

**T.R.
SAKARYA UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES**

**EFFICIENCY ENHANCEMENT OF THERMOELECTRIC (TE)
MODULES OF PHOTOVOLTAIC-THERMOELECTRIC (PV-TE)
HYBRID SYSTEMS**

PhD THESIS

Selçuk BULAT

Nanoscience and Nanoengineering Department

JANUARY 2025

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Thesis Advisor: Prof. Dr. Mustafa ERKOVAN

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The thesis work titled “Efficiency Enhancement of Thermoelectric (TE) Modules of Photovoltaic-Thermoelectric (PV-TE) Hybrid Systems” prepared by Selçuk BULAT was accepted by the following jury on 24/01/2025 by unanimously of votes as a PhD THESIS in Sakarya University Graduate School of Natural and Applied Sciences, Nanoscience and Nanoengineering department.

Thesis Jury

Head of Jury : **Prof. Dr. Mustafa ERKOVAN** (Advisor)
Sivas University of Science and Technology

Jury Member : **Prof. Dr. M. Fatih KILIÇASLAN**
Sivas University of Science and Technology

Jury Member : **Prof. Dr. Süleyman Can KURNAZ**
Sakarya University

Jury Member : **Prof. Dr. Uğursoy OLGUN**
Sakarya University

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Düzce University



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Selçuk BULAT





To my (grand)mother, Hatice ŞENER...



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Selçuk BULAT



TABLE OF CONTENTS

Sayfa

ACKNOWLEDGMENTS	ix
TABLE OF CONTENTS	xi
ABBREVIATIONS	xiii
SYMBOLS	xv
LIST OF TABLES	xvii
LIST OF FIGURES	xix
SUMMARY	xxi
ÖZET	xxiii
1. INTRODUCTION	1
1.1. Scope	4
1.2. Purpose of Thesis	6
1.3. Literature Review	7
1.3.1. Fundamentals of Solar Energy and the Sun	7
1.3.1.1. The Sun and The Earth.....	8
1.3.1.2. Solar Radiation.....	9
1.3.1.3. The Air Mass.....	12
1.3.1.4. The Direct, Diffuse and Albedo Radiation	14
1.3.1.5. The Annual Solar Radiation.....	15
1.3.2. Fundamentals of Photovoltaics	16
1.3.2.1. The Photovoltaic Effect of the Sunlight and the Solar Cell	17
1.3.2.2. The Solar Cell Materials	19
1.3.2.3. The Solar Cell Structure.....	23
1.3.2.4. The Equivalent Circuit	25
1.3.2.5. The Characteristic Equation.....	26
1.3.2.6. The Current Voltage Characteristic Curve.....	27
1.3.2.7. The Power of Solar Cell and MPP	28
1.3.2.8. The Fill Factor	31
1.3.2.9. The Series and Shunt Resistance.....	31
1.3.3. Fundamentals of Thermoelectrics	32
1.3.3.1. Thermoelectric Effect.....	33
1.3.3.2. Thermal Conduction	35
1.3.3.3. Thermoelectric Materials	35
1.4. Hypothesis	39
2. PHOTOVOLTAIC-THERMOELECTRIC (PV-TE) HYBRID SYSTEMS..	41
2.1. Simple PV Cooling Methods.....	41
2.2. PV/Thermal Systems	43
2.3. The Structure of Photovoltaic-Thermoelectric (PV-TE) Hybrid Systems	44
2.3.1. Theoretical modeling of the system	46
2.3.2. Electrical modeling of system.....	49
3. EFFICIENCY ENHANCEMENT METHODS USED IN PHOTOVOLTAIC-THERMOELECTRIC (PV-TE) HYBRID SYSTEMS	53

3.1. Simple PV-TE Hybrid System	55
3.2. PV-TE Hybrid System With Passive Cooling System	59
3.3. PV-TE Hybrid System With Active Cooling System	60
3.3.1. PV-TE Hybrid System With Active Cooling System with Water is Coolant	60
3.3.2. PV-TE Hybrid System With Active Cooling System with Nanofluid as Coolant	62
4. EXPERIMENTAL TECHNIQUES.....	63
5. RESULTS AND DISCUSSION.....	71
5.1. Results	82
6. CONCLUSION AND FUTURE WORK.....	89
6.1. Future Research	94
REFERENCES.....	97
CURRICULUM VITAE	113



ABBREVIATIONS

AC	: Active Cooling
AM	: Air Mass
ARC	: Anti-reflection Coating
AU	: Astronomic Unit
BSF	: Back Surface Field
CVD	: Chemical Vapor Deposition
Egap	: Bandgap Energy
EN	: European Norms
FF	: Fill Factor
IEC	: International Electrotechnical Commission
ISO	: International Organization for Standardization
MPP	: Maximum Power Point
nAC	: Nanofluid-Active Cooling
PECVD	: Plasma Enhanced Chemical Vapour Deposition
PC	: Passive Cooling
PV	: Photovoltaic
PV-TE	: Photovoltaic–Thermoelectric
R	: Reflection
STC	: Standard test conditions
T	: Transmission
TCO	: Transparent Conducting Oxide
TE	: Thermoelectric
TEG	: Thermoelectric Generator
TEPVIS	: Thermal Enhanced PV with Integrated Standing
TSE	: Turkish Standards Institution



SYMBOLS

C	: Celsius
E	: irradiance in W/m^2
I₀	: diode saturation current in A
I_{photon}	: photo current in A
I_D	: Diode current
I_L	: Load current
I₀	: Diode saturation current
K	: Kelvin [Unit]
k	: Boltzmann const.
P_{in}	: The input solar energy
P_{in}	: Incident power density
P_{out}	: The output electrical energy
q	: elementary charge [Unit]
m	: Mass [Unit]
r	: Radius
R_p	: parallel resistor in Ω
R_s	: series resistor in Ω
R_s	: Series resistance
R_{sh}	: Shunt resistance
S	: Solar Constant
T	: absolute temperature in K
t	: The thickness of the thin film layer
t	: Time [Unit]
T_s	: Temperature of the Sun
U_D	: The voltage across the diode
U_L	: Voltage across the load
U_{oc}	: Open Circuit Voltage
W	: Watt [Unit]



LIST OF TABLES

	<u>Page</u>
Table 1.1. Bandgap Values given with the Type of some Semiconductor Materials.	23
Table 1.2. Figure of merit for different TE materials.....	38
Table 4.1. Features and measurements of TEGs used in the research, such as surface and p-n junction area thicknesses.....	64
Table 5.1. Power outputs and performance increase of pure PV, PV-TE with TEG3 without cooling, PV-TE with TEG3 with PC and PV-TE with TEG3 with AC by using distilled water and nanofluid. ($T_a = 25$ $T_h = 50$ $T_c = 10$).	82
Table 5.2. Power outputs and performance increase for pure PV, PV-TE with TEG4 without cooling, PV-TE with TEG4 with PC and PV-TE with TEG4 with AC by using distilled water and nanofluid. ($T_a = 25$ $T_h = 50$ $T_c = 10$).	82



LIST OF FIGURES

	<u>Page</u>
Figure 1.1. The rates of energy sources, expected energy rates in the future [4].....	3
Figure 1.2. Reserves of different energy sources [4].	3
Figure 1.3. Best research cell efficiencies (2024) [7].	5
Figure 1.4. The Sun and its distance to the Earth [4].	8
Figure 1.5. The Sun, seasons of the Earth [4].	10
Figure 1.7. Some Air Mass values [51].....	12
Figure 1.8. Black Body Radiation, AM0 and AM1.5g Radiation [51].	12
Figure 1.9. The Sun's Apparent Motion to an Observer at Latitude 35°N [51].	13
Figure 1.10. Direct, Diffuse and Albedo Radiation [51].....	14
Figure 1.11. The Direct, Diffuse Radiation depending on the weather [51].....	15
Figure 1.12. Insolation map of the Earth [54].	15
Figure 1.13. Global solar radiation map [56].	16
Figure 1.14. Band diagrams of metals, semiconductors and insulators [51].	17
Figure 1.15. A p-n junction in thermal equilibrium with zero bias voltage applied. Light red zone is positively charged. Light blue zone is negatively charged. Gray regions are neutral [60].	19
Figure 1.16. The direct bandgap and indirect bandgap [51].	22
Figure 1.17. Indirect bandgap and phonon assistance [51].	22
Figure 1.18. Busbars and Fingers of Solar Cell [74].....	24
Figure 1.19. Equivalent circuit of ideal solar cell [51].	25
Figure 1.20. The serial resistor R_s [51].	26
Figure 1.21. The full equivalent circuit [51].	26
Figure 1.22. I-U curve of PV solar cell in dark and solar cell under illumination [78].	28
Figure 1.23. Generation consumption of power by the I-U curve [81].....	29
Figure 1.24. Maximum Power Point of Solar Cell [51].	30
Figure 1.25. Maximum Power Points under different solar radiation values [4].....	30
Figure 1.26. Fill Factor of Solar Cells [82].	31
Figure 1.27. The I-U curve and series resistance [51].	32
Figure 1.28. The I-U curve and the shunt resistance [51].	32
Figure 2.1. TEPVIS with a gain in electricity yield of 11.6% [136].....	42
Figure 2.2. Power output of TEPVIS vs. conventional PV module [136].	42
Figure 2.3. The PV/T air collector [137].....	43
Figure 2.4. The PV/T liquid collector [137].....	44
Figure 2.5. The I-U characteristic curves under different solar radiations and temperatures [51].	45
Figure 2.6. PV-TE hybrid system representation [202].	46
Figure 2.7. Schematic of PV-TE hybrid system [140].	48
Figure 2.8. Heat flux and temperature definition of PV-TE hybrid system [140].	48
Figure 2.9. 2-Wire configuration (a) and 4-Wire configuration (b) of PV-TE hybrid system [143].	50

Figure 3.1. Schematic of a simple PV-TE hybrid system [179].....	56
Figure 3.2. Structure of a thermoelectric module.....	57
Figure 3.3. Working principle of TEG [197].	58
Figure 3.4. Schematic representation of a photovoltaic–thermoelectric (PV-TE) system with an integrated passive cooling (PC) system [179].....	59
Figure 3.5. The schematical representation of PV-TE system featuring an active cooling system visual explanation of the system’s configuration and the functioning of its active cooling components [179].....	61
Figure 4.1. Ceramic plated TEGs from left to right labeled TEG1, TEG2, TEG3, TEG4, TEG5.	65
Figure 4.2. TEG with graphite mixed surface TEG6.	65
Figure 4.3. TEG with graphite mixed surface TEG7.	66
Figure 4.4. TE part testing system at TSE.....	67
Figure 4.5. TE part testing method [179].	68
Figure 5.1. Voltage outputs of 7 TEGs without cooling system under 50 °C T_h	73
Figure 5.2. Voltage outputs of 7 TEGs without cooling system under 70 °C T_h	74
Figure 5.3. Current outputs of TEG3 without cooling system, with PC system and with AC system, under 50 °C T_h	75
Figure 5.4. Voltage outputs of TEG3 without cooling system, with PC system and with AC system, under 50 °C T_h	76
Figure 5.5. Current outputs of TEG4 without cooling system, with PC system and with AC system, under 50 °C T_h	77
Figure 5.6. Voltage outputs of TEG4 without cooling system, with PC system and with AC system, under 50 °C T_h	78
Figure 5.7. Power outputs of TEG3 without cooling system, with PC system, with AC system and with AC system with nanofluid, under 50 °C T_h in mW.....	80
Figure 5.8. Power outputs of TEG4 without cooling system, with PC system, with AC system and with AC system with nanofluid, under 50 °C T_h in mW.....	81

EFFICIENCY ENHANCEMENT OF THERMOELECTRIC (TE) MODULES OF PHOTOVOLTAIC-THERMOELECTRIC (PV-TE) HYBRID SYSTEMS

SUMMARY

The consumption of fossil fuels outcomes to greenhouse gases that brings out global warming of the World's atmosphere and nearby to climate change. Under the surface are hidden costs such as security expenses, clean-up efforts, air pollution, environmental damage, war-related expenses and other additional hidden expenses.

Sources of Renewable energy are especially very good energy sources to battle against global warming. Energy from Sun, is a shining renewable energy source, especially for the regions with high solar irradiance.

After the Oil Crisis, happened in 1973, the researchers especially focuses on photovoltaics. Till now the scientists are focusing on improving the efficiency of solar cells and photovoltaic modules. PV-TE Hybrid Systems are especially one of the shining systems of new type of systems, to enhance the module efficiency.

Combining photovoltaic (PV) and thermoelectric (TE) modules into PV-TE systems has shown great promise for maximizing the use of the sun's spectrum, boosting overall power output, and lowering the amount of area needed for PV power plants. With my thesis I focused on enhancing the efficiency of a practical PV-TE system model. Usually, a significant temperature differential is produced across the thermoelectric generator (TEG) module utilizing a variety of heat removal techniques in order to increase the power output of the TE component. These cooling systems makes increase, in performance of TEG module, however, concurrently, they rise the electrical performance of PV. In this thesis, I assessed the performance of PV-TE systems using seven different TEGs and monocrystalline silicon solar cells in four different scenarios. According to Standard Test Conditions EN/IEC 61215, the PV-TE hybrid systems are first tested at 25 °C without a cooling device. We then assess the systems using a passive cooling strategy, improving heat dissipation with aluminum heat sinks. Additional evaluations use an active cooling (AC) system with coolants of water and nanofluid in succession. The evaluations' findings are intended to set a standard for raising the effectiveness of upcoming PV-TE systems.



FOTOVOLTAİK-TERMOELEKTRİK HİBRİD SİSTEMLERİNİN TERMOELEKTRİK MODÜLLERİNİN VERİMLERİNİN ARTTIRILMASI

ÖZET

Fosil yakıtların kullanımı küresel olarak atmosferin ısınmasına ve iklimde değişikliğe yol açan sera gazlarını üretir. Evde gördüğümüz elektrik maliyetleri buzdağının sadece görünen kısmıdır. Görünüşte güvenlik harcamaları, temizlik çalışmaları, hava kirliliği, çevreye verilen zarar, savaşa ilgili harcamalar ve diğer ek gizli maliyetler gibi gizli maliyetler vardır.

Yenilenebilir enerji kaynakları, küresel seviyede ısınmanın durdurulmasına ve iklim değişikliği engelleme veya en aza indirme konusunda uygun enerji kaynaklarıdır. Fotovoltaik Enerji, özellikle güneş ışığı şiddetinin yüksek olduğu yerler için parlayan yenilenebilir enerji kaynaklarından biridir. Öte yandan, güneş enerjisi herkesin kullanımına açıktır ve fotovoltaik modüllerle doğru akım üretilerek kullanılabilir hale getirilebilir. Küresel enerji talebi için en iyi çözüm olma potansiyeline sahiptir. Güneş ışığı için bir ücret ödemediğimiz gibi, Dünyamıza ulaşan bu sınırsız enerji, güneşten gelen fotonlarla elde edilen bu enerjiyi sürdürülebilir ve temiz bir enerji yapar. Ayrıca, güneş enerjisi emisyon veya kirlilik üretmez, bu da onu temiz bir enerji çözümü olarak çekici hale getirir.

Güneş ışığı Dünya'daki yaşam için çok önemlidir. Sadece fiziksel evrensel sistemler ve döngüler için neredeyse tüm enerjiyi sağlamakla kalmıyor, aynı zamanda yüzey sıcaklıklarını da etkileyerek Dünya'yı biyolojik organizmaların gelişebileceği bir gezegen haline getiriyor. Güneş ışığı, besin zincirinin temeli olan bitkilerde fotosentezi sağlar. Güneş olmasaydı Dünya'da canlı organizmaların yaşaması mümkün olmazdı.

Yüzeye ulaşan güneş enerjisi miktarı sabit değildir. Bu değişkenlik iki ana faktörden kaynaklanmaktadır: Dünya kendi etrafında dönerken Dünya ve Güneş arasındaki uzaklık değişir ve Güneş ışığının açısının sürekli değişmesine neden olan Dünya ekseninin eğimi.

Güneş etrafında dönerken Dünyanın kullandığı yörünge daire değil bir elips olduğundan, Dünya ve Güneş'in arasında bulunan uzaklık takvim yılı içinde devamlı değişiklik gösterir. Mesafedeki bu değişiklik Dünya'ya ulaşan güneş ışığının yoğunluğunu etkiler. Ek olarak, Dünya ekseninin eğimi, güneş ışığının Dünya yüzeyine çarpma açısının yıl içinde devamlı değişmesine sebep olur. Bu eğim mevsimlerin değişmesini sağlar. Bu açı, güneş ışığının yoğunluğunu ve Dünya yüzeyinin emdiği enerji miktarını etkiler.

Bu faktörler, dünyanın farklı bölgelerine farklı zamanlarda ulaşan güneş enerjisinin değişkenliğine katkıda bulunur; iklimi, hava durumunu etkiler.

Güneş ışığının doğru akıma dönüştürülmesi anlamına gelen fotovoltaik, geleceğin teknolojisi olmasının yanı sıra çevre dostudur. Güneşten gelen enerji yalnız başına Dünyanın gereken enerji gereksinimini karşılamaya yeterli ve esasen sınırsızdır.

Fotovoltaik çağın başlangıcı, Fransız deneysel fizikçi Edmund Becquerel'in fotovoltaik etkiyi keşfetmesine kadar uzanabilir. 1839 yılında iki metal elektrotun içinde olduğu bir iletken çözeltinin bulunduğu bir elektrolitik hücre üzerinde deneyler yaparken ışığa maruz kalmanın hücre içindeki akımı arttırdığını gözlemledi.

1973 Petrol Krizinden bu yana araştırmacılar özellikle fotovoltaik üzerine yoğunlaşıyorlar. Şimdiye kadar bilim adamları güneş pillerinin ve fotovoltaik modüllerin verimliliğini artırmaya odaklanıyorlar. Fotovoltaik-Termoelektrik (PV-TE) Hibrit Sistemler modül verimliliğini artırma konusunda gelecek vaat eden sistemlerden biridir.

Fotovoltaik (PV) araştırmacıları üç ana stratejiye odaklandılar: yeni malzemeler geliştirmek, enerji geri kazanımı için güneş ışığından yararlanmayı iyileştirmek ve ısıyı elektriğe dönüştürmek için fotovoltaik-termoelektrik (PV-TE) sistemlerden yararlanmak. Artan küresel nüfus, gelecekteki PV enerji santralleri için mevcut araziye sınırlıyor, bu da güneş pili verimliliğinin ve fotovoltaik sistem etkinliğinin iyileştirilmesi ihtiyacını vurguluyor ve PV-TE bir çözüm olarak ortaya çıkıyor. Hibrit enerji üretim sistemleri, özellikle PV-TE, son yıllarda büyük ilgi görmüştür.

PV-TE sistemlerinde termoelektrik jeneratörlerin (TEG'ler) kullanılması, termal enerjiyi toplamak ve sistemde üretilen enerjiyi arttırabilme adına harika bir imkan sunar. Önceki laboratuvar testleri, tek başına PV ile karşılaştırıldığında PV-TE ile güç çıkışında %39'a kadar artış olduğunu göstermiştir. TEG'ler, yüksek enerjili fotonlara dayanan fotovoltaik hücrelerin aksine, modül içindeki sıcaklık farklılıklarına bağlı olarak ısı enerjisini elektriğe dönüştürebilmektedir. Bu, ısının TE bileşeni tarafından elektrik enerjisine dönüştürülmesi nedeniyle, ısının PV güneş pilleri üzerindeki olumsuz etkilerini ortadan kaldırır.

PV-TE hibrit sistemler, daha çok elektrik enerjisi üretebilmek için tüm spektrumda güneş ışınımından yararlanır. Özellikle güneş ışınımının yüksek olduğu bölgelerde etkilidirler ancak bir soğutma mekanizmasıyla donatıldıklarında güneş ışınımının düşük olduğu bölgelerde de karlı olabilirler.

TE modülleri katı hal güvenilirliği sunar, ancak maliyetleri her zaman verimlilikle uyumlu değildir. Daha ucuz modüller bazen malzemelere, çalışma sıcaklıklarına ve boyuta bağlı olarak pahalı olan modüllerden daha iyi performans gösterebilir. PV-TE hibritlerdeki aktif soğutma sistemi, TE modülünün soğuk tarafını daha soğuk halde tutarak enerji üretimini artırır. Bu sistem, geleneksel PV sistemlerinin, PV modüllerinin arka tarafındaki sıcaklığı ortam sıcaklığının üzerine çıkarma ihtiyacını ortadan kaldırır.

Fotovoltaik (PV) ve termoelektrik (TE) modüllerin PV-TE sistemlerine entegrasyonu, güneş spektrumunun kullanımının genişletilmesi, toplam güç çıkışının artırılması ve Güneş ışığı ile elektrik elde edilmesi için birim güç için gereken alanın azaltılması yönünde potansiyel göstermiştir. Bu tezde pratik bir PV-TE sistem modelinin veriminin artırılması yöntemleri araştırılmaktadır. Tipik olarak, TE bileşeninin güç çıkışını artırmak için, çeşitli ısı giderme yöntemleri kullanılarak termoelektrik jeneratör (TEG) modülü boyunca önemli bir sıcaklık farkı indüklenir. Bu soğutma teknikleri yalnızca TEG modülünün verimliliğini arttırmakla kalmaz, aynı zamanda PV bileşeninin performansını da artırabilir.

PV-TE sisteminin üst kısımda PV modülü, alt kısımda ise TE modülü bulunur. Foton enerjisi yarı iletkenin bant aralığı enerjisini (E_{gap}) aşarsa, PV modülüne gelen güneş ışığı elektron-delik çiftleri oluşturur ve bu da elektrik enerjisiyle sonuçlanır. Ancak

düşük enerjili fotonlar modülün sıcaklığını artırır ve sıcaklık-direnç ilişkisi nedeniyle direncini artırır. Bu, PV modülünün verimliliğini azaltır. TE modülü doğrudan PV modülün arka yüzeyine yapıştırılarak PV modülünde üretilen termal enerjinin TE modülüne aktarılmasına olanak sağlar. TEG'ler, farklı sıcaklıklardaki iki farklı iletkenin birleşim yerinde meydana gelen Seebeck Etkisinden yararlanarak bir elektrik potansiyeli oluşturmak üzere tasarlanmıştır. Bu olay sayesinde TEG'ler termal enerjiyi elektrik enerjisine dönüştürebilmektedir. Gelişmiş ve çeşitli stratejiler yoluyla TE modüllerinde verimliliğin artırılmasının sağlanması zorunludur. Bu alandaki geliştirmeler, enerji dönüşüm verimliliğinde önemli gelişmeler sağlamayı vaat etmekte ve böylece bu hibrit sistemlerin çeşitli sektörlerdeki etkinliğini ve potansiyel uygulamasını arttırmaktadır.

Bu tez çalışmasında, monokristalin ve polikristalin silikon güneş pilleri ve yedi farklı TEG ile donatılmış PV-TE sistemlerinin dört farklı koşuldaki verimliliklerini değerlendiriyoruz. Başlangıçta PV-TE hibrit sistemler, 25 °C ortam sıcaklığında soğutma mekanizması olmadan test edilir (STC EN/IEC 61215). Daha sonra, gelişmiş ısı dağılımını kolaylaştırmak için alüminyum soğutucuların kullanıldığı pasif soğutma yaklaşımıyla sistemleri inceliyoruz. Diğer testler, soğutucu olarak su ve ardından nanoakışkan kullanan aktif bir soğutma sistemini içerir. Bu değerlendirmelerden elde edilen sonuçlar, gelecekteki PV-TE sistemlerinin verimliliğini artırmak için bir kıyaslama oluşturmayı amaçlamaktadır.



