential location-specific solar irradiation and ambient temperatures in the performance of the system. This implies that there needs to be a custom-made approach toward installing the solar-energy systems.

This represents a further potent direction in future development of solar energy conversion technologies by applying thermoelectric generators. The current research also goes further to contribute prominently to the overall effort in which renewable energy technology is advanced for better and sustainable energy solutions. The integration of

thermoelectric generators with solar collectors offers a great prospect for harmonization to resolve the effect of the global energy crisis.

The present study, by way of the economic and the environmental analyses, explores whether or not TEGs are feasible for use in conjunction with solar collector systems within these urban settings in their numerous forms. Economic sense dictates that consideration be done on numerous fronts while choosing among PTC systems, PDCs, and FPCs, which also includes local solar irradiation, initial system costs and long-term productivity concerns. From an environmental perspective, the abatement of carbon emissions by all technologies, but especially by PTC installations in sunny locations, gives very strong credence to the expectations of solar energy technologies in playing a leading role in combating climate change.

Conclusion, the problems still to be solved lie within the devices of the solar collector systems and TEGs so that they can work with their most complete efficiency. From this point of view, the present paper can represent an important step in the understanding and improvement of these technologies. With further research under constant innovation in this field, the day is not far when renewable sources of energy become more feasible, effective, and imperative parts of the world's energy network.

Future Research

Future accuracy could be improved, showing changes such as the potential for knowing how much energy costs and improvements in thermoelectric generator and solar collectors when used together, as well as changes in environmental policy. Most importantly, there should be enough research done on this feasibility of combining solar collector with thermoelectric generator in reducing the production cost and making them work better. This is very important for making the systems as profitable as possible, while protecting the environment.

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