1. INTRODUCTION

Because of growing global demand for electricity, fossil fuels are being used extensively, frequently without taking into account their negative repercussions. The release of CO₂ and release of greenhouse gases is now a major environmental concern, with scientists predicting a global temperature rise of 0.6 – 2.5 °C within 50 years, which would have serious consequences for our environment. Fossil fuels, which are predicted to last about another century, are in charge of about 80% of greenhouse gas emissions. To minimize these effects, we must urgently shift away from fossil fuels.

A suitable solution could be the using of nuclear power. Currently, there are nearly 400 nuclear power plants worldwide. With the addition of 5000 more nuclear power plants, it would allow us to supply global energy demand. Additionally, the Chernobyl disaster remains as an unforgettable sign of the dangerous side of nuclear power.

Carbon sequestration is a potential method for managing emissions from fossil fuel use. It involves capturing emissions and storing them in underground cavities.

Transitioning to renewable energy sources offers a more sustainable solution. By relying solely on renewable energies, we can earn the energy needed for World with giving no harm to the environment. Photovoltaic solar power alone has the potential to satisfy global electricity demand. Other renewable sources such as tidal, nuclear, hydroelectric and wind power are also environmentally friendly options.

It's worth noting that while these renewable sources can drastically cut greenhouse gas emissions. However, with continued research and development, renewable energies may play important role at addressing our energy needs while mitigating environmental impacts.

Tidal power is a viable solution primarily for countries with access to seas and oceans, making it only localized answer not only a global one.

Hydroelectric power is effective for countries with abundant water resources. However, hydroelectric power plants may harm ecosystems and local communities.

Related to the advancements about technology, the world's population increase and worldwide industry, the world's energy demand is constantly rising more quickly. By 2040, it is anticipated that the world's energy consumption would have grown by 30% [1]. PV energy is maybe the most dependable renewable energy sources that are available to meet the highly growing need for electricity worldwide [2]. Solar energy is a plentiful, clean, free and non-polluting source of power and heat [3].

The world's yearly power needs could easily be able to get by the sunlight energy gained from the sun in just one hour. Only 17–18% of the heat energy we become from sunlight can be transferred into electricity by PVs [3]. The limitations of PV technology that prevent the full utilization of available solar energy are dust collection, low conversion efficiency and high surface temperature. Because of the unequal, erratic and sporadic sunlight radiation that falling on surface, the PV surface temperature distribution is not symmetrical. To optimize conversion efficiency, the PV cell's area needs to be increased, which raises the cost and deteriorates market insights. As a result, a practical method for lowering PV heat loss and increasing their efficiency must be found.

Everyone can easily use solar energy and may be harnessed with high-efficiency photovoltaic generators. It may be the best energy source for global energy demand. Sunlight is not just only free it is also unlimited, making solar energy a sustainable and constant energy source. Additionally, solar energy does not produce emissions or pollution, further enhancing its appeal as a clean energy solution.

Figure 1.1 illustrates the current and potential future rates of different energy sources, especially showing the increasing role of renewable energies. It suggests that renewable energies, particularly after 2030, will show a higher role in the energy usage rate of the Earth.

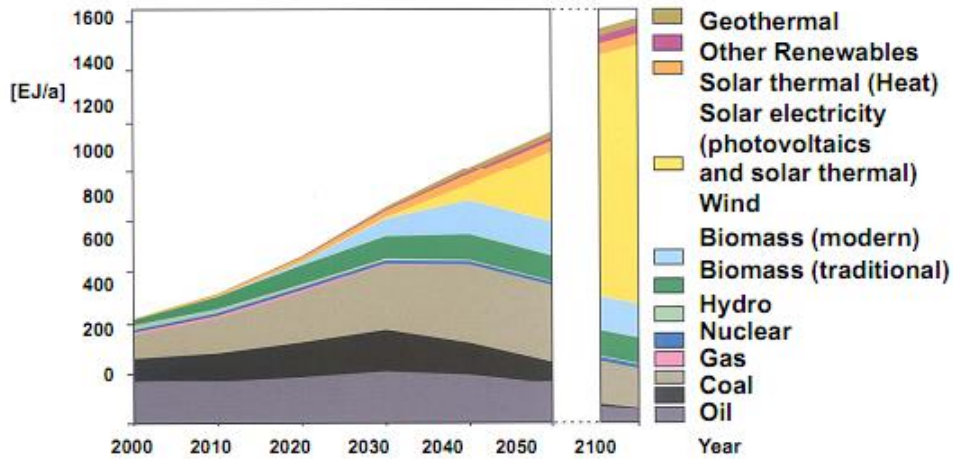


Figure 1.1. The rates of energy sources, expected energy rates in the future [4].

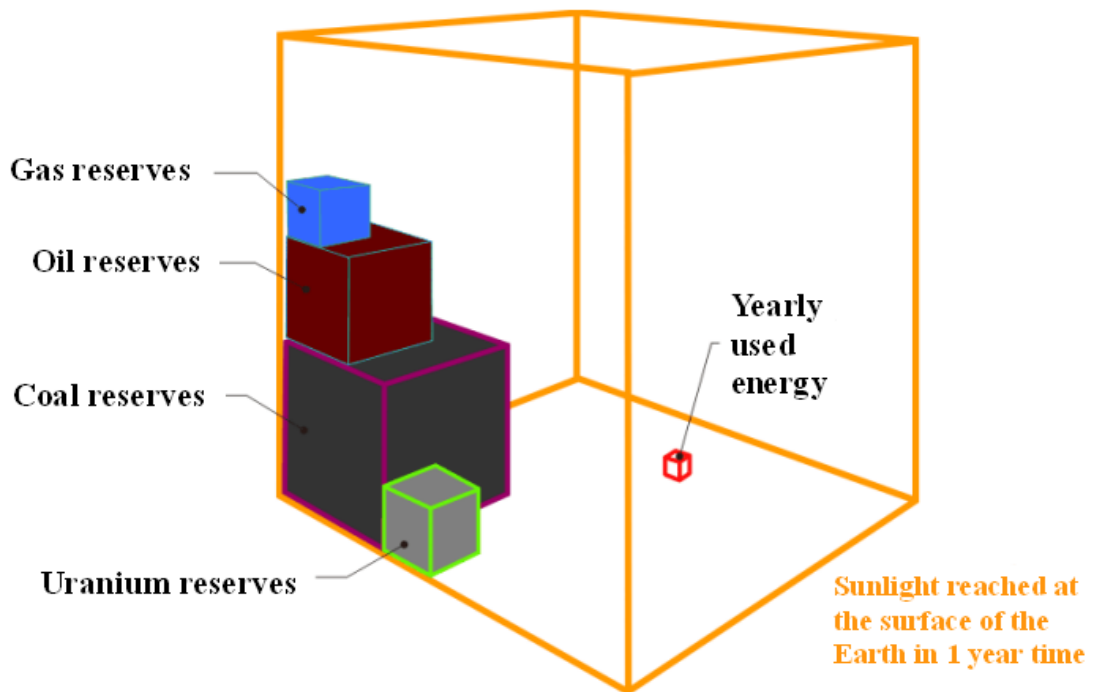


Figure 1.2. Reserves of different energy sources [4].

Regarding photovoltaics, is not only a promising technology, but at the same time environment friendly. Figure 1.2 provides insights into the amount of various energy sources, their reserves, the annual global energy demand, energy from sunlight illuminating the Earth's whole surface. It indicates that solar energy alone is sufficient to catch the Earth's energy demand and is essentially limitless.

After Edmund Becquerel, Willoughby Smith, in the year 1873, discovered the selenium photoconductivity and just four years later, W.G. Adams produced the first

selenium cell. Another four years passed before selenium wafer solar cells were described. However, these early solar cells had only 1% efficiency.

The pivotal moment came in 1954 when Chapin reported a solar conversion efficiency of 6% using a silicon crystalline solar cell. This marked a significant advancement in solar cell researches.

1.1. Scope

Numerous facets of solar energy, photovoltaics, thermoelectrics and PV-TE hybrid systems are investigated for this thesis. Starts with the Sun for our planet and how the Sun-Earth geometry affects photovoltaics. It covers topics such as solar radiation, the black body principle, extraterrestrial and terrestrial solar radiation, direct radiation, diffuse radiation, albedo radiation and the air mass term. Additionally, it explains two important terms in photovoltaics: annual solar radiation and insolation [4].

The fundamentals of photovoltaics are then described, including the photovoltaic effect of sunlight, the principle of photovoltaics, the materials used in photovoltaic technology [4].

The evolution history and improvements of solar cells are discussed, along with production sequences and information about the losses of solar cells. Terms related to solar cells, such as ARC (Anti-reflection Coating), etching, texturing and BSF (Back Surface Field) are explained. The chapter also offers comprehensive details on the various kinds of thin-film, bifacial and crystalline solar cells.

To boost power output, a lot of research has been done on PV thermal management and providing chances for waste heat recovery, which supports the idea of photovoltaic-thermal (PVT) systems [5]. Thermo Electric Generators (TEGs) have drawn significant interest among the different cooling techniques proposed for this aim, because they have ability to generate electricity and cool the PV through the use of waste heat from photovoltaic cells [6].

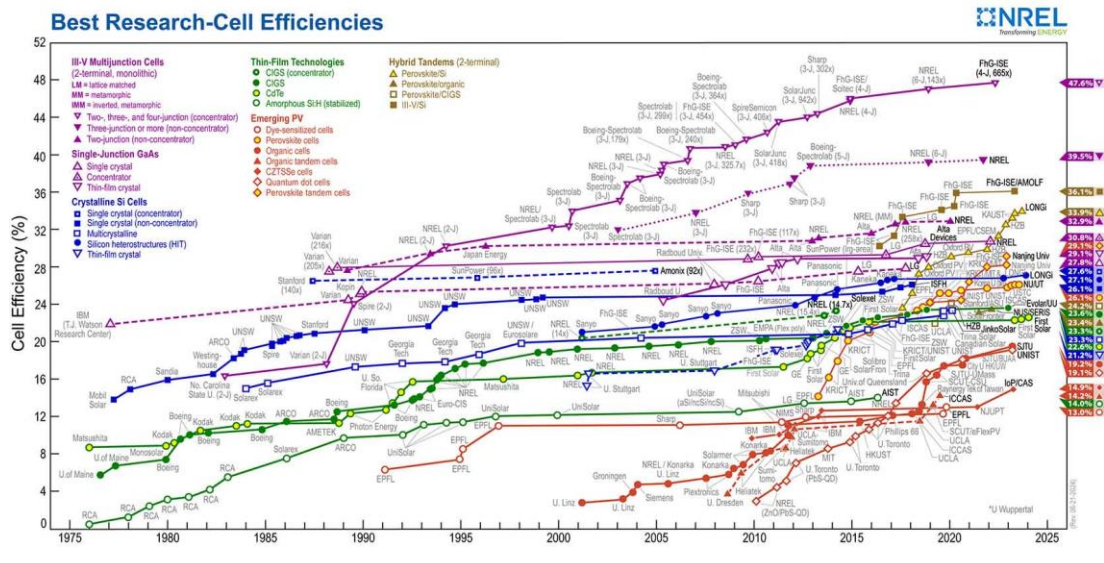


Figure 1.3. Best research cell efficiencies (2024) [7].

In the Figure 1.3, a graph with the efficiencies of the best research cells is given. Highest efficiencies of different PV types can give us a clear information, with which methods can the efficiency of PV solar cells increased. The graph below clearly illustrates the variations in crystalline PV cells, thin film PV cells, tandem PV cells and some hybrid tandem PV solar cells [7].

Methods to enhance photovoltaic generators efficiency, are explained, including information about sun tracking methods and PV/T systems for PV-TE Hybrid Systems. The fundamental information about Thermoelectric Systems is also described, along with methodologies to enhance the efficiency of TE modules.

But one important purpose of this thesis study, was not only to get and use the highest efficiency with a research PV cell. In this thesis, the TEGs, which are standard are employed in the market to observe a higher outcome for a commercial future use of PV-TE systems. At the end an useful result for the direct conversion of PV Solar Systems to PV-TE Solar Systems, which can be used commercially, is found.

Otherwise the research could unfortunately, only be useful for the academic people and regrettably couldn't be utilized with ease at PV market directly. But with the results we know now, when a PV module with the information of the TEGs power and also with which TEG with the information of the characteristical information about the TEG, we can nearly predict information about increasing in the PV-TE hybrid system compared to the PV system.

1.2. Purpose of Thesis

Researchers working about Photovoltaic (PV) have focused on three main strategies: developing new materials, improving sunlight utilization for energy recovery and utilizing photovoltaic-thermoelectric systems that convert heat into direct current. The increasing population limits available land for future PV power plants, emphasizing the requirement for increased photovoltaic system efficacy and solar cell efficiency, with PV-TE showing promise as a remedy. Hybrid power generation systems, particularly PV-TE, got a significant focus throughout the last few decades [8-10].

One possible way to capture thermal energy and boost power output in PV-TE systems is by utilizing thermoelectric generators (TEGs). Previous laboratory experiments showed a 49,1% increase in power output with PV-TE compared to PV alone [11-14]. TEGs possess the capacity to generate electrical power from thermal energy, based on temperature differences within the module, unlike PV cells that depend on on high-energy photons [15-16]. This eliminates the negative consequences of heat on PV solar cells, as the waste heat energy transforms into direct current via the TE module [17-22]. PV-TE Hybrid systems have earned more attraction in the last decades [23-32].

PV-TE hybrid systems utilize solar irradiation across the full spectrum to generate more energy efficiently [33-37]. Although they can be profitable in areas with lower sun radiation, they are more beneficial in areas with high solar irradiation, when equipped with a cooling mechanism [38-42].

Although TE modules are solid-state reliable, their cost and efficiency aren't necessarily equal. Depending on the materials, operating temperatures, and size, less expensive modules can occasionally perform better than more expensive ones. In PV-TE hybrids, an active cooling system maintains the cold side of the TE module cool, reducing environmental impacts and enhancing energy efficiency. Normal PV systems are no longer required due to the fact that this solution raises the backside temperature of PV modules above ambient temperature [43].

This thesis assessed the effectiveness of PV-TE systems. Because of this, for the TE part, TEGs with the same plate dimensions but with different properties, like plate material or p-n junction dimensions are provided. In the market we could find 7 different TEGs according to our acception. These TEGs were tested in 4 different conditions to be able to increase their power output. Initial experiments were done

under 25 °C ambient temperature, without using a cooling mechanism for the TE module. Subsequent tests included a passive cooling system with aluminum heat sinks and an active cooling system by using distilled water and by using nanofluid as coolants. Those tests offer insightful information to increase PV-TE's efficiency systems.

Enabling efficient temperature control could increase PVs' efficacy and lifespan. Since PV conversion efficiency and surface temperature are inversely correlated, cooling of PVs as an emerging subject of research requires consideration. One often used thermal management strategies to increase the efficacy of PVs and integrated systems is the insertion of TEG. The TEG produces the extra electric power production with using of the waste heat directly from PVs.

1.3. Literature Review

This chapter, firstly provides a summary of our source of solar energy; Sun, solar energy. And then information about photovoltaic, simple PV technologies of harvesting energy from sunlight. Later methods to increase the energy of the PV systems so called hybrid technologies are explained. Also the Fundamentals of thermoelectric is given in this chapter. In addition to hybrid systems like photovoltaic/thermal (PV/T) and photovoltaic/thermoelectric (PV/TE), this also includes single systems like PV and thermoelectric. The optimization of PV-TE system design has been the main focus of theoretical research. The cooling of the PV using thermoelectric elements (TEGs) has been the subject of certain theoretical studies.

1.3.1. Fundamentals of Solar Energy and the Sun

In order to have a look at the fundamentals of solar energy, we have to focus on the Sun, the importance of the Sun. Then the physical relation of the Sun and Earth should be examined to see the effects of sunlight on PV systems. The solar radiation, the Black Body principle, extraterrestrial and terrestrial solar radiation subjects are also very important to understand the photovoltaic systems. Radiation types such as direct radiation, diffuse radiation, albedo radiation and their differences give us important knowledge for the relation of PV and the sunlight in the Earth's atmosphere. Some terms like Air Mass and annual solar radiation and insolation are given as information in this chapter.

1.3.1.1. The Sun and The Earth

For photovoltaics and also commonly solar energy, the Sun is a fundamental term. Only with the sunlight from the Sun, the PV cells and solar energy systems can generate enough electricity for the human beings.

For 1000s of years, people have been coming up with inventive ways to use the Sun's light and heat. However, the process of turning solar energy into electrical power is less than 200 years old [44].

To give information about the fundamentals of photovoltaics, the physical relation of Sun and Earth should be examined.

Our Sun is not only stays in center of Solar System but also at the origin of life on World. Without the Sun, living things on Earth, could not exist. Located approximately 150 million kilometers away from Earth, the Sun having a core temperature of around 15.6 million Kelvin. The photosphere, the outer part layer of our Sun, has an enormous temperature of 5800 Kelvin [45].

The Sun is essentially a giant fusion reactor, producing an enormous amount of energy, approximately 4.10^{20} megawatts [45]. This energy is a must for sustaining a suitable place for organisms on Earth, providing warmth and light that drive the planet's climate and ecosystems.

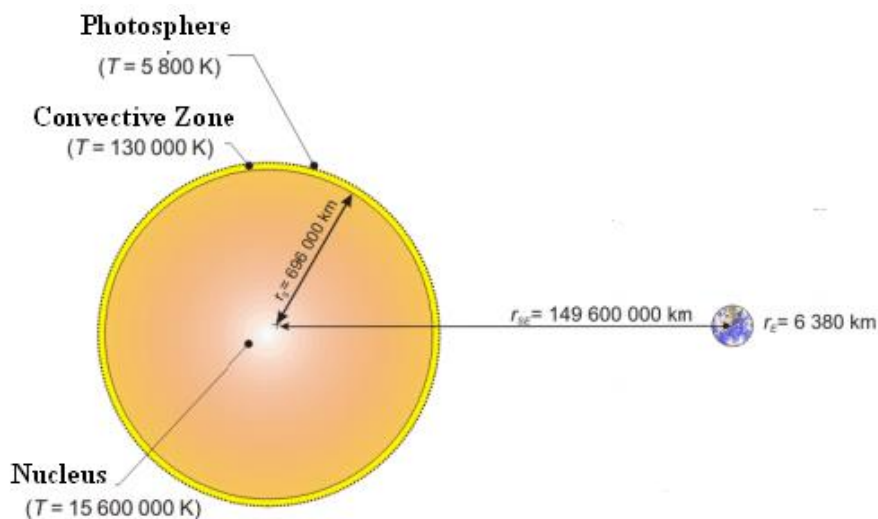


Figure 1.4. The Sun and its distance to the Earth [4].

Figure 1.4 shows us theoretically the position of our Sun and the physical position of the Earth.

When exposed to light, "photovoltaic" solar cell generates free electrons, which in turn generate an electric current. The Greek term "photo," which means light and the contemporary word "volt" or "voltage," which denotes a unit of electrical potential, are the roots of the word photovoltaic [46]. The volta part of photovoltaic comes from Alessandro Volta, an Italian physicist who lived from 1745 to 1827, is credited with creating the first chemical battery [46].

Sunlight is composed of photons, which are particles of solar energy. The varied wavelengths of the sun spectrum correspond to the varying energy levels of these photons [47]. PV cells are made of semiconductor material. Photons can either pass through a photovoltaic cell, be absorbed by the semiconductor material, or bounce off the cell when they strike it. Only the photons that are absorbed provide the energy required to generate electricity. When the semiconductor material gets enough sunlight, its atoms release electrons. The front surface of the PV cell becomes more receptive to the released, or dislodged, electrons, enabling them to migrate naturally to the cell's surface when the surface is properly treated during manufacturing [47].

1.3.1.2. Solar Radiation

Sunlight is a must for organisms living on Earth. It not only provides nearly all energy for physical universal systems and cycles but also influences surface temperatures, making Earth a planet where biological organisms can thrive. Our Sun has a leading role by regulating the Earth's climate and weather patterns.

Total solar energy reaching to Earth is not constant. Because of 2 primary variables which contribute this variability: the changing interspace between them because the Earth orbits around it and slope of Earth's axis, that causes the sunlight's angle to alter continuously.

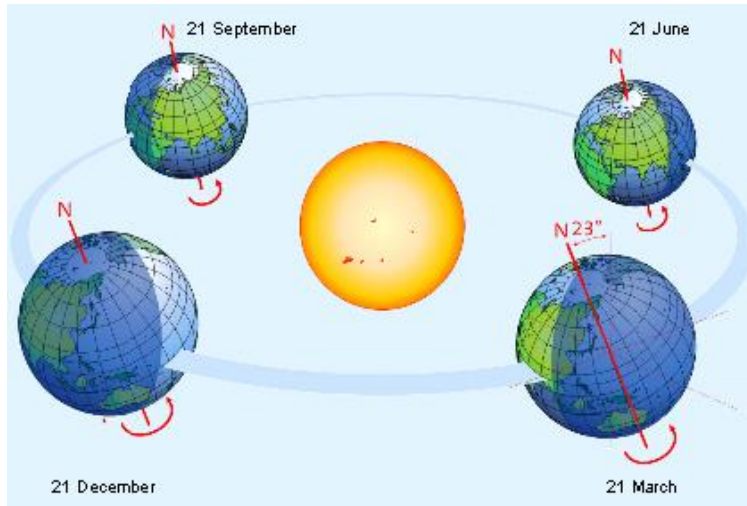


Figure 1.5. The Sun, seasons of the Earth [4].

Earth's orbit, is not circular, it is an ellipse, because of this, the interspace between them, varies in the year. The variation in distance, affects the amount of photons reaching the Earth. Figure 1.5 gives information about this variation.

Only twice in a year, by the equinoxes, does sunlight fall directly between the two tropics, creating a right angle with the Earth's surface. This angle affects both the strength of sunlight and the potential amount of energy that the Earth's surface can absorb.

These elements add to the fluctuations in solar energy reaching different places on the Earth at unrelated times, influencing climate, weather patterns and the solar energy for renewable energy systems.

1.3.1.2.1. The Extraterrestrial Solar Radiation

The Sun is composed of hydrogen (about 73.5% by mass), helium (about 25%) and heavier elements (about 1.5%). It has a core temperature of approximately 13.6 million Kelvin and a surface temperature of around 5800 Kelvin. The outer visible layer of the Sun is, photosphere.

Photosphere is modeled as a black body, which means it soaks up all radiation and then emits radiation based on its temperature [48]. An example of a black body is a coal-burning stove with a small opening. The stove absorbs all the heat and releases heat and light as radiation. Similarly, the photosphere of the Sun absorbs the energy produced in its core and emits light and heat into space.

$$\text{Black Body: } A = 1 \quad (R + A + T = 1 \rightarrow R = T = 0)$$

(R: reflection, A: absorption, T: transmission)

Stefan-Boltzmann Law proves that the radiation released by black body system only depends on its temperature.

One crucial factor in photovoltaic technology is the solar constant, denoted with S [49]. The solar constant represents the power of energy on the outer part of atmosphere, which is approximately 1369 W/m^2 with a radius of $D=149,596,000$ kilometers, nearly $150,000,000$ kilometers.

The average interspace between the Sun and Earth, is the Astronomic Unit (AU). The total solar radiation received by Earth is equal to the solar constant which is increased by the Earth's cross-sectional area.

1.3.1.2.2. The Terrestrial Solar Radiation

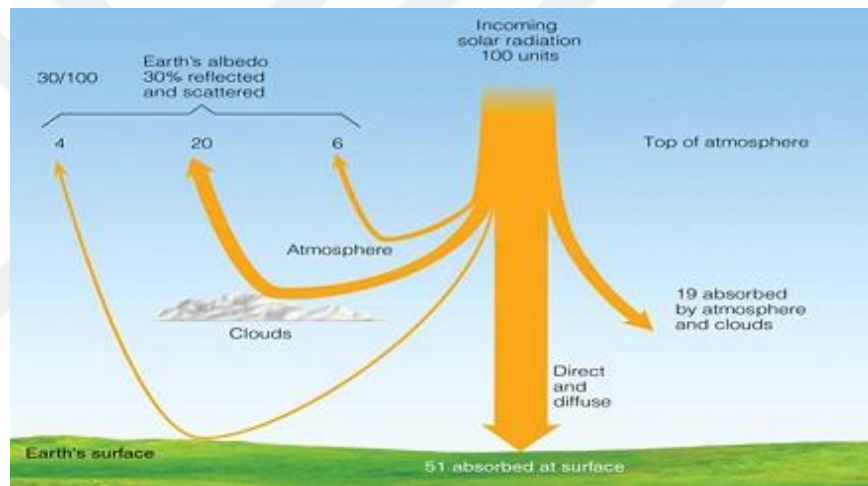


Figure 1.6. The Losses of Radiation [4].

Figure 1.6 illustrates that the energy is not entirely absorbed by the surface. The atmosphere absorbs an average of 67 W/m^2 and reflects an average of 77 W/m^2 of the incoming solar radiation. Additionally, reflects 30 W/m^2 off the Earth's surface. Thus, only 168 W/m^2 of the radiation energy is caught by the Earth's surface [50]. The amount of energy falling as Sunlight on the Earth's surface every hour, exceeds the energy needed by human population in a year [50].

1.3.1.3. The Air Mass

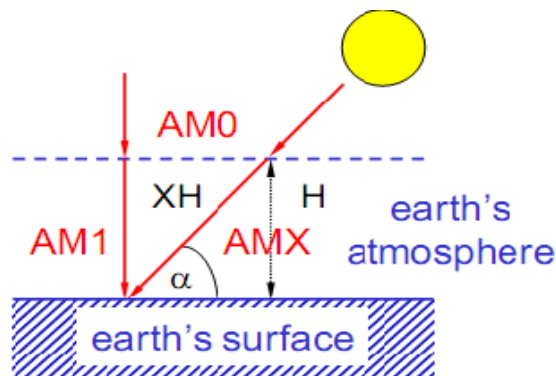


Figure 1.7. Some Air Mass values [51].

The amount of solar energy travelling through the atmosphere depends on its thickness. The air mass quantifies the losses of sunlight energy radiating through the atmosphere [52]. It is the length of the path, sunlight travels in the Earth's atmosphere, is split by the shortest route length that occurs when the sun is completely overhead [53]. Figure 1.7 shows us some important Air Mass values.

Some examples for the Air Mass values:

AM0: radiation from sources outside of Earth's atmosphere

AM1: the radiation at sea level under a clear sky at high noon which is $1000 \text{ (W/m}^2\text{)}$

AM1.5G: the global irradiation at Earth's surface.

AM1.5D: Only energy from direct radiation strikes the Earth's surface.

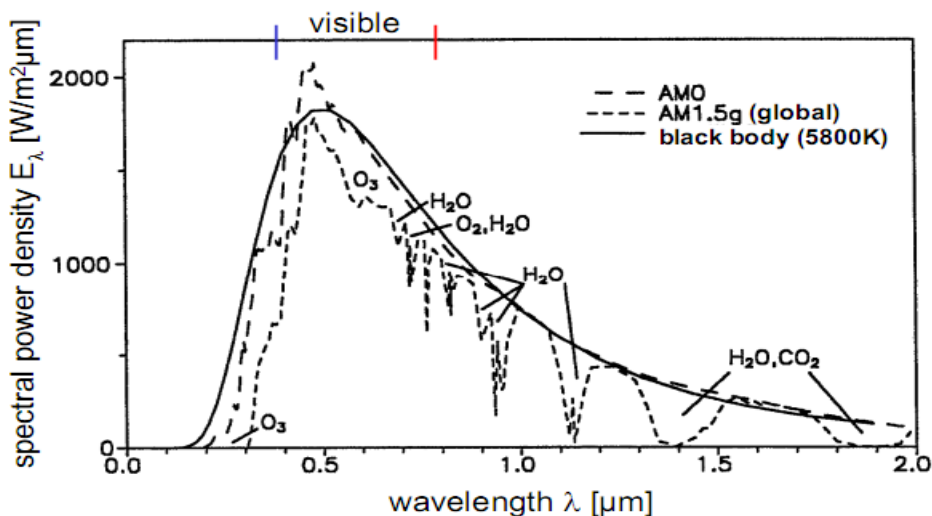


Figure 1.8. Black Body Radiation, AM0 and AM1.5g Radiation [51].

Figure 1.8 allows us to compare the radiation energy of a Black Body, AM0 and AM1.5g. We note that the radiation of AM0 exceeds the Black Body radiation with a small amount of the visible light area, primarily because of the light's reflection in the Earth's atmosphere. Additionally, we see that O₃ (ozone), H₂O (water vapor), O₂ (oxygen) and CO₂ (carbon dioxide) have an effect on AM1.5G, indicating the influence of atmospheric components on solar radiation.

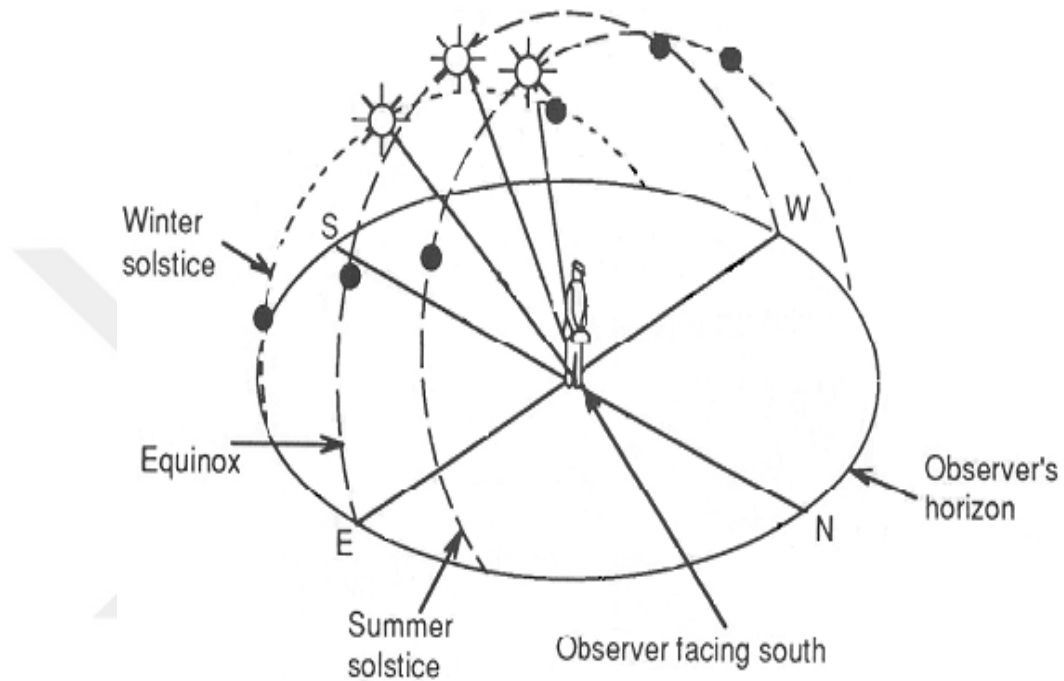


Figure 1.9. The Sun's Apparent Motion to an Observer at Latitude 35°N [51].

For an observer at latitude 35°N, like in Figure 1.9, the sunlight photons reaching the Earth's surface with varying Air Mass (AM) values throughout the year. On December 22nd, the sunlight has the highest AM value. On March 21st, the equinox, the AM value is lower, meaning the starting of the spring. On June 21st, the sunlight has the lowest AM value. Finally, on September 23rd, the start of autumn, the sunlight has a higher AM value again.

1.3.1.4. The Direct, Diffuse and Albedo Radiation

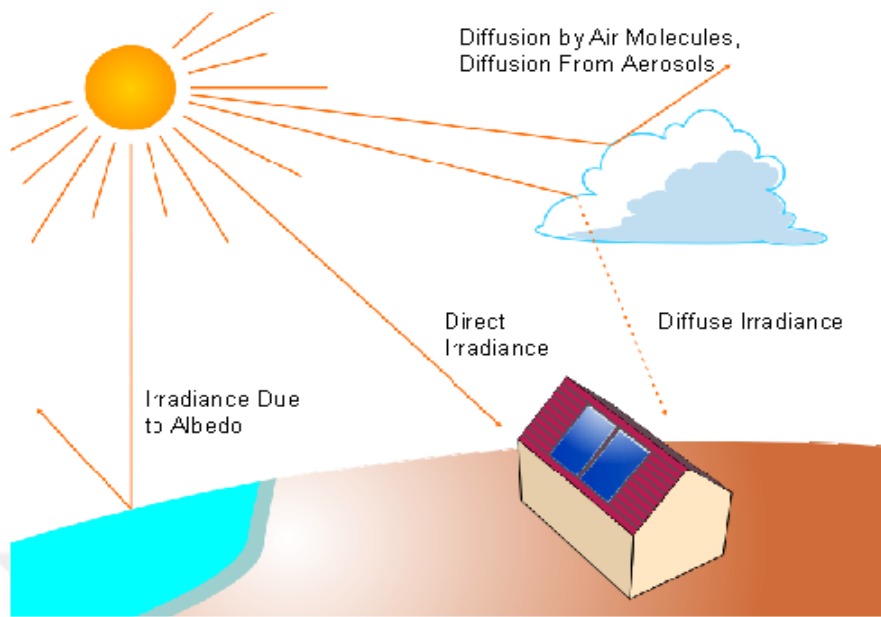


Figure 1.10. Direct, Diffuse and Albedo Radiation [51].

Diffuse radiation is made up of sunlight photons that are reflected by clouds, the Earth's surface and like other things, whereas direct radiation is sunlight that comes straight from Sun. Figure 1.10 displays albedo, diffuse and direct radiation. Two terms must be defined related to this topic:

Absorption:

O_3 , H_2O , O_2 , CO_2 these particles absorb the sunlight

Scattering:

Rayleigh Scattering, the particles having smaller wavelength than the sunlight have small effects on the sunlight for example blue sky, red sunrise and red sunset.

Mie scattering, the particles having bigger wavelength than sunlight have bad effects on the sunlight, for example grey sky.

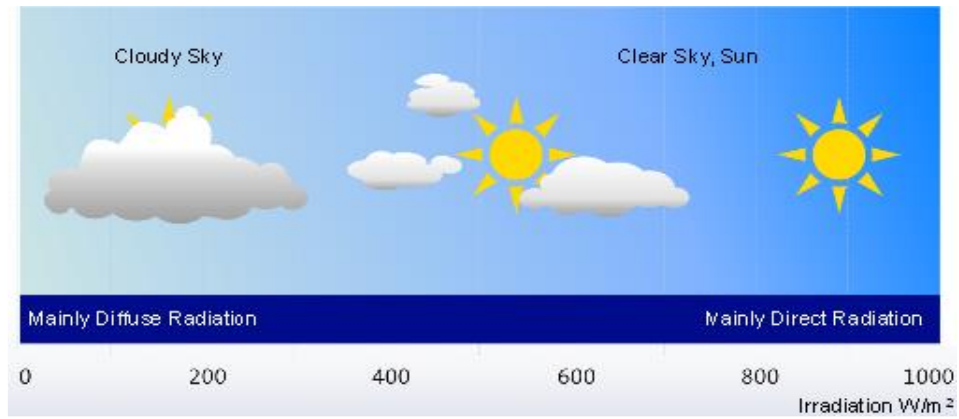


Figure 1.11. The Direct, Diffuse Radiation depending on the weather [51].

Figure 1.11 shows a foggy sky with largely diffuse radiation; on the other side, no clouds and sunlight can readily reach the surface, with mostly direct radiation.

1.3.1.5. The Annual Solar Radiation

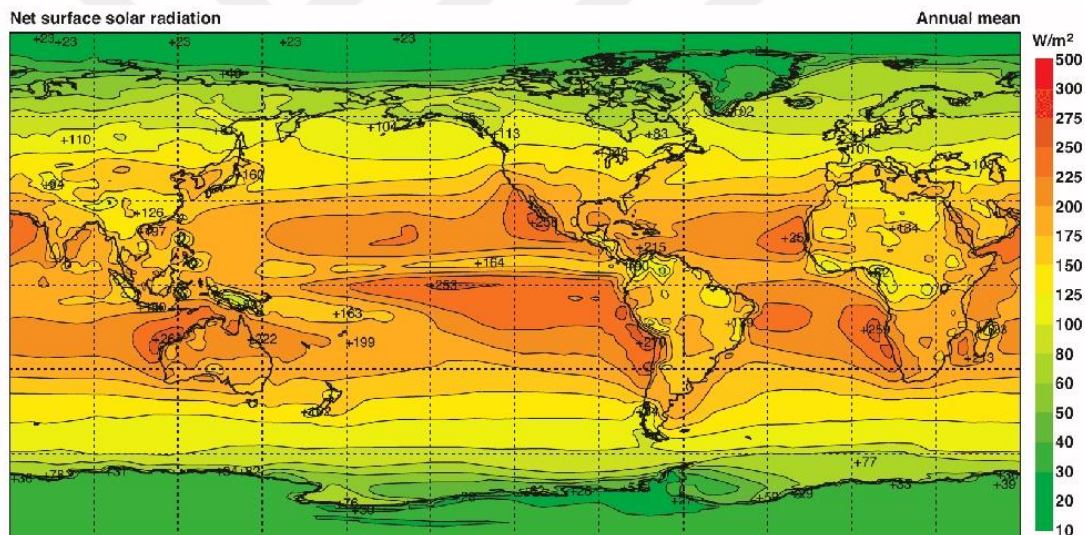


Figure 1.12. Insolation map of the Earth [54].

Figure 1.12 is an insolation map of the Earth. An important term related to solar radiation is insolation [55]. It is the sunshine, expressed in W/m^2 , that reaches a particular place at a that moment. Insolation is affected by factors, like region, season, time of day, climate and air pollution.

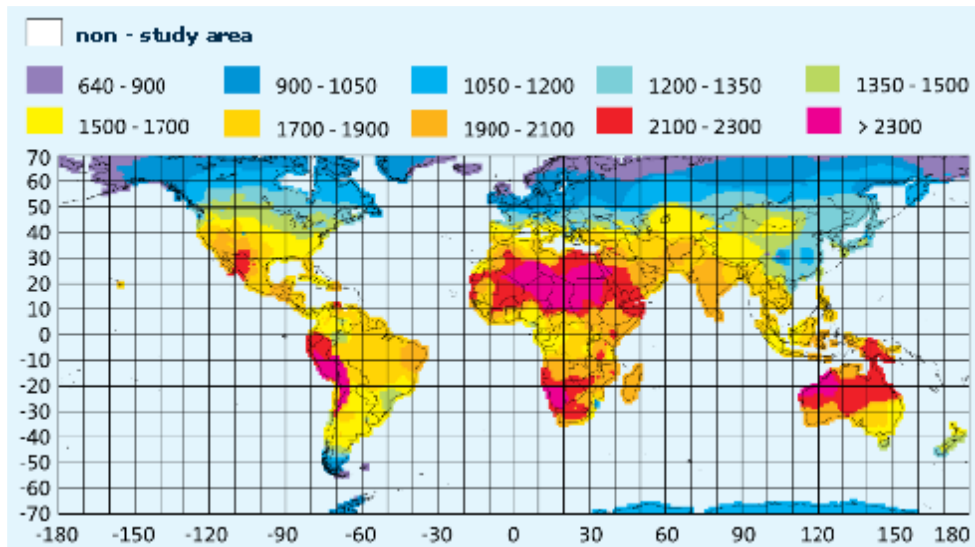


Figure 1.13. Global solar radiation map [56].

The geographical location of PV (photovoltaic) modules is planned using annual sun radiation maps. The radiation is measured in kWh/m² or Wh/m².

Insolation and annual solar radiation values are crucial for planning PV generators. Higher solar radiation at a location means that a smaller PV module may be planned for the same household compared to a location with lower solar radiation. Figure 1.13 provides a clear overview of global annual solar radiation. Additionally, the map's highlights indicate, the region between the 2 tropics receives more sunlight. Furthermore, compared to coastal regions at the same latitudes, deserts typically have higher solar radiation values, demonstrating the influence of climate on yearly solar radiation. However, most of Europe receive lower solar radiation than regions like the USA, North Africa, or Turkey.

1.3.2. Fundamentals of Photovoltaics

This chapter informs about fundamentals of photovoltaics, including the photovoltaic effect of sunlight, solar cells working principle, materials used in photovoltaic technology, materials used in photovoltaic technology. The curve of U-I of PV cell is explained and terms Maximum Power Point (MPP) and Fill Factor (FF) are explained. Also explores the history and improvements of solar cells, production processes and losses associated with solar cells. Numerous terms related to solar cells, such as ARC, BSF, etching and texturing, are explained. Information about different types of crystalline solar cells, bifacial and thin-film solar cells is given.

1.3.2.1. The Photovoltaic Effect of the Sunlight and the Solar Cell

Scientists determined that sunlight consists of photons with varying energy levels. When sunlight hits a semiconductor material, some photons are absorbed. The energy from these photons is given to the semiconductor material's atoms' electrons, allowing the electrons to move from their normal positions and create an electric current. These semiconductor materials with photovoltaic capability are structured to supply voltage.

First silicon solar cells were not very efficient. For example, in 1941, the solar cell developed by Ohl had an efficiency of only 1% [57]. However, in 1954, three scientists, Chapin, Fuller and Pearson, created the earliest contemporary silicon solar cell had an efficiency of 4.5% [58]. Just four years later, when solar cells were added to the Vanguard I spacecraft in 1958, they became well-known [59].

The conversion of photovoltaic energy directly from sunlight to electrical energy is a direct process, unlike other solar energy techniques that first convert it to thermal energy. The principle of the method is based on a simple p-n junction. In doped semiconductor materials, the balance of electrons and holes changes. By a semiconductor material doped with p-type, then there is an excess of holes, while by a semiconductor material doped with n-type, there is an excess of electrons. However, the Fermi level is closer to the valence band in a p-type semiconductor and closer to the conduction band in an n-type semiconductor.

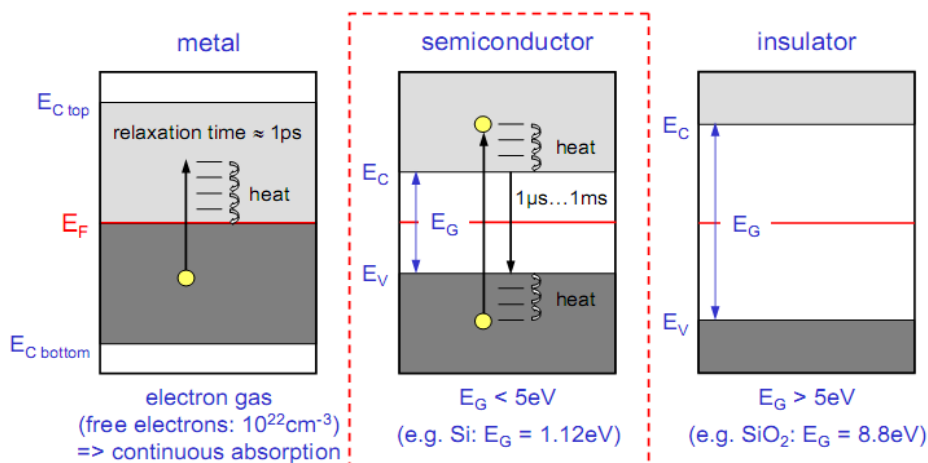


Figure 1.14. Band diagrams of metals, semiconductors and insulators [51].

Figure 1.14, the distinction among insulators, semiconductors and metals is illustrated. Semiconductors possess a suitable energy gap, typically less than 5 eV, making them ideal for photovoltaic applications. Insulators, Conversely, possess an energy gap

exceeding 5 eV, rendering them unsuitable for photovoltaic applications. The ideal energy gap is a crucial element to ascertain a material's suitability for use in photovoltaics. The assumptions for the ideal energy gap are [51]:

- All photons are absorbed
- Each photon with $E \geq E_g$ generates exactly one electron-hole pair
- Electron-hole-pairs Energy is E_g

When a semiconductor material of the p-type is allied with an n-type semiconductor material, consequently, a p-n junction results.. But this junction is not created by simply placing an n-type semiconductor material layer directly in connection with a p-type semiconductor material layer. Instead, it is formed an n-type dopant is diffused into a side of a p-type wafer. This process equalizes the Fermi level for the two materials.

After the band bending, it becomes difficult for electrons to move upward and for holes to move downward. This characteristic defines a diode and is also the main principle of p-n junctions. Nearby, in photovoltaics, this property is utilized. When the photons energy, is lower compared with the bandgap energy, the photon passes straight through the semiconductor material. When the photons energy is more than E_g , than the semiconductor material absorbs the photon. The absorbed energy allows electrons to get out of their positions, becoming free in the lattice structure and leaving behind holes. The natural tendency of electrons to move downward and the natural tendency of holes to rise. After this movement, the amount of holes and the amount of electrons increases. This movement results in a voltage difference. Some collectors are sometimes made of n-type and p-type external parts connected by means of resistance. This connection results in a flow of charge, producing an electric current.

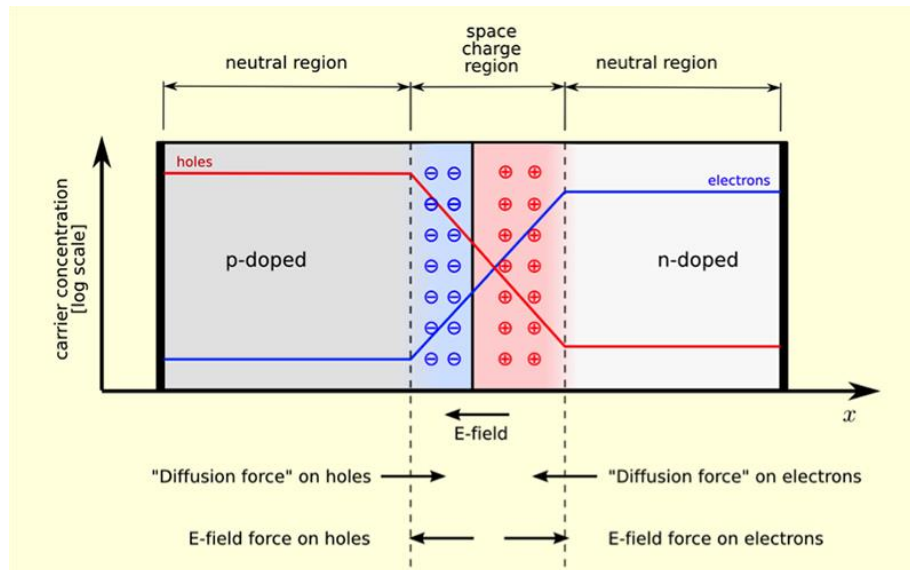


Figure 1.15. A p-n junction in thermal equilibrium with zero bias voltage applied. Light red zone is positively charged. Light blue zone is negatively charged. Gray regions are neutral [60].

In the Figure 1.15 p-n junction in different conditions is explained. If we have a look at the working principle of a solar cell; an electron-hole pair is created when photons from the light excite electrons on the p-n material's surface to move into the conduction band. If this happens in the n-doped side of the p-n junction, the newly excited electron is pushed away from the junction and the hole is swept across the junction to the p-doped side. This electron-hole pair separation is caused by the electric field in the space charge region. By providing the external circuit (a wire) between the p- and n-semiconductors, we can then initiate the electron's passage from the n-doped side to the p-doped side, where it recombines with a hole. This photo-induced electric current is the usable energy.

1.3.2.2. The Solar Cell Materials

The main component of solar cells is silicon, which can be amorphous, polycrystalline, or monocrystalline. However, the manufacturing of solar cells also uses a wide variety of different semiconductor materials [61]. The materials used to make solar cells fall into the following groups:

Silicon

- Monocrystalline Silicon type
- Polycrystalline Silicon type

- Amorphous Silicon type

Thin Films

- Copper Indium Diselenide (CIS) type
- Cadmium Telluride (CdTe) type
- Thin-film Silicon type
- Gallium Arsenide (GaAs) type

Manufacturers or end users may choose materials based on several aspects, which include [62]:

- **Crystallinity:** Materials structure, if it is crystalline or amorphous.
- **Absorption:** How well the material absorbs sunlight.
- **Bandgap:** The energy gap that determines the efficiency
- **Complexity of Manufacturing:** The ease involved in producing solar cells from the raw material.

To see deeply the differences betwixt these materials, it's important to introduce and examine various aspects:

Crystallinity: The crystallinity of the material explains us information about how atoms are arranged within the material. And in case of single crystallinity, the atoms are arranged into a beautiful substance, it is a crystal structure also the entire substance consists of a single crystal. Due to this structure, no deformation occurs and nothing acts as a recombination center [63]. There are also contacts between these different crystals and therefore unsatisfied overhang points that act as recombination centres. Realizing a single crystal cell is more expensive than realizing a polycrystalline cell. In the years 80s and then in the years of 90s, monocrystalline solar cells began to be produced more than polycrystalline solar cells. However, companies have started to produce more polycrystalline solar cells especially in the last decade. Polycrystalline solar cells have a bit lower efficiency, but also their production costs are also lower, by polycrystalline solar cells. However, there is another type of solar cell called amorphous solar cell, which lacks a crystal structure. Also the production price is low, but the productivity is also low [64].

Absorption: The absorption of solar cell is directly proportional to its absorption coefficient, which indicates the depth at which light of a specific energy can penetrate before being fully absorbed [65]. A smaller absorption coefficient implies that light is less easily absorbed by the material.

Factors Affecting Absorption Coefficient:

Material Composition: Materials used to realize the solar cell, has important role in determining its absorption coefficient. Different materials exhibit varying levels of light absorption [66].

Light Energy: Here the energy level of the incident light also affects the absorption coefficient. Light with higher energy levels may penetrate deeper into the solar cell before being absorbed [67].

Understanding the absorption coefficient is decisive for amending the performance of PV solar cells, as it directly encounters their ability to efficiently convert light to electrical energy. By selecting materials with appropriate absorption characteristics, solar cell manufacturers can enhance their overall efficiency and effectiveness [68].

Bandgap Energy: In a semiconductor material, E_{gap} , is the minimum energy difference between the valence band's energy and the conduction band's energy. This parameter is crucial because the bandgap energy ought to be less than the photon's energy which the material will be exposed [69].

Important points about Bandgap Energy:

The bandgap energy determines the types of photons that a semiconductor material can absorb and utilize for energy conversion in photovoltaic devices [69].

Direct vs. Indirect Bandgap: Types of the bandgaps: direct and indirect.

Understanding the bandgap energy and its type is essential for designing efficient photovoltaic materials, because it affects their ability to absorb and convert light energy into electrical energy right away. By selecting materials with suitable bandgap energies, researchers can optimize the efficiency of PV solar cells and other PV devices [70].

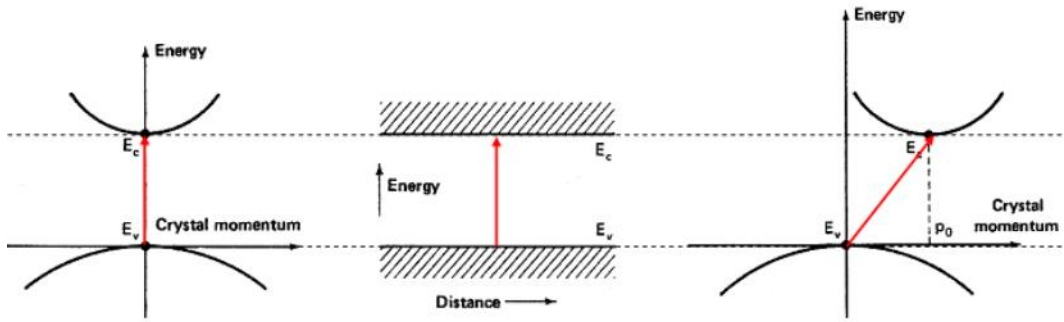


Figure 1.16. The direct bandgap and indirect bandgap [51].

Materials featuring indirect bandgaps, creation of electrons and holes pairs, relies on both photon absorption and assistance from phonons, which represent the quantum of lattice vibration within the material's crystal structure Figure 1.16.

Understanding the role between photon absorption and phonon assistance is crucial for grasping the mechanisms governing electron-hole pair generation in materials with indirect bandgaps. Such comprehension is necessary to maximize solar devices' performance and efficiency for utilizing these materials [71].

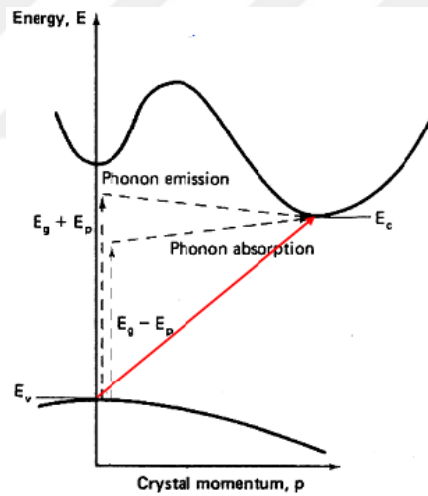


Figure 1.17. Indirect bandgap and phonon assistance [51].

Figure 1.17 provides a typical interpretation of how phonon assistance operates. It demonstrates that when E_p is higher than E_{gap} , phonon emission occurs, while phonon absorption takes place [72].

Table 1.1 provides the bandgap energy values, measured in eV, of some materials used in photovoltaic technology

Table 1.1. Bandgap Values given with the Type of some Semiconductor Materials.

Semiconductor Material	Bandgap E_g	Indirect / Direct
c-Si	1.12	Indirect
GaAs	1.424	Direct
InP	1.35	Direct
A-Si	1.8	Direct
CdTe	1.45 – 1.5	Direct
CuInSe ₂ (CIS)	0.96 – 1.04	Direct

Complexity of manufacturing: In commercial solar cell production, the intricacy of the manufacturing process holds significant importance.

Throughout the evolution of photovoltaic technology, three primary techniques have been predominantly employed for solar cell manufacturing [73]. The first involves producing ingots and subsequently cutting them, which is cost-prohibitive. The 2nd method, is the ribbon method, offers economical alternative to ingot production. Finally, the third and most cost-effective technique deposits a thin coating of inexpensive substrates with semiconductor material.

1.3.2.3. The Solar Cell Structure

The primary and integral components of a PV solar cell include:

Front contact: On the upper side that faces the sun, responsible for gathering the charge. Throughout the evolution of photovoltaic solar cells, studies were made to reduce front contacts thickness. This is because larger grids tend to obstruct more light, resulting in decreased efficiency.

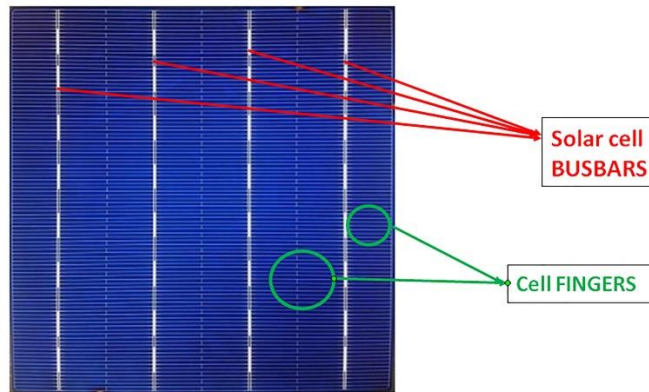


Figure 1.18. Busbars and Fingers of Solar Cell [74].

Essentially, it resembles a collection of busbars and extremely thin metal fingers on the photovoltaic cell's surface and depicted in Figure 1.18. Their function is gathering the charge while maintaining minimal thickness to prevent light blockage. Some photovoltaic cell designs omit the front contact altogether. In such cases, the top semiconductor layer possesses high electrical resistance. The optimal number of fingers must be calculated to maximize charge collection while minimizing electrical resistance losses. In earlier photovoltaic cell models like Ohl (1941), the front contact consisted of a thick layer in a square ring configuration, which proved inefficient. By the 1960s, scientists began utilizing two parallel fingers as the front contact, although this setup was inadequate for maximizing charge collection [74].

During the early 1960s, Ti/Ag was commonly employed for the front contact, later replaced by Ti/Pd/Ag. A new model emerged to mitigate light loss in the 1980s: rear point contact cells. These cells feature no contact on the front face; instead, both contacts are situated on the rear face [51].

An alternative technology for the front contact involves employing a Transparent Conducting Oxide layer (TCO), such as tin oxide (SnO_2), instead of the metal fingers of the grid. This approach has benefits: it is visible and eliminating shadowing issues.

Back Contact: Back contact serves as a metal contact that collects charges from the p-type layer. This is simpler than the front contact and does not pose shadowing problems.

The solar cell comprises a thick p-type semiconductor material, along with an n-type semiconductor layer that is thinner than the layer of p type. This layer's thickness is computed to ensure that light easily reaches the p-n junction level.

Antireflection Coating (ARC): Antireflection coating is essential for the solar cell, essential for achieving high efficiency. Its principal aim is to reduce sunlight reflection and maximize light absorption by the solar cell. Without ARC, the front part of the semiconductor reflects a lot amount of the light. The ARC layer significantly reduces this reflection, enhancing the solar cell's light absorption capabilities.

1.3.2.4. The Equivalent Circuit

Under illumination, the solar cell functions as a current source, meaning it generates a current, known as Photocurrent (I_{ph}) and is produced by the basic p-n junction of the photovoltaic solar cell, that is equivalently represented as a diode [75].

A voltage difference occurs between its two sides, known as the U_{OC} , when there is no load connected to the solar cell. Additionally, it generates a forward biased I through the diode. In this scenario, the current generation is depicted by a source and the generated current is shorted through a diode that flows parallel to the I source.

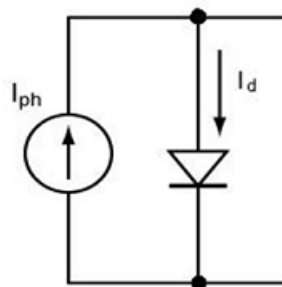


Figure 1.19. Equivalent circuit of ideal solar cell [51].

Figure 1.19, the current source, where current generation occurs, which parallel to current source, a diode represents the way through which the I generated is shorted.

If connected, the current lowers the voltage across the cell by causing a drop in V across it. Also this voltage drop in the solar cell occurs due to the current being shorted through the diode.

When holes and electrons flow through the bulk material, resistance emerges in series with the load, represented by a series resistor connected to the external load.

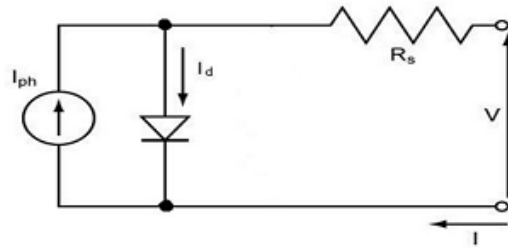


Figure 1.20. The serial resistor R_s [51].

Figure 1.20, R_s illustrates the bulk materials resistance and the resistance between the bulk material and the metal contacts.

There is also a recombination process where electron-hole pairs, although initially separated, recombine before reaching the external load. This phenomenon can be drawn as an equivalent circuit. While the photocurrent represents the total number of formed electron-hole pairs, a portion of these pairs recombine before reaching the load. Consequently, after the diode, some do not reach the load; instead, they are shunted by a shunt resistor. The recombination of these pairs before reaching the load is symbolized in the equivalent circuit by R_{sh} . Figure 1.21 shows the equivalent circuit, with R_{sh} shown in parallel to the diode.

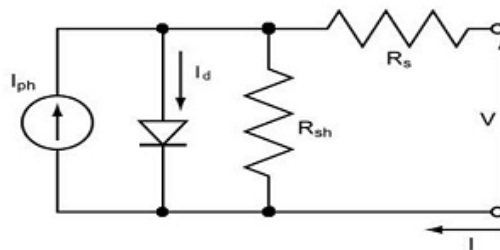


Figure 1.21. The full equivalent circuit [51].

1.3.2.5. The Characteristic Equation

Despite having the equivalent circuit, understanding the relation of V and I on the external load is essential for advancing photovoltaic applications [76]. The characteristic equation delineates this relationship, though simplifying it often involves disregarding the shunt resistance due to its negligible impact.

It is possible to solve this equation to find the operational current for the operating voltage (I) for a particular voltage (U). However, it can be solved numerically. When no load is connected, a solar cell's output voltage, or U_{OC} , reaches its maximum. The greatest U_{OC} of photovoltaic solar cells is observed at zero output current.

The saturation current, in turn, is contingent on recombination processes within the solar cell, rendering the U_{OC} a gauge of recombination levels.

$$I = I_L - I_o \left\{ \exp \left[\frac{V + JR_S}{nV_T} \right] - 1 \right\} - \frac{V + JR_S}{R_{SH}}$$

1.3.2.6. The Current Voltage Characteristic Curve

The I-U curve illustrates the bound between I and V in the photovoltaic solar cell, providing insights into their interplay. The complete characteristic equation is employed to generate this curve.

While the structure of this full characteristic equation is intricate, The output V and I have a non-linear relationship. By substituting the output voltage with the short-circuited circuit value about this equation, the I_{sc} density is obtained, which is pointed on y-axis of I-U curve. This short-circuit current density varies with solar radiation because the output voltage always remains zero.

Figure 3.13 illustrates the I-U characteristic curves for a multicrystalline solar cell under different solar radiations (AM1.5) and temperatures (25 °C). A clear indication that the short-circuit value undergoes more significant changes than the U_{OC} for the same solar radiation. Additionally, the curves' red points show the MPP for the solar cell corresponding to specific solar radiation levels. The I-U curve serves as a crucial representation of a solar cell's characteristics. Additionally, the location of any point on this curve depends on the load is termed the operating point, offering insights into the relation between current and voltage for that point. In essence, the I-U curve of ideal solar cell mirrors the diode characteristic curve in the dark, shifted along the current axis by I_{ph} [77].

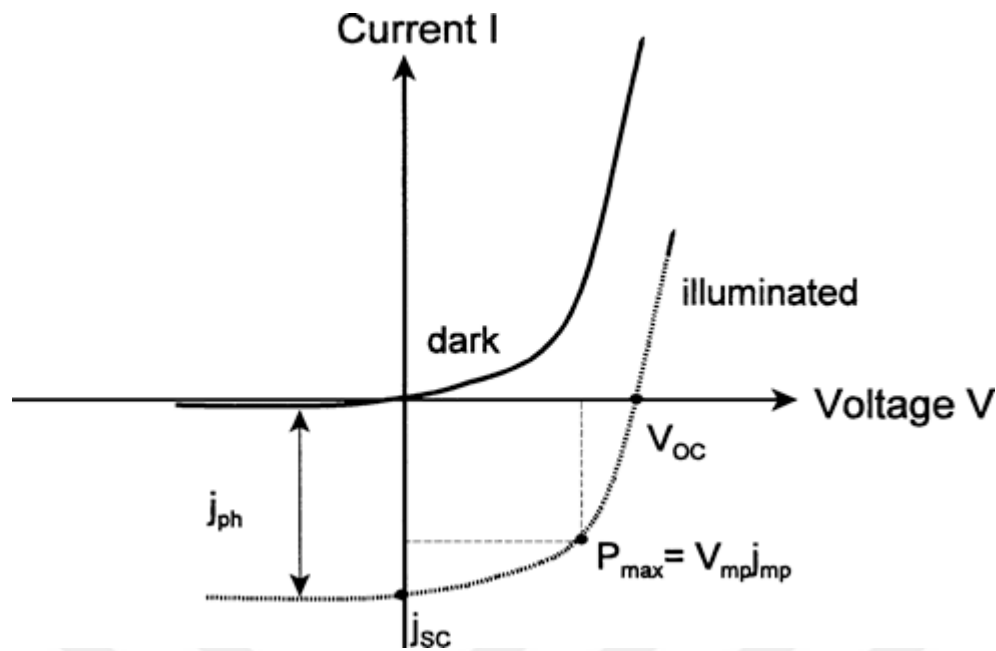


Figure 1.22. I-U curve of PV solar cell in dark and solar cell under illumination [78].

The relationship between the diode's and a solar cell's curves is shown in Figure 1.22. When a photovoltaic solar cell is illuminated, the I-U curve is shown with the bold line; when it is dashed, the I-U curve is illustrated with a dashed line. Also the value of I_{ph} is demonstrated by how these two curves differ at the same voltage [79].

1.3.2.7. The Power of Solar Cell and MPP

In Figure 1.23, a significant contrast is observed between I-U characteristic curve of photovoltaic solar cell under illumination and solar cell in darkness, primarily due to I_{ph} . The figure highlights three different places: 2 in the blue-marked regions and one in the red labeled area. In the blue-marked zones, both V and I flow in the same way and results a power consumption, akin to a photodiode. Conversely, in the red-marked area, the current and voltage exhibit opposite directions, signifying power generation, characteristic of a solar cell [51].

The solar cell's power supply is a multiplication of the I and V at the operating point [80]. When the operating point is situated near to the I_{sc} density or the U_{oc} point, the resulting area is minimized, leading to reduced power output to the load.

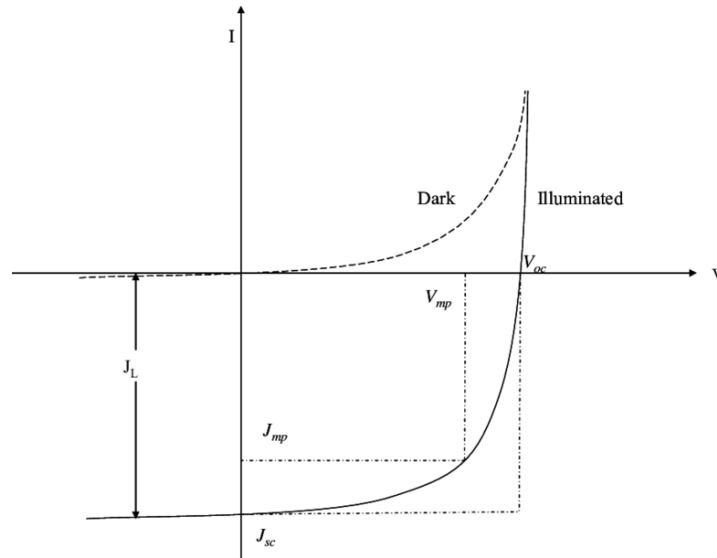


Figure 1.23. Generation consumption of power by the I-U curve [81].

The power reaches to zero at two specific operating points. First instance happens at the I_{sc} density point, where there is I but no V , resulting in a zero product and hence zero power. Similarly, at U_{oc} point, there exists voltage but no current, yielding another zero product and zero power. Consequently, the curve exhibits two minimum points, necessitating a presence of maximum point known as the MPP. At this juncture, the multiplication of I and V attains its maximum value, thereby giving the load the most power possible. I value at MPP is denoted as the Maximum Power Current Density (I_{mp}), while the voltage value is termed as Maximum Power Voltage (V_{mp}). In Figure 1.24, the maximum W of the solar cell is drawn within the yellow-marked region. Positioned between the 2 minimum values of this curve, the MPP represents the multiplication of I_{mp} and V_{mp} .

To optimize system efficiency, it's crucial to carefully select loads that ensure the solar cell operates close to the MPP. The solar cell's performance is straightforward and highly significant.

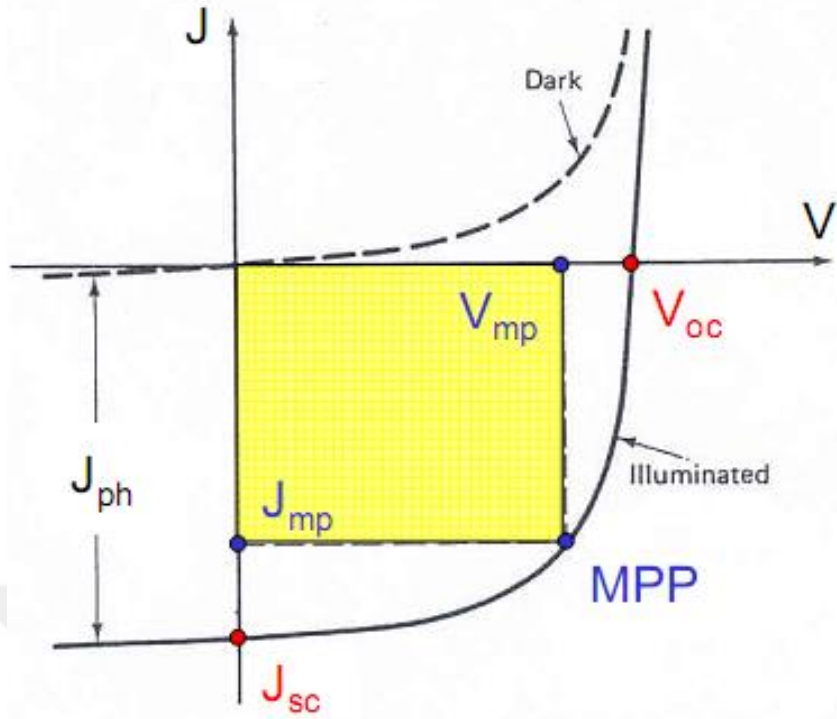


Figure 1.24. Maximum Power Point of Solar Cell [51].

Figure 1.25 illustrates that changes in current are more than changes in voltage. Moreover, fluctuations in solar irradiation through the day also impact the MPP.

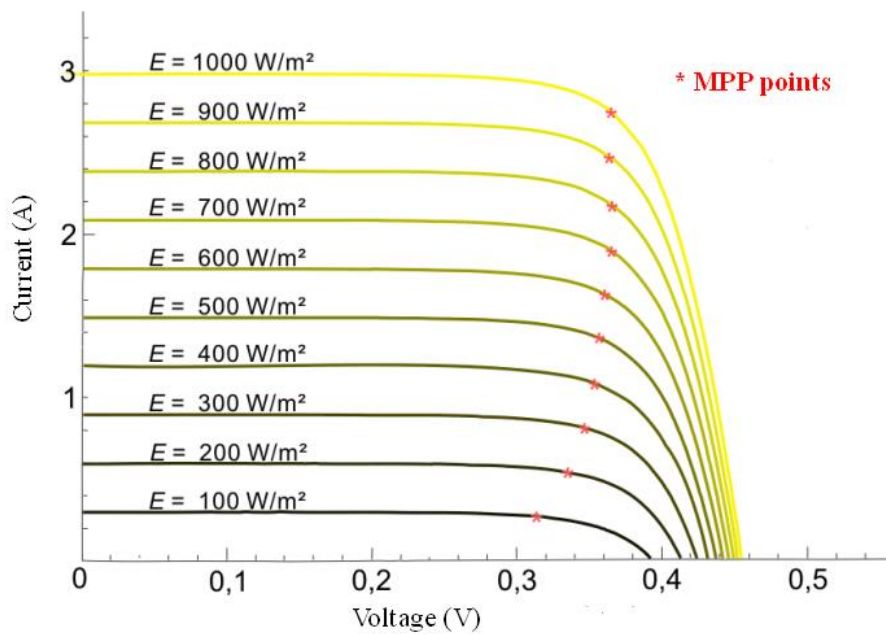


Figure 1.25. Maximum Power Points under different solar radiation values [4].

1.3.2.8. The Fill Factor

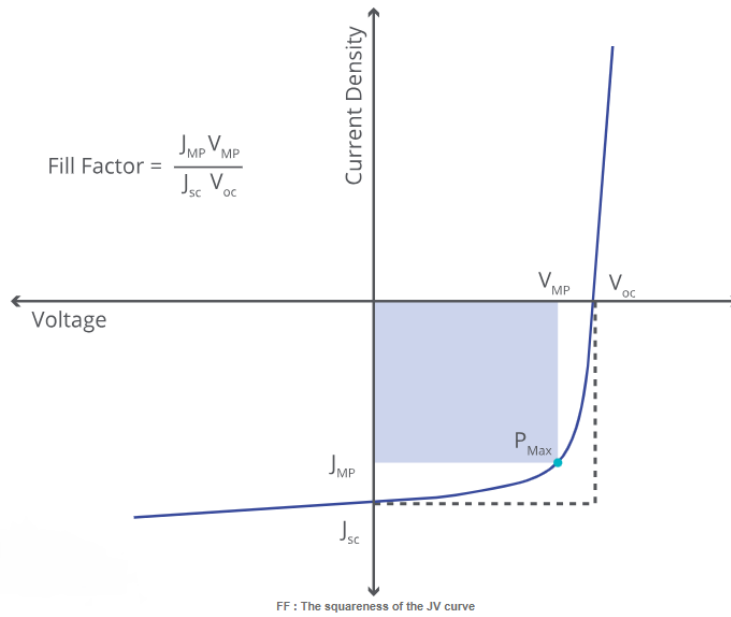


Figure 1.26. Fill Factor of Solar Cells [82].

Because it clarifies the special characteristics of a PV cell, the fill factor is very important. Fill factor is often referred to as a representation of the squareness of the IV curve, as depicted in figure 1.26.

You must divide a cell's maximal power output by its actual power output in order to determine the fill factor. You can use this measurement to evaluate how well your solar cell is working. Because they are more efficient, solar cells with a greater fill factor are more sought after [82].

The characteristic curves of solar cells, also when they share same U_{oc} and I_{sc} density, can vary, leading to different fill factors. Hence, it's insufficient to rely only on the values of U_{oc} and I_{sc} density; understanding FF of solar cell is essential for specific applications.

1.3.2.9. The Series and Shunt Resistance

Characteristic curve of a PV cell is influenced by both R_s and also by R_{sh} . This results in the current-controlled characteristic curve beginning to decline from the origin, bringing a decrease in the load V and a low reduction of I_{sc} density. The I_{sc} density decreases with increasing series resistance, suggesting that series resistance is dominant and that the photovoltaic solar cell behaves similarly to a resistor [77]. The

series resistance should ideally be less than $0.5 \Omega\text{cm}^2$ [83]. Figure 1.27 shows how the I-U curve is affected by series resistance.

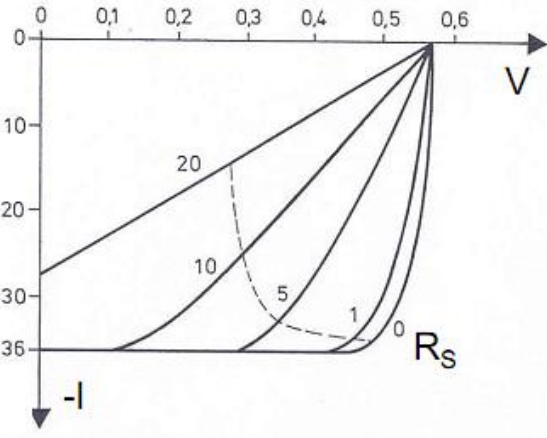


Figure 1.27. The I-U curve and series resistance [51].

The I passing through the shunt increases as the shunt resistance falls. The voltage-controlled characteristic curve then begins to decrease from the origin as a result, bringing to decrease in I and a few reduction of the U_{OC} . Lower values of shunt resistance brings to a decrease in the U_{OC} , causing the solar cell to behave more like a resistor [77]. The impact of R_{SH} on I-U curve is clearly depicted in Figure 1.28 [83].

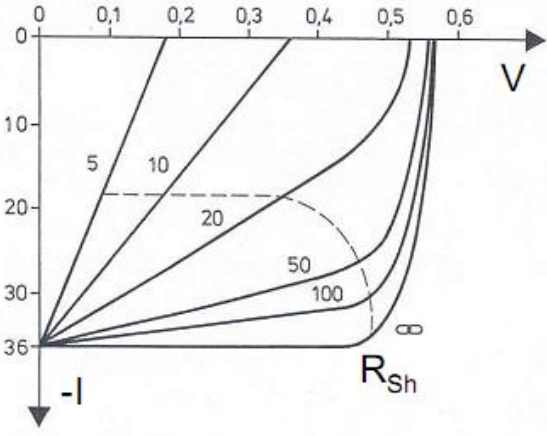


Figure 1.28. The I-U curve and the shunt resistance [51].

1.3.3. Fundamentals of Thermoelectrics

This chapter informs about fundamentals of thermoelectrics, The Seebeck effect and then Peltier effect and also Thomson Effect. This chapter later gives information about different thermoelectric materials and their characteristic information.

The main driver of improved thermoelectric performance is the advancement of physical and chemical theories [84]. The foundations of thermoelectric technology is explained, goes further with introducing the Peltier and Seebeck effects before outlining the mechanism of direct heat-to-electric conversion from the standpoint of how charge carrier distributions in thermoelectric materials are impacted by the electrical potential and temperature gradient. Simulations of thermoelectric properties are then shown using the developed equations of thermoelectric properties, indicating the significance of controlling carrier concentration in improving thermoelectric performance [84].

Research on thermoelectricity focuses on the direct coupling of heat and electricity in a solid-state material [85-86]. Thermoelectric (TE) devices are appealing as heat engines or heat pumps because of high power densities, scalability, durability, low maintenance requirements and absence of moving components [87]. They need to become more efficient in order to compete with alternative energy conversion technologies on a high scale and be widely used outside of a few specialized applications. Also it became clear that thermoelectric materials offer the highest potential for increasing conversion efficiency [87].

Thermoelectric qualities are determined by properties of electrons and phonons, whose mean free pathways vary from nanometers to microns [88]. Nanostructures of this length scale or less can significantly affect electron and phonon transport and enhance thermoelectric properties if constructed properly.

This introduces the Seebeck and Peltier effects and provides an overview of the current state of the art in the field and the basic thermoelectricity equations [89]. The synthesis of thermoelectric nanocomposites will be discussed. As a real function of the temperature, the three thermoelectric characteristics are often tested separately. The explanation of thermoelectric characterisation methods will highlight the pressing necessity of device measurements.

1.3.3.1. Thermoelectric Effect

A solid state energy source called thermoelectric power generation uses electrons as a working fluid to transform heat into electrical power [90-91]. It doesn't make noise [92], has no moving parts and is eco-friendly [93]. The Seebeck effect and Peltier

effect and also Thomson Effect [94], which are explained below, are its three main components.

An electrical potential difference is created when a material experiences a temperature differential; entropy and heat are also transferred when a substance is subjected to an electrical current. The Seebeck effect and the Peltier effect, which bear the names of the scientists who initially noticed them, are two examples of thermoelectric effects. Charge carriers like electrons and holes are also entropy and heat carriers, which is the basic physics explanation for thermoelectric phenomena [95]. As conclusion, heat transfer and current flow are related phenomena, it will be covered in brief in the next two sections..

1.3.3.1.1. Seebeck Effect

Thermocouples have long employed the Seebeck effect to measure temperature. Metals or metal alloys are used to make conventional thermocouples. They produce tiny voltages in response to a temperature differential that is applied. Thermoelectric power conversion makes use of the same Seebeck effect. An electrochemical potential difference (ΔV) proportionate to the temperature differential will form when a material has zero electrical current and a temperature gradient [96]. The proportionality constant between the generated electric potential and the temperature gradient is known as the Seebeck coefficient.

Although all materials have the thermoelectric effect in theory, semiconductor materials are now the best thermoelectrics. Simply charge carriers are what causes the Seebeck. Hot carriers move and disperse more quickly than cold carriers because they have more kinetic energy, velocity. Charge carriers build up on the cold plate side of a temperature gradient, producing a Seebeck voltage [97].

1.3.3.1.2. Peltier Effect

One element of the heating and cooling action that happens when two dissimilar materials come together is the Peltier effect [98]. Changing according via the flow direction, a junction between 2 conductors may heat up or cool down when current passes through it.

1.3.3.1.3. Thomson Effect

Thomson effect, or the development or absorption of heat, happens when a single-material circuit is subjected to electric current with a temperature differential along its

length [99]. The common heat production linked to electrical resistance to currents in conductors is overlaid on top of this heat transmission.

1.3.3.2. Thermal Conduction

Lattice waves and the random diffusion of electrons are the physical causes of thermal conductivity. Lattice waves, also known as phonons, are a quantum mechanical manifestation of vibrational motion in crystals. Vibrational interactions between atoms send some of their energy to their closest neighbors. The material's thermal conductivity and temperature gradient affect the transfer rate. The atom-to-atom connection in a crystal can be thought of as a mechanical spring that uses elastic phonon dispersion to transfer some of its heat energy. In essence, the material stores energy in its crystal structure by producing acoustic waves, the thermal capacity of which is dependent on the higher frequencies of these waves [100].

High energy free electrons transfer energy from a place of material to the other by diffusing across it from the hot plate side to cold plate side, much like thermal convection does [101].

1.3.3.3. Thermoelectric Materials

Because of their extremely poor efficiency, TE materials have only been used in thermocouples for temperature monitoring since their development. Only in the 1960s did pertinent research on thermoelectric semiconductors lead to the development of other power production and refrigeration applications. There was only a low enhancement by the figure of merit (ZT) between the discovery of thermoelectric semiconductors and 1993 [102]. Following that date, theoretical projections indicated that employing nanostructure engineering might significantly increase the efficiency of TE materials [103].

In order to achieve greater yields, traditional bulk materials with nanostructured components were investigated and developed concurrently using contemporary synthesis and characterisation techniques [104]. Therefore, there are currently two methods to raise the ZT factor: (i) using bulk samples that contain nanomaterials and (ii) using nanoparticles directly. Also it should be known: the high sample requirements on the nanoscale make it challenging to precisely create small

(nanostructured) materials [105]. Also there are two types of thermoelectric materials: novel materials and conventional materials.

Typical thermoelectric materials consist of semiconductor alloys that have been bulk doped or chalcogenides, divided in 3 groups based on temperature range at which they perform best: SiGe for use at temperatures above 500 °C [58–60], TAGS [(AgSbTe₂)_{1-x}(GeTe)_x] and PbTe-based materials for intermediate temperature ranges (150–500 °C) and Bi₂Te₃-based materials for ambient temperature applications (<150 °C). To expand the temperature range by integrating materials with different temperature ranges in a segmented architecture is possible [106].

The most well-known is Bi₂Te₃, which at normal room temperature have a ZT near the unit. However, these materials cannot be employed in air at high temperatures because they are easily oxidized and evaporated [107]. Bismuth and Telluride are used as functional materials in nearly 70% of TE modules that are now on market [108]. The most newest researches on the formation of the Bi₂Te₃ nanostructure using different techniques and its characterisation using theoretical and analytical methodologies were recently reviewed by Mamur et al. [109]. The authors have determined that if materials, created in a nanostructure form, the figure of merit (ZT) has an increase from 0.58 to 1.16.

An excellent TE material for the applications needing mid-temperatures increases to 900 K is lead telluride (PbTe). PbTe has strong chemical strength, low vapor pressure, chemical stability and high melting temperature of 1190 K [110]. Its effective usage in multiple NASA space missions starting with Transit 4A spacecraft and Apollo missions, was made possible by its high figure of merit, which was close to 0.8. Maximum ZT values of around 1.4 for single phase PbTe-based materials and 1.8 for homogeneous PbTe-PbSe materials have been observed in recent studies provide an overview of research and development on PbTe and related chemicals, alloys and composites, as well as PbTe-based nanostructured composites [111-113].

Among the best TE materials documented, for high-temperature applications ($T_h > 500^\circ\text{C}$) are silicon–germanium alloys. They are also among the least expensive and safest thermoelectric materials. $ZT = 1.88$ at 873 K was reported by Delime-Codrin et al. [114] as significant figure of merit for nanostructured Si_{0.55}Ge_{0.35}(P_{0.10}Fe_{0.01}).

The complicated intermetallic cage structure of phonon-glass electron-crystal materials, as postulated by Slack [115], offers them good electrical properties like crystals while also having low thermal conductivity like glass [116]. Two relatively new material families that are commonly considered to be PGEC materials are clathrates and skutterudites [117]. Half-Heusler alloys have garnered significant interest among other TE materials because to their abundant element combinations, relatively high Seebeck coefficients and appealing electrical transport characteristics [118]. Additionally, they possess a variety of physical attributes, such as remarkable thermal stability at elevated temperatures and mechanical strength [119]. These are usually semiconductors with a complicated structure and a tiny bandgap. Best values obtained for ZT ranged from 1 to a peak value of 1.5 in the several studies that have since been reached [120-121].

Since the first discovery, a lot of work has been done to develop high-performance TE materials for energy systems first ceramic thermoelectric material twenty years ago [122]. One TE oxide that works well, is safe for the environment, essentially stable at high temperatures is $\text{Ca}_3\text{Co}_4\text{O}_9$ ($ZT \sim 1$) [123].

There is an attention in recent decades in other oxides at high temperatures without oxidizing [124].

Because of its poor heat conductivity and powerful electrical characteristics, the thermoelectric metal chalcogenide produces a raised figure of merit (ZT) when band engineering and sophisticated nanostructuring are used. Chalcogenides additionally present a wealth of opportunities for enhancing thermoelectric performance because they are simple to convert into various configurations. At 800–900 K, the greatest ZT values measured with lead selenide (PbSe) varied between 1.4 and 1.7 [125]. For Tinchalcogenides Sn (Se,Te), ZT values of 2.3 were found for single-crystal SnSe at 723–973 K [126] and nearly 1.6 for SnTe-based materials at 923 K [127]. These materials' affordability and ability to function at high and even mild temperatures is an additional benefit. Their usage in practical applications is, however, limited by their poor mechanical qualities, low thermal stability and occasionally the presence of hazardous metals (such as Pb).

Ever when conductive polymers were discovered, organic TE materials attracted a lot attention [128]. They are flexible, lightweight and suitable for room temperature

applications, frequently produced using fairly basic methods in contrast to other semiconductor-based materials. The Seebeck coefficient, low electrical conductivity and polymer stability limits their usage in TE applications, however, even if they are intrinsically poor heat conductors [129]. Nevertheless, due to the wealth of carbon resources, organic or polymeric TE materials have some advantages over inorganic TE materials, such as a relatively simple production method and the possibility of low prices. Furthermore, a rather broad use of changes in molecular architectures of certain polymers may affect physical and chemical characteristics [130]. With ZT values as high as 0.42, the characteristics of polymers and polymer-based TE composites have improved [131]. It is noteworthy that additionally, outcomes have been acquired employing the hybridization method, which entails combining all of the previously listed thermoelectric materials [132].

Since its discovery, graphene (a substance composed of carbon atoms, a crystalline two-dimensional structure) has become a deal of attention via its several unique thermoelectric and thermal transport capabilities [133]. Graphene and C_{60} clusters gained with chemical vapor deposition have demonstrated a thermoelectric figure of merit in a recent study, (ZT) of up to 1.4 [134]. Another theoretical work using a twisted bilayer graphene nanoribbon connection revealed 3 peak ZT values of 2.0, 2.7 and 6.1 at 300 K [135]. Table 1.2 gives the figure of Merits of different materials.

Table 1.2. Figure of merit for different TE materials.

Thermoelectric Material	Material	Manufacturing type	ZT_{avg}	Scenario Temperature
Chalcogenides	Bi_2Te_3	bulk	0.74	low
Chalcogenides	$Bi_{0.52}Sb_{1.48}Te_3$	bulk	1.05	low
Chalcogenides	$Bi_{0.52}Sb_{1.48}Te_3$	nanobulk	0.52	low
Chalcogenides	$Na_{0.0283}Pb_{0.945}Te_{0.9733}$	nanobulk	1.45	high
Silicongeranium	$SiGe$	bulk	0.3	high
Silicongeranium	$Si_{80}Ge_{20}$	nanowire	0.53	high
Silicongeranium	$SiGe$	nanobulk	0.22	low
Skutterudites	$CeFe_4Sb_{12}$	bulk	0.77	high
Skutterudites	$Yb_{0.2}In_{0.2}Co_4Sb_{12.40}$	bulk	0.93	high
Skutterudites	$Ca_{0.18}Co_{3.97}Ni_{0.03}Sb_{12.40}$	bulk	0.77	high
Oxides	$Ca_{2.4}Bi_{0.3}Na_{0.33}Co_4O_9$	bulk	0.13	high

1.4. Hypothesis

This thesis offers multiple hypotheses based on the study idea, regarding PV-TE hybrid systems.

1st hypothesis: By using TEG Modules as TE part of PV-TE system, this hybrid system outputs higher energy than a normal PV system.

2nd hypothesis: By using a passive cooling system to cool TEG Module, the hybrid system outputs more energy than the hybrid system without a cooling system.

3rd hypothesis: By using an (AC) active cooling method to cool TEG Module, the hybrid system outputs higher energy than the hybrid system with passive cooling system.

4th hypothesis: By using an (AC) active cooling method with a nanofluid as coolant to cool TEG Module, the hybrid system outputs higher energy than the hybrid system with an active cooling system where as coolant distilled water is used.



2. PHOTOVOLTAIC-THERMOELECTRIC (PV-TE) HYBRID SYSTEMS

Photovoltaic modules are heating up due to dark color and electrical working principle. Additionally, the MPP of PV solar cell is negatively impacted by temperature. Cooling the PV modules is required to minimize the detrimental impacts of temperature and to boost efficiency. Basic cooling methods may be used for cooling PV module, or a PV/T hybrid system can be utilized to boost the efficiency of PV module portion while simultaneously increasing overall efficiency through the employment of an additional thermal output system.

Photovoltaic modules and generators are heating up due dark color. MPP of PV solar cell is negatively impacted by high temperatures. Cooling the PV modules is so necessary to minimize adverse effects of temperature and to boost efficiency.

To understand the efficiency enhancement methods of PV systems, the previous researchs about the subject should be remembered.

This chapter also explains previous ways of enhancing the electrical performance of a Photovoltaic generator, descriptions of some PV/T systems. This leads into most important point about this thesis: the PV-TE Hybrid system. Essential information about thermoelectrics is provided.

2.1. Simple PV Cooling Methods

In earlier research, the photovoltaic modules were cooled using basic cooling systems to boost the PV system's efficiency.

For small photovoltaic systems, the energy required for cooling exceeds the energy difference obtained from cooling the system. Some options are used for cooling tiny systems without requiring any electricity. The PV system should be exposed to the wind if it is mounted on a roof. To get it another way, there must be no obstructions such as metal or building elements between the PV system and the wind direction. The system may also be installed above a water tank. And this tank can be the building's or residence's drinking or municipal water tank. The city water tanks in

Turkey, for instance, are appropriate for this kind of system. However, because of the rust, it needs to be done cautiously. Along with improving the PV system's efficiency and reducing its temperature, such a system is going in order to raise the tank's water temperature and provide somewhat warmer water to the building's occupants.

There are some experiments done by Prof. Krauter in Berlin and in Africa about this subject. For example TEPVIS(Thermal Enhanced PV with Integrated Standing) shown in the figure 2.1, having a water tank which is used as mounting part and also used to cool the PV System. This system showed an energy gain up to 12% [136].

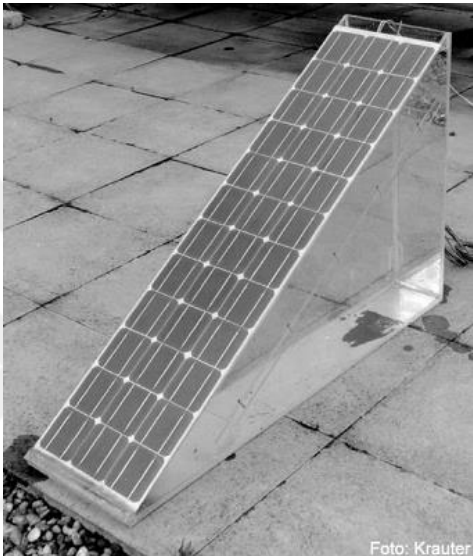


Figure 2.1. TEPVIS with a gain in electricity yield of 11.6% [136].

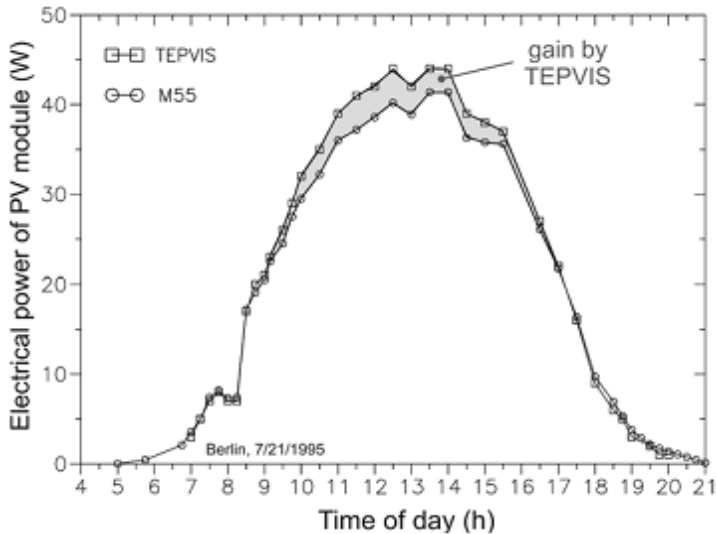


Figure 2.2. Power output of TEPVIS vs. conventional PV module [136].

The figure 2.2 shows us the output gain of TEPVIS. The electrical power in the figure of TEPVIS and the normal PV module is compared to the time of that day. Also it is

evident that TEPVIS is more beneficial during the midday hours when temperature is at its max. At that time because the high outdoor temperature is and the falling radiation more is the temperature by the PV module increases and with the cooling system of TEPVIS the efficiency increases [136].

2.2. PV/Thermal Systems

The PV module's cooling may be done by using simple cooling solutions or the PV/T hybrid system may be used to get higher efficiencies from PV module part and also increase the total efficiency by using an extra thermal output system.

PV/Thermal systems (PV/T) are hybrid photovoltaic/thermal devices. PV part of the hybrid system turn the solar energy into electrical power. also the other part is used to bring the heat of the PV part away from the hybrid system or use the heat as a second energy source. The main idea for the PV part is that, by increasing the energy output by thermal way, also the temperature of the photovoltaic part declines and the photovoltaic component's efficiency rises.

There are mainly 4 different PV/T systems:

- **PV/T Air Collectors**

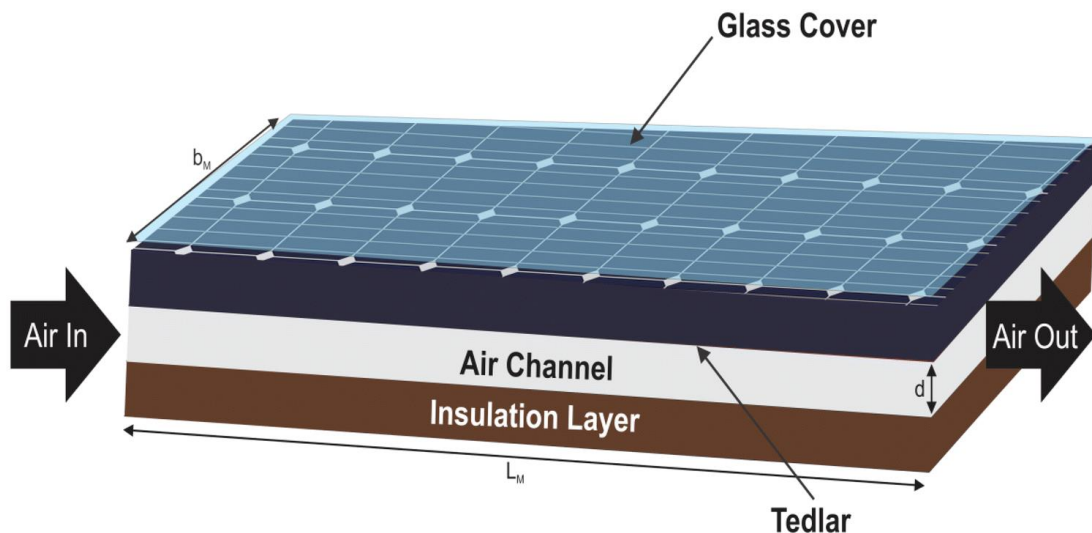


Figure 2.3. The PV/T air collector [137].

These collectors are like traditional underflow air collector with photovoltaic laminate used as top of air tunnel. Figure 2.3 there is a cross section of PV/T air collector is depicted [137-138].

- **PV/T Liquid Collectors**

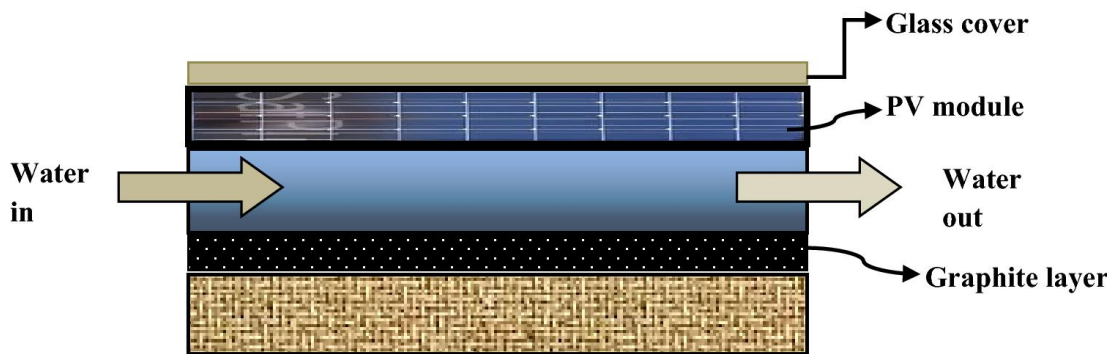


Figure 2.4. The PV/T liquid collector [137].

These collectors are like traditional flat plate liquid collectors that have an absorber with a serpentine tube and a photovoltaic laminate covered. In the figure 2.4 PV/T liquid collector may be seen.

- **Ventilated PV With Heat Recovery**

In the normal PV modules used on roofs or facades, there is an air gap at the rear side to cool the PV module. If this opening is linked to structure and hot air that heats it, then this is a ventilated PV with heat recovery.

- **PV/T Concentrators**

If reflectors are used lot to directly focus the light to the cells then these cells will reach to high temperatures. And they must be cooled. By the active cooling this heat may be used.

2.3. The Structure of Photovoltaic-Thermoelectric (PV-TE) Hybrid Systems

One viable option for thermal energy harvesting is a thermoelectric (TE) module. The temperature differential between the module's two sides determines its capacity to produce electrical energy directly from thermal energy. A TE generator can be incredibly dependable and absolutely silent while it is a solid-state apparatus devoid of moving components. It can generate electricity for many years. However, in nonconcentrated solar energy technologies, the current TE modules have low conversion efficiencies and are rather costly. A new kind of solar energy technology may be made possible by emerging nanotechnology in TE cells.

By utilizing TE generators to capture the heat released by photovoltaic cells, solar energy conversion may be improved. It is actually commonly known that photovoltaic cells only effectively convert photons at the frequency that matches the energy gap of the component or components they absorb. Larger photons partially transform their energy into heat, which determines the cell temperature, but smaller photons are actually not absorbed. Thus, in theory, such heat might be recovered and turned into energy using TEs.

Combining photovoltaic (PV) module with thermoelectric (TE) module into PV-TE systems has demonstrated promise for increasing solar spectrum utilization, increasing overall power output and lowering the area needed for PV power plants. The features of a realistic PV-TE system model are covered in this work. Usually, a large temperature differential is created across the TE module utilizing a variety of heat removal ways to enhance power of the TE component. These cooling methods may also boost the PV component's performance added to increase the TEG module's efficiency.

The Peltier and Seebeck phenomena of TE materials allow the heat to convert into electrical power. An unconventional power sources being actively sought in research is a TEG, which immediately transforms a part of heat absorbed into electrical power. An n-type semiconductor element with a p-type semiconductor element make up the fundamental unit of a TEG.

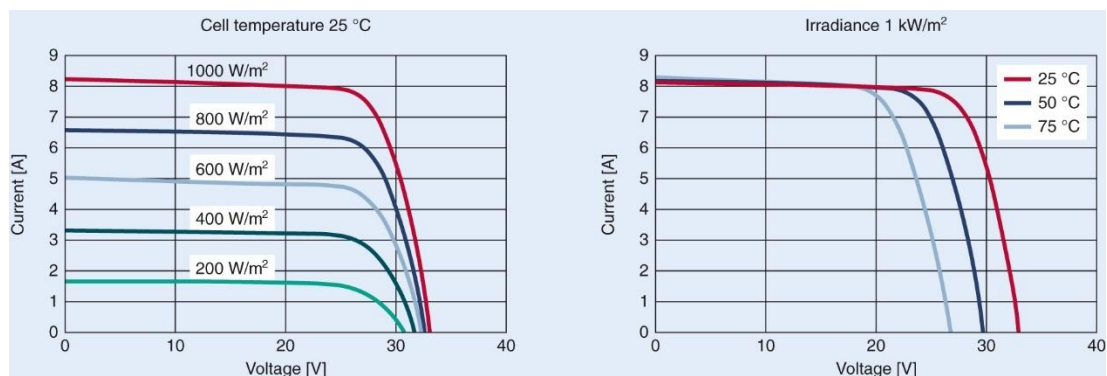


Figure 2.5. The I-U characteristic curves under different solar radiations and temperatures [51].

Figure 2.5 illustrates that compared to the current change, the voltage change is smaller. And the changing Solar Radiation during the day also effects the MPP too.

The main idea of PV-TE systems from one side the temperature of PV subsystem is going to decline and the effectiveness of this subsystem will increase and from other side the TE subsystem is going to produce electricity.

2.3.1. Theoretical modeling of the system

Figure 2.6 depicts a schematic of such a PVTE system, with the two blocks standing in for the PV and TE modules. The second block transforms the thermal energy which is produced in the first block into electrical power. Since improving TEG's efficiency is the main goal to enhance Thermal flux and temperature distribution in TEG must be evaluated for the PV-TE hybrid system to be functional.

It is logic to think of these components independently since the effects that lead to current can be viewed as independent of one another. In actuality, there is minimal effect on the performance, even if TE module is incorporated into solar panel posteriorly and utilizes modules rear temperature.

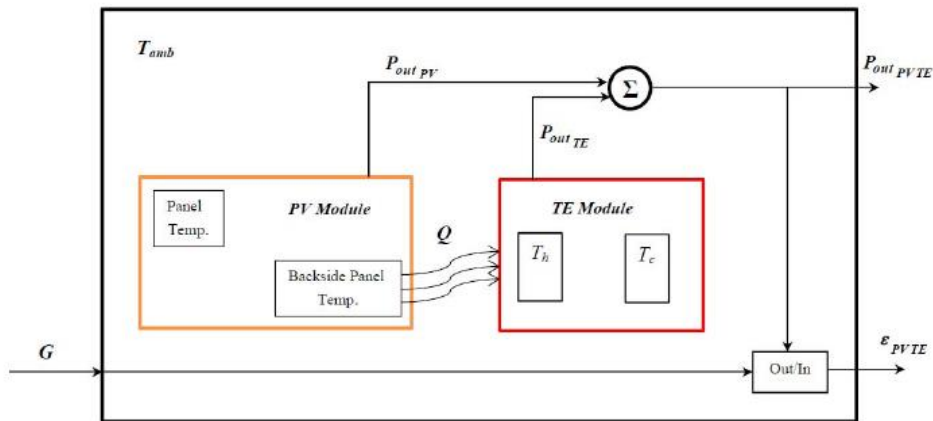


Figure 2.6. PV-TE hybrid system representation [202].

The system uses solar radiation as an input and then total amount of electricity it generates as an output while operating at room temperature. The PV module temperature can increase to 50 °C –60 °C degrees with high solar irradiation and it deviates from ambient temperature by roughly 30 °C –40 °C degrees (T). These figures vary depending on the location, integration type and time of year. The PV module temperature, which is influenced by incident light, operating conditions and installation parameters, was calculated using the following relationship [139]:

$$T = T_{amb} + c \cdot G$$

being c ($\text{K} \cdot \text{m}^2/\text{W}$), a coefficient depends on the PV panel's installation circumstances and G (W/m^2), the irradiance. For roof PV panels integrated, the values of c are $0.058 \text{ K} \cdot \text{m}^2/\text{W}$; for roof tops with short roof-module distances ($<10 \text{ cm}$), they are $0.036 \text{ K} \cdot \text{m}^2/\text{W}$; for roof tops with wide roof-module distances ($>10 \text{ cm}$), they are $0.027 \text{ K} \cdot \text{m}^2/\text{W}$; and for free standing, they are $0.020 \text{ K} \cdot \text{m}^2/\text{W}$.

T_{amb} is the ambient temperature.

Performance of complete system should be described using both generated electric power and total system efficiency, demonstrating how the characteristics of material being utilized affect them as well as outside variables like temperature and radiation.

There are two plate sides on the TE modules. The hot plate side of PV-TE systems is the side that is connected to the PV module; the cold plate side is the other side. In the most basic PV-TE systems, the cold side, which is unconnected to any equipment, merely releases heat into the atmosphere, while the hot side absorbs heat from the PV component. A functioning PV module's back side and the surrounding air have a temperature differential of about 25 to $30 \text{ }^\circ\text{C}$. In a relatively warm environment, the TE module's cold plate side heats up rapidly, possibly reaching the hot side's temperature.

The theoretical conversion efficiency of TEGs is:

$$\eta_{\text{max}} = \left(\frac{T_{\text{H}} - T_{\text{C}}}{T_{\text{H}}} \right) \frac{\sqrt{1 + (zT)_{\text{avg}}} - 1}{\sqrt{1 + (zT)_{\text{avg}}} + \left(\frac{T_{\text{C}}}{T_{\text{H}}} \right)}$$

where T_{C} cold side temperature and T_{h} hot side temperatures and the average figure-of-merit for thermoelectric (TE) materials is $(zT)_{\text{avg}}$. Additionally, ZT is a dimensionless component that depends on materials and is defined

$$zT = \frac{\sigma S^2}{\kappa} T$$

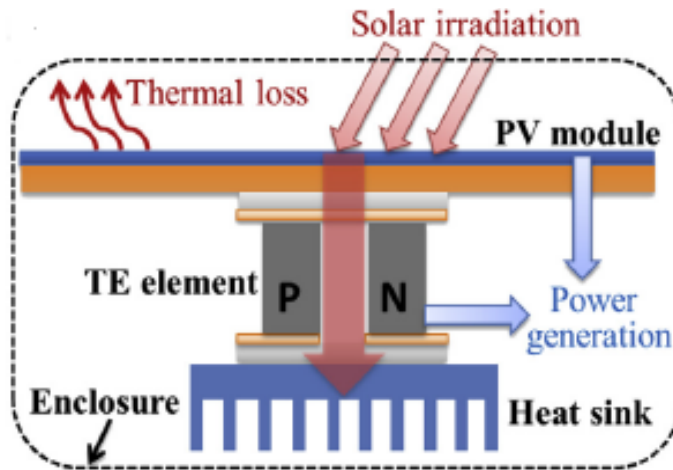


Figure 2.7. Schematic of PV-TE hybrid system [140].

In figure 2.7 schematic of PV-TE hybrid system with passive cooling system is shown. Heat energy produced by heat of PV part which is a combination of non used photon heat and heat which is caused by the temperature increasing of PV part is transferred to the TE part of the system.

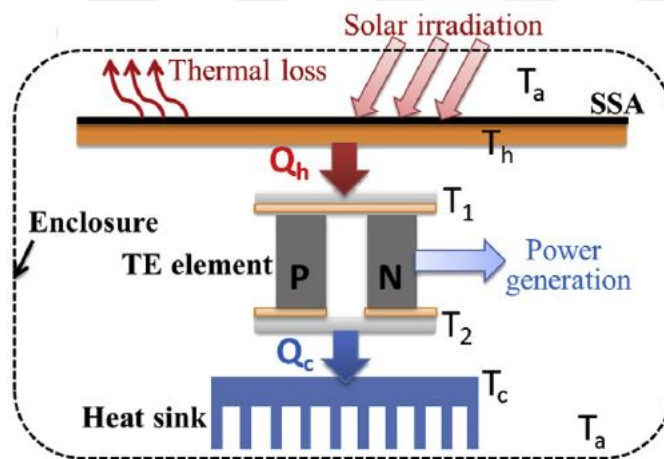


Figure 2.8. Heat flux and temperature definition of PV-TE hybrid system [140].

In figure 2.8, heat flux system and temperature definition in an enclosure is shown. The heat energy given to TE part from PV part makes a temperature differential between thermoelectric generator's cold plate side and hot plate sides. And the thermoelectric generator converts this temperature difference to electricity.

By using a heat sink which is stuck to cold side of thermoelectric generator, a higher temperature difference may be created. A higher temperature difference enhances the efficiency of the TE part and also complete PV-TE hybrid System.

Analyzing the interaction between the optical features of PV absorbing material and the optimum TEG to be coupled to it appears to have received little attention, despite the stated current research on coupling PV and TE conversions. Optimizing TEG thermal resistance may also contribute to hybrid device's increased overall efficiency, as thermal matching of TEG is known to control its output power [141].

The two potential HTEPV device implementations that will be examined are the effect of an additional absorbing layer converting into heat in the region of the sun spectrum with photon energies lower than E_g and a straightforward coupling between the PV cell and its TE part, in which the TEG only converts the heat produced by thermal relaxation of hot carriers injected by the region of spectrum with photon energies larger than E_g . In fact, we discovered [142] that in the latter scenario, the tandem device's performance might be noticeably better than the PV cell's.

2.3.2. Electrical modeling of system

Two methods to obtain the total energy using power and voltage in order to demonstrate the hybrid system's PV and TE components working together; a two-wire system, which conducts the cables for the TE and PV components. However, this is not oft used in this manner since the output power efficiency is not appropriate for this combination.

The second method uses a four-wire arrangement, which gives us varied energy from the TE and PV components. Both efficiency and research benefit from this approach. Also for laboratory researches, this is better to examine the efficiency increasing of both parts of PV-TE system.

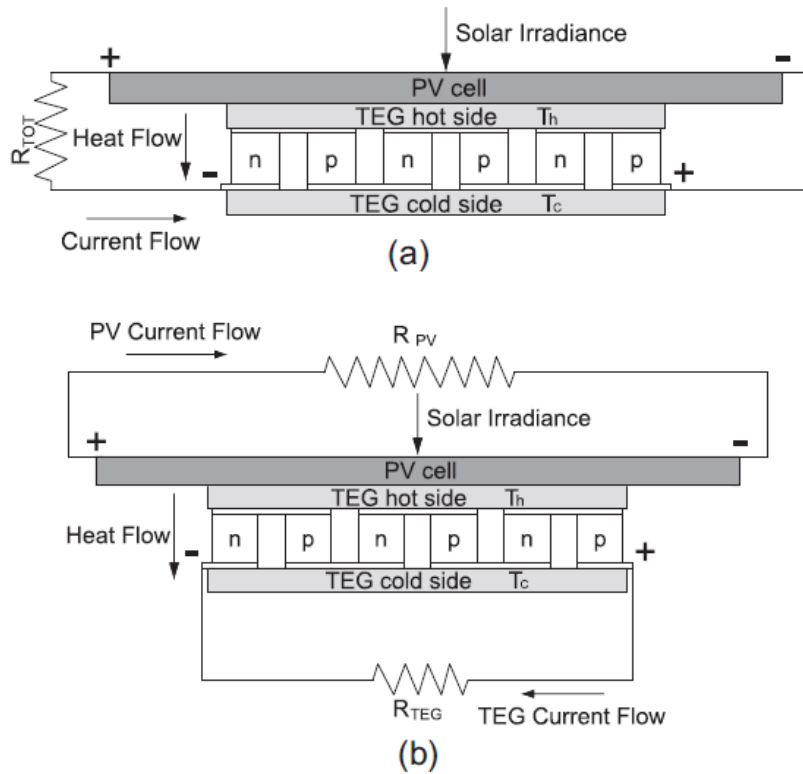


Figure 2.9. 2-Wire configuration (a) and 4-Wire configuration (b) of PV-TE hybrid system [143].

There are 2 different methods obtaining the total energy using power and V in order to demonstrate the hybrid system's PV and TE components working together. The first method is a two-wire system, which conducts the cables for the TE and PV components. However, we are unable to have a significant number of PV-TE systems in this manner since the output power efficiency is not appropriate for this combination. In figure 2.9 (a) is a 2-wire configuration of PV-TE hybrid system is shown.

The second method uses a four-wire arrangement, which gives us varied energy from the TE and PV components. . In figure 5.9 (b) is a 4-wire configuration of PV-TE hybrid system is shown. Both efficiency and research benefit from this approach. Also for laboratory researches, this method is better for examining the efficiency increasing of both parts of PV-TE System.

The total electrical power generated will be equal to total electricity produced by system by the two modules. Assuming this, the rate of electric power generated by each module to the power of input system, or how much solar energy the PV module can absorb also may be utilized to determine system's total efficiency. In this instance,

the performance of the PV and TE modules will be determined by the front face temperature (T) and the operating temperature of the TE (T_m), respectively. Both the ambient temperature (T_{amb}) and the incident solar radiation flux (G) will affect the temperature of the cells inside the PV module (T); the back panel temperature (T_h) and the ambient temperature (T_{amb}) will affect the operational TE temperature (T_m). It's important to note that heat (Q) travels from the PV to the TE module before dissipating through it. Lastly, the following losses need to be taken into account in order to maintain the energy balance:

- 1) transformation losses brought on by the PV module's conditioning circuits;
- 2) Joule effect losses in the PV module;
- 3) Joule effect losses in the TE module;
- 4) Dispersion current losses;
- 5) Convection losses.



3. EFFICIENCY ENHANCEMENT METHODS USED IN PHOTOVOLTAIC-THERMOELECTRIC (PV-TE) HYBRID SYSTEMS

The silicon solar cell PV industry has expanded quickly in recent years. However, solar energy conversion's low efficiency and the high price of high-purity silicon materials and their time-consuming manufacturing process have prevented its widespread adoption [144].

Three main approaches have been followed by photovoltaic researchers: creating novel materials, improving the usage of the sunlight for recovering energy and generating electricity from heat utilizing photovoltaic-thermoelectric (PV-TE) systems. The need for more efficient solar cells and photovoltaic systems efficacy is highlighted by the growing global population, which limits the amount of land accessible for future photovoltaic power plants. PV-TE is one notable solution to this problem. In particular, hybrid power production systems, such as photovoltaic hybrid systems like PV-TE, have grown in popularity.

A small part of sunlight that strikes the PV cell is transformed into electricity. Most of energy will be transformed into thermal energy inside the cell, which could raise the junction temperature if the heat isn't efficiently released into the surrounding air [145].

The most popular active cooling technique is photovoltaic/thermal (PV/T), which may produce heat and also energy [146-150]. As a result, it is more effective in converting absorbed solar light than a typical photovoltaic module. In order to decrease working temperature of PV modules and maintain an acceptable degree of electrical efficiency also PV/T systems can collect heat from the modules and heat water or air [151].

Furthermore, it is suggested creating a PV-TEG hybrid device by affixing TEGs to the rear of PV modules in order to utilize the thermal waste [152]. The TEG can produce more power and increase the hybrid device's efficiency due to the temperature difference between the ambient air and the PV module's back side.

A thermoelectric (TE) module is one practical choice for thermal energy collection. The module's capacity to directly transform thermal energy in electricity depends on temperature differential between its two sides. A TE generator can be very quiet and

dependable while it is a solid-state device without any moving parts. It can keep producing electricity for many years. However, in nonconcentrated solar energy technologies, the current TE modules have low conversion efficiencies and are rather costly. A new kind of solar energy technology may be made possible by emerging nanotechnology in TE cells.

One viable method of capturing thermal energy and increasing power output in PV-TE systems is to use thermoelectric generators (TEGs). TE modules use the temperature differentials between the module's plains to directly transform thermal energy into electrical power. Unlike photovoltaic cells, which rely on high-energy photons, TEGs may convert heat from lower-energy photons into electricity without increasing the cell temperature of the PV segment.

Since TE component of PV-TE system transforms this heat into electrical energy, one benefit of PV-TE system is destruction of negative influencing element of heat for PV solar cell. Utilizing solar radiation in its complete spectrum and producing more energy is possible with a PV-TE hybrid system. The development, testing and proposal of PV-TE hybrid systems aims to increase the total efficiency of solar energy. PV-TE hybrid systems have drawn increased interest and development surrounding PV-TE theory and technology [152–169]. Performance of the hybrid devices were examined both theoretically and empirically by Van Sark [152] and Wang et al. [163], who suggested using the thermal waste by affixing the TEG to the rear of PV modules for energy harvesting. A spectrum splitting PV-TE hybrid system was mentioned and developed by Vorobiev et al. [159], Kraemer et al. [170] and Xing Ju et al. [164], who also demonstrated that the hybrid system may help maximize the conversion efficiency.

To improve performance, makers of panels are currently very interested in merging thermoelectric (TE) and photovoltaic (PV) effects. Although there were limitations on the usage of TE in generation of electricity due to its low energy conversion efficiency, this technology is developing [171].

However, if the thermal input is free or waste heat to recover, TE generators are recommended. Common uses for this conversion include powering autonomous sensors, recovering energy from waste heat of electrical hot components and heating and cooling photovoltaic parts to boost their efficiency [172–175]. The most recent

uses of TE conversion in PV systems include active cooling and supplementary power generation for PV panels, both of which employ the temperature differential between T_a and the elevated panel temperature brought on by solar radiation. This figure of merit (Z) of the TE material or the dimensionless ZT_{avg} product [176-177], which is TE modules average temperature (T_{avg}), act as an illustration of a TE module's performance.

The figure of merit Z , reliant on the TE material, shows how electricity is produced from well heat energy. High electrical conductivity, low heat conductivity and a big Seebeck coefficient are necessary to maximize this value.

Bismuth chalcogenides like Bi_2Te_3 or Bi_2Se_3 materials has with maximum figure of merit for these kind of applications close to room temperature (300 K); magnesium group IV compounds are primarily favored for midtemperatures (500–900 K); silicon–germanium materials are usually employed for high temperatures.

ZT_{avg} typically ranges between 0.7 and 0.8, however materials in the market may reach values of 1; for nanostructured Bi antimony telluride bulk alloys, ZT_{avg} exceeds 1.2 [178].

3.1. Simple PV-TE Hybrid System

Simple kind of PV-TE hybrid system is normally composed of a PV part and a TE Part and has no passive or active cooling component. Figure 3.1 depicts a schematic of PV-TE system, with the two blocks standing in for the PV and TE modules. The second block transforms thermal energy of first block into electrical power. These elements can be logically evaluated independently since the effects that generate current, considered independent of another. In actuality, the impact on the solar cells' performance is negligible even if TE module is incorporated into the solar panel posteriorly and utilizes panel's rear temperature.

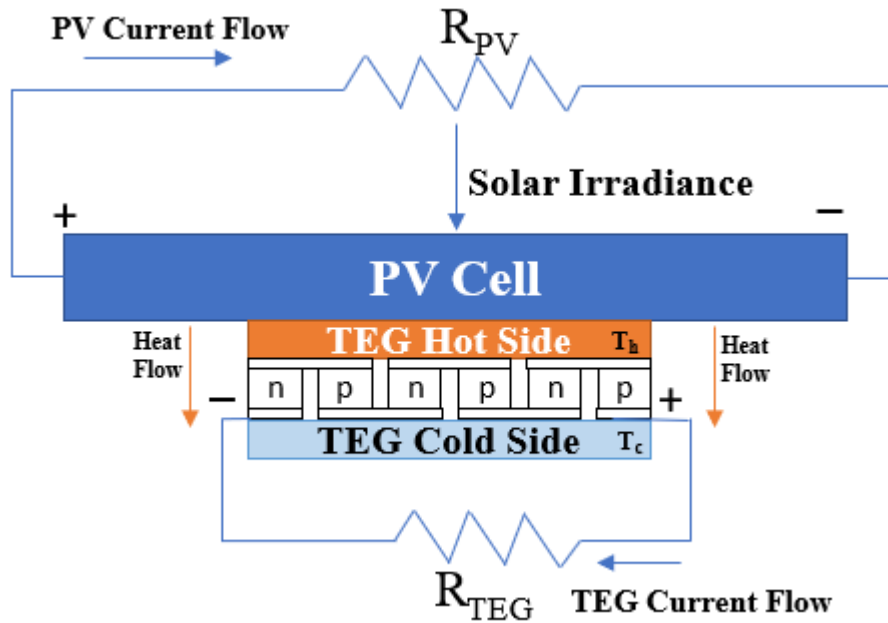


Figure 3.1. Schematic of a simple PV-TE hybrid system [179].

System uses solar radiation and heat of PV Module as an input while operating at room temperature. The PV module temperature (T_{max}), which varies by roughly 30 to 40 degrees Celsius from ambient temperature, can reach 50 to 60 degrees Celsius with high solar irradiation. These figures vary depending on the location, integration type and time of year. The equation is to determine PV panel temperature (T), that is highly dependent on incident light, operating circumstances and installation parameters [180]. The thermocouple, the simplest component of a TE module, is made up of 2 legs of distinct doped semiconductor material. These legs are of n-type and p-type doped semiconductors and joined by a metal plate, often composed of copper.

Figure 3.2 shows a generic TE module with NTE thermocouples linked parallel thermally and electrically in series. The copper contact length is denoted by h_c , ceramic plate length by h_p and thermoelements' length and cross-sectional area by h_t and Δt .

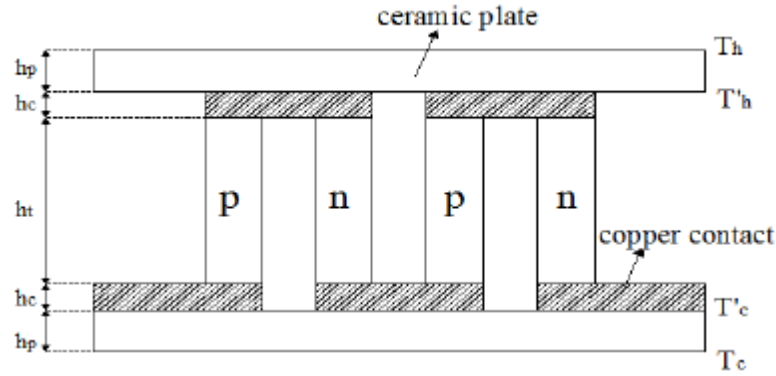


Figure 3.2. Structure of a thermoelectric module.

Thermal power produced by TE module is modeled by Peltier, Joule and Fourier effects using thermoelement geometry according to the cold plate side T_c and hot plate side T_h temperatures, as well as the material's Seebeck coefficients s , electrical resistivity ρ and thermal conductance λ [181].

TE modules provide solid-state dependability, but efficiency and affordability aren't necessarily compatible. In actuality, a less costly TE module may function better than a more costly one. Materials, operating temperatures and size all affect their price. The temperature of the PV component drops as TE module transforms heat into energy, increasing PV efficiency. In PV-TE hybrids, an active cooling system continuously cools cold plate side of TE module, improving energy efficiency. With TE module underneath PV module, the heat generated by classical PV systems—which raise backside temperature of PV modules to 25–30 °C over the ambient temperature—is immediately transformed into electrical energy, removing the environmental concern [182].

The TE component of a PV-TE system can provide electricity even in areas with lower solar radiation when it has a cooling mechanism, which makes the hybrid systems profitable and commercially feasible [183–187]. Particularly effective are PV-TE hybrid systems in areas with high levels of solar radiation [188–192].

Figure 3.2's PV-TE system architecture shows the TE module and the PV module in the upper portion. When photon energy exceeds E_{gap} of a semiconductor, incident sunlight on the PV module produces electron–hole pairs, which in turn produce electrical energy. However, because of the temperature–resistance relationship, lower-energy photons raise the module's temperature, which in turn raises its resistance. Consequently, the efficiency of the PV module is decreased. The thermal energy in the

PV module can travel to the TE module since it is directly attached to the back surface of the PV module. TEGs generate an electric potential by means of the Seebeck Effect, which occurs at the junction of two dissimilar conductors at different temperatures. Thermal energy can be converted to electrical energy by TEGs. Higher TE module efficiency must be sought using complex and diverse approaches in order to maximize the overall functionality and performance of PV-TE systems. Improvements in this area result in notable increases in energy conversion efficiency, it would improve these hybrid systems' efficacy and potential applications in a variety of industries [193–196].

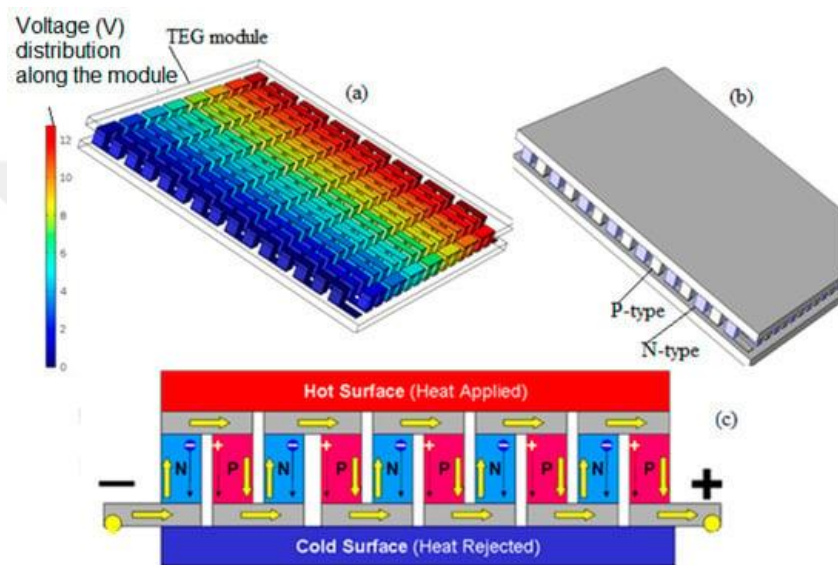


Figure 3.3. Working principle of TEG [197].

Physically, a TEG device is primarily made up of thermoelectric modules (TEMs), which feature a hot and a cold side to create a temperature differential. A typical TEG device is depicted in the a part of Figure 3.3. A TEG module is made up from arrays of semiconductors of n and p types (b part of Figure 3.3), where electric power generated by linking a heat source on hot side and a cold heat sink on the other side. Free electrons or holes in a thermoelectric material carry positive and also negative charges, if the free charges are p-type material produces a positive potential. Negative free charges will likewise result in a negative potential (c part of Figure 3.3). The TEG module consists of several semiconductor components that are thermally coupled in parallel and electrically connected in series via metal strips.

3.2. PV-TE Hybrid System With Passive Cooling System

There are 2 plate sides on the TE modules. Hot side of PV-TE systems is the side that is attached to PV module, whereas the cold side is the opposite. In the most basic PV-TE systems, cold side, which is unconnected to any equipment, merely releases heat into the atmosphere, while the hot side absorbs heat from the PV component. Normally, there is a 25–30 °C temperature differential between the back of a functional PV module and ambient air. A comparatively warm ambient temperature causes the TE module's cold side to heat up rapidly, possibly reaching the hot side's temperature. Accurate temperature control is necessary for assessing the PV-TE system.. The ambient temperature (T_a), as described above, is fixed at 25. But this doctoral research's first goal is to control the TEG's hot side temperature (T_h) utilizing continuously calibrated test apparatus from our lab. We tested TEGs at T_h values between 30 °C and 70 °C for this investigation. However, the 50 °C and 70 °C levels are crucial for commercialization, because the TE portion gets its energy from the hot and cold sides' disparate temperatures, which are connected to back sheet of PV part.

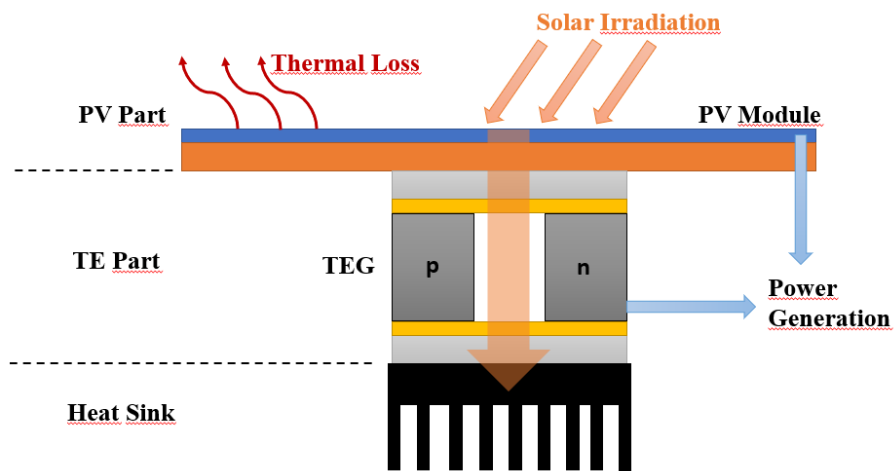


Figure 3.4. Schematic representation of a photovoltaic–thermoelectric (PV-TE) system with an integrated passive cooling (PC) system [179].

PV module's back sheet temperature is directly connected with the TE's hot plate temperature. Typically, the PV part's backside is 25–30 °C warmer than the T_a . This indicates that when the T_a is 25 °C, T_h is almost 50 °C. TEG (T_c) started from the same value as the T_a . However, a liquid having a temperature of 10 °C was supplied to test system for active cooling systems.

The next stage in increasing PV-TE efficiency is to add an aluminum heat sink underneath the TE module's cold side, as shown graphically in Figure 3.4. This method significantly improves our research by extending the time that the temperature equalization occurs on the sides of the TE module.

We chose to employ a suitable aluminum heat sink for this experiment because its dimensions matched those of the TE modules that were being used. With this method, the PV-TE system is successfully converted to a passive cooling (PC) system. In our graphical representations, the findings produced by this technology are denoted by the label "PC" (passive cooling). Our research has made progress as a consequence of this strategic endeavor. It describes the potential advantages of adding passive cooling techniques to PV-TE system in an effort to improve overall effectiveness and performance.

3.3. PV-TE Hybrid System With Active Cooling System

3.3.1. PV-TE Hybrid System With Active Cooling System with Water as Coolant

As part of our research technique, we installed an active cooling system to boost the electrical efficiency of the PV-TE system. A liquid tank holding a refrigerant with a constant temperature is set in this method. Throughout the experiment, this liquid's temperature is carefully kept at a consistent level. Flexible pipes, an aluminum water cooling block heat sink, and a liquid pump are some essential parts of the active cooling system. The plate dimensions of these parts are the same. These elements cooperate to encourage the circulation of the cold liquid, which is necessary for actively cooling the system's TE component, shown in Figure 3.5.

Our research efforts to maximize the PV-TE system's overall performance and efficiency have advanced significantly with integration of an active cooling (AC) system. We can investigate the possible advantages and complexities of active cooling through meticulously regulating the flowing liquid's temperature, that will advance the field of thermoelectric power generation. Distilled water served as coolant for AC studies throughout this stage of our investigation. The active cooling system circulates cold water having 10 °C temperature.

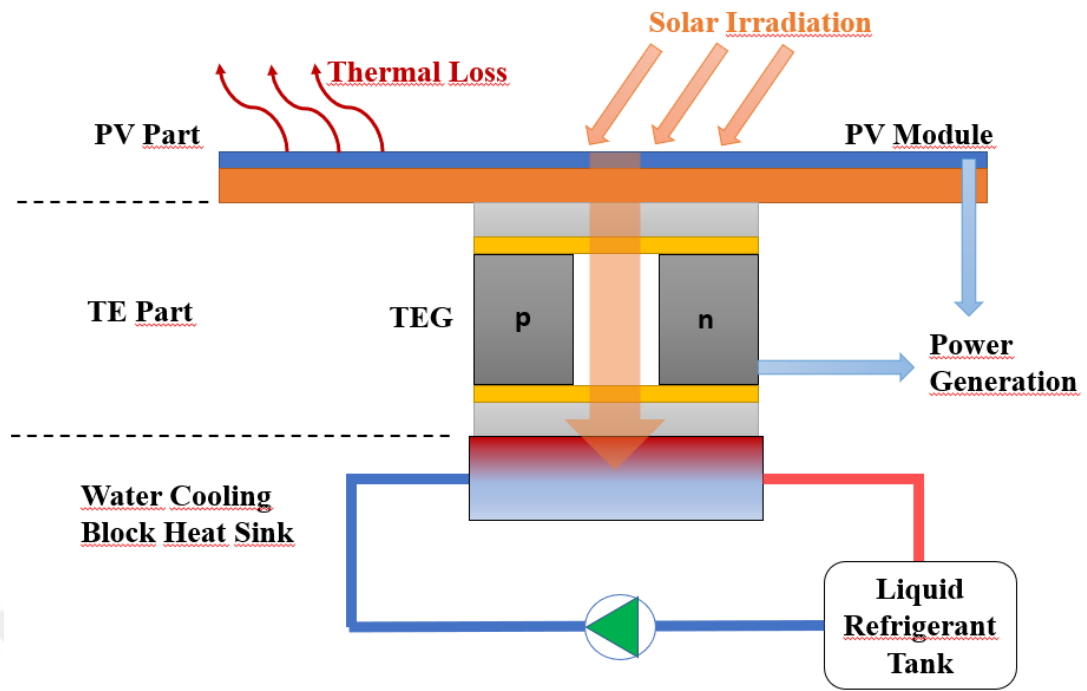


Figure 3.5. The schematical representation of PV-TE system featuring an active cooling system visual explanation of the system's configuration and the functioning of its active cooling components [179].

System increases temperature differential between TE section's cold plate and hot plate sides and TE part of PV-TE system demonstrated greater experimental efficiencies. By our graphical representations, the outcomes of this active cooling technique—which used distilled water as the coolant—are clearly identified by name "AC". This strategy has increased efficiencies in PV-TE system, which is promising and shows Active temperature dynamics control's potential benefits for thermoelectric power generation.

Also, enabling efficient temperature control could increase PVs' efficacy and lifespan. Since PV surface temperature inversely correlated with conversion efficiency, cooling of PVs as a developing field, requires consideration. One of the often used thermal management strategies to enhance performance of PVs and integrated systems is the insertion of a thermoelectric generator (TEG). The TEG produces the extra electric power production by using the waste heat from PVs.

3.3.2. PV-TE Hybrid System With Active Cooling System with Nanofluid as Coolant

Increasing the temperature differential inside the TE module by using nanofluids as a coolant is another way to increase efficiency. Our graphical representations use the term nanofluid-active (nAC) cooling to explicitly indicate the results. To achieve higher voltage, current, and power outputs, we used a Gamma aluminum oxide (Alumina, Al₂O₃) nanofluid as the coolant. More specifically, the fluid was in the Gamma phase, with an average particle size ranging from 20 to 50 nm. According to this decision, an active cooling system that uses nanofluids produces better electrical outputs than one that uses distilled water as the coolant [198,199].

A new type of heat transfer fluid called nanofluid may increase thermal conductivity and transfer heat more quickly than conventional fluids. The basic idea and theory of PV/T, thermal conductivity of nanofluid and also the practical and theoretical investigation of PV/T performance utilizing nanofluid are all covered in recent studies on the subject. Numerous research have assessed the potential of nanofluid as an optical filter and heat transfer fluid in PV/T system, according the literature. High stability and long-term homogeneity of nanofluid depend heavily on the preparation of fluid also size of nanoparticles, concentration and preparation of the nanofluid all affect its thermal conductivity.

Additionally, by our last efficiency enhancement method for PV-TE hybrid systems, using nanofluids instead of using distilled water, TE module performed better.

According to previous PV-TE research papers and our own experiments using nanofluids as coolant b PV-TE hybrid systems with active cooling systems, can be applied to optimize PV-TE system performance.

Nanofluid cooling considerably enhances the performance of photovoltaic/thermal-thermoelectric generator (PV/TE) systems compared to traditional cooling because the nanofluid allows superior thermal characteristics over conventional cooling fluids. A symmetrical temperature differential is made possible by the TEG, with a cold side brought on by the cooling of the nanofluid and a hot side from the heat from PVs.

4. EXPERIMENTAL TECHNIQUES

This study focused on enhancing performance of PV-TE hybrid systems by integrating 7 distinct thermoelectric generator (TEG) configurations with monocrystalline silicon solar cells. The investigation was conducted under four systematically designed operational conditions to evaluate and optimize system efficiency. Initially, performance of PV-TE systems was examined under baseline conditions without the implementation of any cooling mechanisms, at standard ambient temperature of 25 °C. Following this, a PC system employing aluminum heat sinks was introduced, significantly enhancing heat dissipation and stabilizing thermal management. Subsequently, active cooling (AC) systems were assessed, first utilizing distilled water as a cooling medium and later incorporating advanced nanofluids to further improve thermal conductivity and energy output. The comprehensive findings derived from these diverse testing conditions have established a critical framework for advancing the efficiency and practical application of PV-TE hybrid systems, demonstrating synergistic potential of thermoelectric integration and effective thermal management strategies.

A thorough analysis of performance of PV-TE hybrid systems was carried out for this thesis. Integrating 7 distinct thermoelectric generators (TEGs) with monocrystalline silicon solar cells under varying temperature conditions. Detailed specifications of these TEGs—including manufacturer information, total thicknesses, surface layer thicknesses, p-n junction area thicknesses, model identifiers, thermoelectric materials and plate material compositions—are provided in Table 4.1.

Five of these TEGs, designated as TEG1 through TEG5, utilize ceramic aluminum oxide (Al_2O_3) as the plate material. These devices were central to the experimental analysis and are visually depicted in Figure 4.1. Two additional TEGs employ ceramic graphite as the plate material. Specifically, TEG6, illustrated in Figure 4.2, shares the same thermoelectric material, bismuth telluride (Bi_2Te_3), as the first five TEGs, consequently, comparable evaluations based on plate material differences. The final TEG, labeled TEG7 and shown in Figure 4.3, also features a ceramic graphite plate

but differentiates itself by utilizing a thermoelectric material composed of a lead (Pb) and bismuth telluride alloy, introducing a variable in thermoelectric material composition.

Table 4.1. Features and measurements of TEGs used in the research, such as surface and p-n junction area thicknesses.

Name	Manufacturer	Thickness of TEG in mm	Thickness of Surface in mm	Thickness of p-n Junction area in mm	Model	TE Material	Plate Material
TEG1	Hebei, Shanghai, China	3.87	0.71	2.45	TEC1-12706	Bi ₂ Te ₃	Ceramic Al ₂ O ₃
TEG2	Euroquartz, Shanghai, China	3.71	0.73	2.25	SP1848 27145 SA	Bi ₂ Te ₃	Ceramic Al ₂ O ₃
TEG3	Kuongshun, Shenzhen, China	3.77	0.71	2.35	SP1848 27145 SA	Bi ₂ Te ₃	Ceramic Al ₂ O ₃
TEG4	Adaptive, Leicestershire, UK	3.59	0.89	1.81	ETH-127-10-13-S-RS	Bi ₂ Te ₃	Ceramic Al ₂ O ₃
TEG5	Marlow, Dallas, TX, USA	3.9	0.7	2.5	RC12 91826	Bi ₂ Te ₃	Ceramic Al ₂ O ₃
TEG6	TEC, Calgary, AB, Canada	3.56	0.86	1.84	TEG2-07025HT-SS	Bi ₂ Te ₃	Ceramic graphite
TEG7	TEC	4.81	0.99	2.83	TEG1-Pb-12611	Pb, Bi ₂ Te ₃	Ceramic graphite

The experimental protocol investigated four distinct operational configurations of these PV-TE systems: (1) systems without any cooling mechanism to establish baseline performance metrics, (2) systems incorporating passive cooling through aluminum heat sinks to enhance heat dissipation, (3) systems utilizing active cooling with distilled water as the coolant medium to improve thermal management and (4) systems employing active cooling with a nanofluid coolant to further augment thermal conductivity and system efficiency.

To facilitate precise measurement and independent analysis of the photovoltaic and thermoelectric components, the hybrid systems were electrically configured using a four-wire system. This configuration enabled separate quantification of energy outputs from the PV and TE modules, allowing for accurate determination of their individual efficiencies. Each component was equipped with a dedicated electrical output circuit, ensuring that performance characteristics of PV and TE components could be

evaluated independently and without interference, therefore offering a more sophisticated comprehension of hybrid system's overall performance.

The experimental procedures conducted in this research adhered strictly to the fundamental requirements outlined in EN ISO/IEC 17025. The Turkish Standards Institution (TSE) granted formal authorization for the testing, which was carried out within its accredited Photovoltaics and Calibration Laboratories [200]. To guarantee the accuracy and dependability of the experimental results, all apparatus used in the study underwent meticulous calibration processes.

In accordance with the EN/IEC 61215 standards, the tests were conducted in a controlled environment at 25 °C under Standard Test Conditions (STC) [201]. For thermoelectric component of PV-TE hybrid systems, temperature of hot side was systematically varied in precise increments of 5 °C, ranging from an initial 30 °C to a max of 70 °C. This incremental adjustment facilitated a comprehensive evaluation of the thermoelectric performance across a spectrum of thermal conditions, offering vital information about the effectiveness and behavior of hybrid systems under varying operational environments.



Figure 4.1. Ceramic plated TEGs from left to right labeled TEG1, TEG2, TEG3, TEG4, TEG5.



Figure 4.2. TEG with graphite mixed surface TEG6.

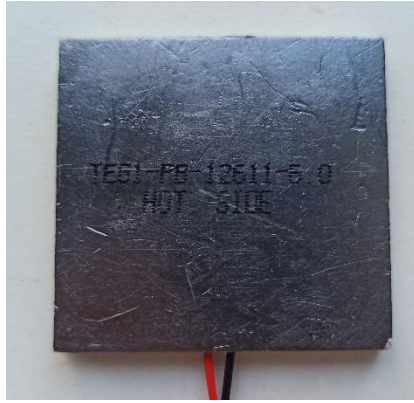


Figure 4.3. TEG with graphite mixed surface TEG7.

The temperature of the back sheet of photovoltaic module is closely related to hot plate side's temperature (T_h) of thermoelectric (TE) module. Under typical conditions, PV modules back side is seen to be approximately 25–30 °C warmer than T_a . For instance, when T_a is maintained at 25 °C, the corresponding T_h reaches nearly 50 °C, reflecting the system's thermal properties.

For the thermoelectric generator (TEG), cold plate side temperature (T_c) was initially set to temperature of the T_a during both non-cooled and cooling system-equipped tests. However, for active cooling system evaluations, a liquid coolant maintained at 10 °C was introduced into the testing setup. This controlled cooling medium facilitated the dissipation of heat more effectively, enabling a thorough examination of the effects of active cooling mechanisms on the PV-TE's electrical and thermal performance.

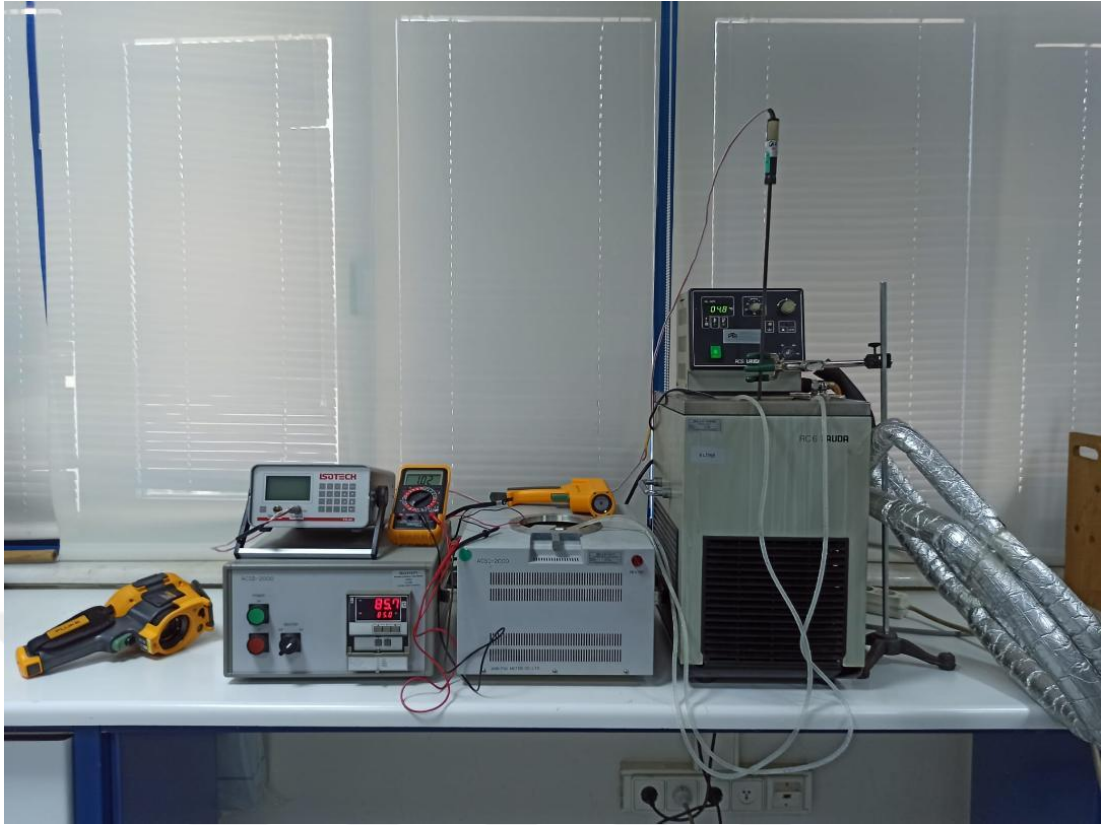


Figure 4.4. TE part testing system at TSE.

The experimental investigations involving the thermoelectric component of the photovoltaic–thermoelectric hybrid system were carried out at the Turkish Standards Institution's Calibration Laboratory (TSE), an accredited facility ensuring adherence to international standards. To assess the PV-TE system's performance, a heated plate from the ACSII-2000 Temperature Calibration System, manufactured by Anritsu Meter Co., LTD, Tokyo, Japan, was employed. This equipment was instrumental in simulating and maintaining precise temperature conditions for PV component of hybrid system.

The TE component testing system, as depicted in Figure 4.4, was specifically designed to ensure accurate thermal regulation and measurement consistency throughout the experimental process. This setup facilitated a comprehensive evaluation considering the PV-TE system's electrical and thermal properties under controlled conditions, supporting the validity and dependability of the study's conclusions.

Heating plate within this unit is engineered to maintain a consistent and precise temperature throughout the testing process, making certain that the TE component's

hot side stays stable at designated level. This stability is critical for obtaining accurate and reproducible measurements during the experimental evaluation of PV-TE system. Schematic representation of TE component testing procedure, as illustrated in Figure 4.5, gives a thorough rundown of the experimental configuration. For all test configurations conducted in this study, T_h of the TE component was systematically varied in increments of 5 °C, spanning between 30 °C to 70 °C. This controlled temperature adjustment enabled a thorough examination of the thermoelectric performance across diverse thermal conditions, offering valuable insights into the operational efficiency and behavior of the system under varying environmental scenarios.

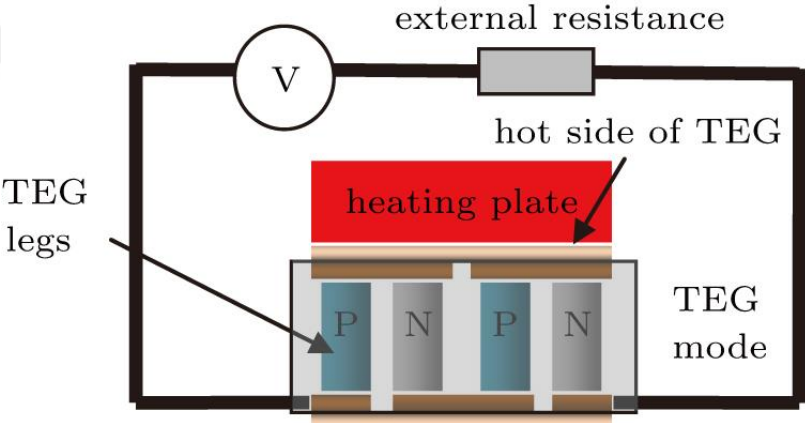


Figure 4.5. TE part testing method [179].

The initial testing of TE modules was conducted without a cooling system. Installing an aluminum heat sink underneath the cold plate side of the TE is the next stage in increasing PV-TE efficiency, as shown graphically in Figure 3.4. By prolonging the time that the temperature equalization takes place on both sides of TE module, this technique greatly enhances our research.

The aluminum heat sink's dimensions matched those of the TE modules (40 mm X 40 mm). The PV-TE system is effectively transformed into a passive cooling (PC) system using this technique. The results of this method are labeled "PC" in graphical representations. Intentional effort has resulted in significant advancements in our research. To enhance overall performance and efficacy, it outlines the possible benefits of incorporating PC techniques into PV-TE system.

As part of our research technique, we installed an AC system to increase PV-TE system's electrical efficiency. This method involves setting a liquid tank with a liquid

refrigerant at a steady temperature. This liquid's temperature is carefully remained steady throughout the experiment. Important components of the AC system include an aluminum water cooling block heat sink, flexible piping and a liquid pump.

Using nanofluids as coolant to increase the temperature differential inside TE module is next step forward in efficiency improvement techniques. In our graphical representations, the term "nAC" (nanofluid-active cooling) is used specifically to indicate the results of this technology. We used a Gamma aluminum oxide (Alumina, Al_2O_3), using a nanofluid as the coolant, particularly in the Gamma phase, with average particle sizes ranging from 20 to 50 nm, aims to increase outputs of voltage, current, and power. This choice is supported by prior research and theoretical considerations, which demonstrate that an active cooling system employing nanofluids generates superior electrical outputs in comparison to one that uses distilled water as the coolant.



5. RESULTS AND DISCUSSION

In this chapter, also our extensive research on optimizing photovoltaic–thermoelectric (PV-TE) systems is summarized. We concentrate on the material composition of thermoelectric generators (TEGs) and performance improvements made possible by sophisticated cooling techniques. Because of their quick temperature equalization, we discovered that ceramic-plate TEGs function noticeably better than their graphite counterparts, especially at higher working temperatures. By combining passive and active cooling systems, this superiority is further increased. Nanofluids have been shown to significantly improve the electrical system's efficiency and the TEG modules' resulting power. This demonstrates the significance of nanofluids in upcoming PV-TE applications and presents encouraging opportunities to improve system performance. Our research highlights how important cooling systems are to PV-TE hybrid systems. Because of the characteristics of micro- and nanoparticles, TEGs with ceramic plates exhibit more effective heat transfer and energy output than those with graphite. Gamma aluminum oxide nanofluid and an aluminum heat sink were also added to active cooling systems, which represented a major improvement in system performance and design. Cost-effectiveness is another important component for these systems' economic success.

Experimental results of thermoelectric (TE) modules evaluated under baseline conditions, without any cooling mechanism, largely aligned with our initial expectations. The voltage-time test outcomes for the 7 thermoelectric generators (TEGs) operating at a constant T_h of 50 °C are presented in Figure 5.1. One significant finding from these experiments, is the exceptionally short duration required for the temperatures on both sides of TEGs to reach equilibrium. This rapid thermal stabilization highlights the thermal dynamics and material properties inherent to the TEGs under study.

In particular, TEG2 and TEG3, both utilizing ceramic plates, exhibited superior performance at a T_h of 50 °C, consistently outperforming their counterparts. This finding underscores the enhanced thermal conductivity and efficiency of ceramic-

based TEGs in managing heat transfer under operational conditions. Furthermore, it is significant to note that, under Standard Test Conditions (STC), this hot-side temperature is quite similar to the temperature on the back sheet of photovoltaic (PV) modules, providing a realistic representation of the thermal environment within PV-TE hybrid systems. These results establish a foundational understanding of the TEGs' behavior in the absence of cooling mechanisms, serving as a benchmark for subsequent evaluations involving passive and active cooling configurations.

In comparison to their ceramic-based counterparts, the two thermoelectric generators (TEGs) utilizing graphite plates demonstrated noticeably lower output performance. This discrepancy highlights the intrinsic thermal and material properties that differentiate these TEG setups. The reduced efficiency of graphite-based TEGs can be attributed to their higher thermal conductivity, which disrupts the maintenance of an optimal temperature gradient across the module—a critical factor for maximizing thermoelectric efficiency.

These results offer insightful information about the function of plate materials in influencing overall system performance. They underscore the importance of selecting materials with favorable thermal properties to achieve enhanced energy conversion efficiency in PV-TE systems. Furthermore, the observed performance variations stress the need of giving serious thought to material characteristics during the design and optimization of thermoelectric systems, as these differences can significantly affect their operational reliability and integration into hybrid energy systems.

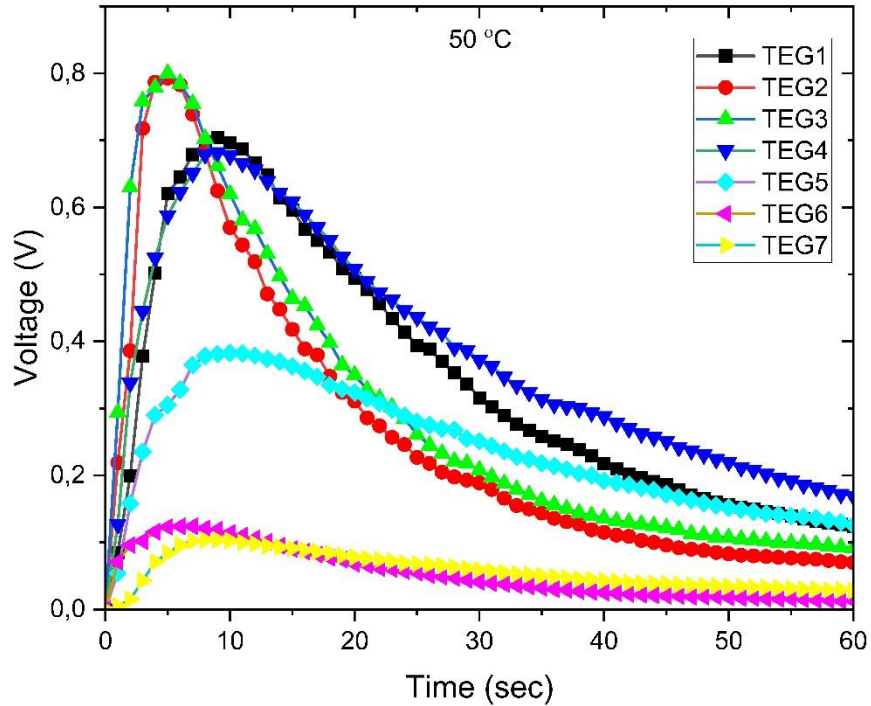


Figure 5.1. Voltage outputs of 7 TEGs without cooling system under 50 °C T_h .

Building upon our experimental findings, Figure 5.2 demonstrates that thermoelectric generators (TEGs) with ceramic plates consistently outperform those with graphite plates, even when subjected to elevated hot-side temperatures (T_h) of 70 °C. Notably, TEG2 and TEG3 maintain superior output performance, aligning closely with the results observed at a T_h of 50 °C. This consistency reinforces the robustness and efficiency of ceramic-based TEGs across a broad temperature range, highlighting their suitability for high-performance PV-TE systems.

The pronounced performance disparities between TEGs with ceramic and graphite plates, as illustrated in the data, confirm the inherent limitations of graphite-based plates. These materials exhibit lower output levels due to their thermal properties, which hinder the maintenance of the temperature gradient essential for efficient thermoelectric conversion. These discrepancies persist even at higher operating temperatures, emphasizing the critical role of plate material in determining overall system efficiency.

To further enhance performance of PV-TE systems, the next step, as depicted in Figure 3.4, involves incorporating an aluminum heat sink beneath cold plate side of

thermoelectric module. This addition is expected to prolong the duration required for temperature equalization between cold and hot sides, thereby improving thermal management. Such an approach not only optimizes the thermoelectric efficiency but additionally enhances the system's dependability and stability under varied operational conditions, signifying a major breakthrough in the design and performance optimization of PV-TE systems.

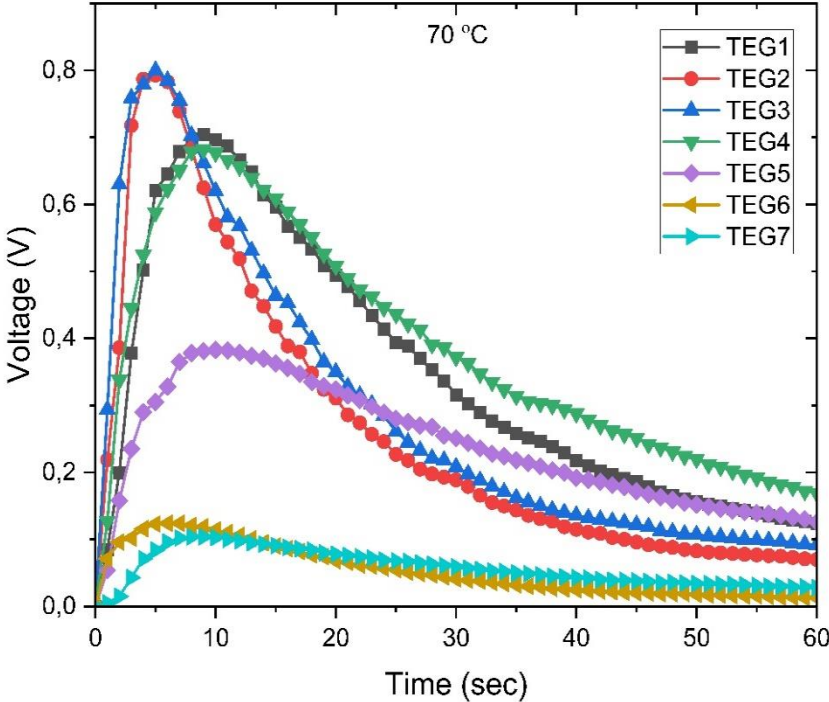


Figure 5.2. Voltage outputs of 7 TEGs without cooling system under 70 °C T_h .

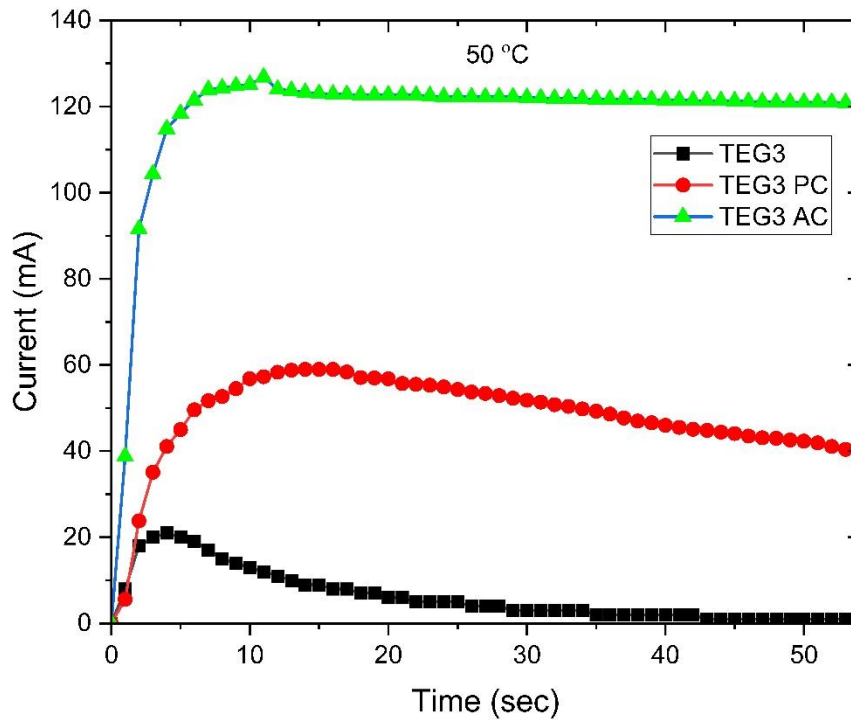


Figure 5.3. Current outputs of TEG3 without cooling system, with PC system and with AC system, under 50 °C T_h .

Figures 5.3 and 5.4 illustrate significant variations in the V and I outputs of TEG3 under 3 distinct operating conditions, providing critical insights into the system's performance dynamics. A clear and consistent pattern emerges from these results: TEG3 achieves substantially higher voltage and current outputs when equipped with an active cooling (AC) system. This improvement is attributed to the enhanced thermal management facilitated by the active cooling system, which effectively maintains a stable temperature gradient across the thermoelectric module.

An additional advantage of the active cooling system is its ability to rapidly achieve steady and reliable voltage and current levels. This capability minimizes the amount of time needed for the system to operate in a steady state, thereby enhancing both the effectiveness and reliability of TEG3. The reduction in stabilization time not only optimizes the energy output but also improves the PV-TE hybrid system's efficiency in operation, particularly in applications requiring consistent and dependable performance.

These results highlight the substantial advantages of adding an AC system within PV-TE systems. By enhancing both output characteristics and system stability, active cooling mechanisms are essential for optimizing performance. and dependability of hybrid energy systems, further supporting their potential for broad use and commercialization.

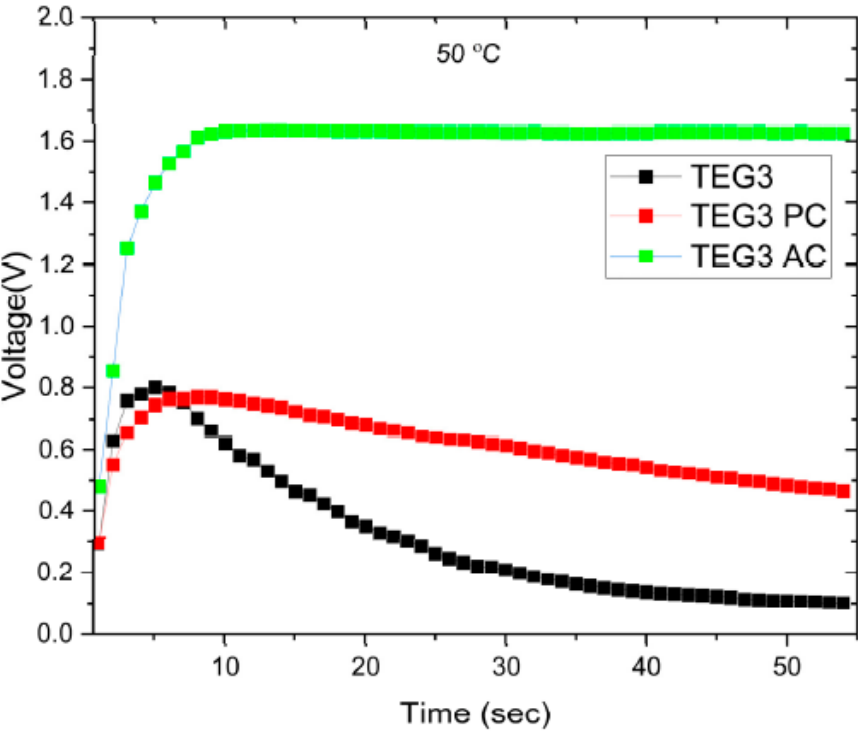


Figure 5.4. Voltage outputs of TEG3 without cooling system, with PC system and with AC system, under 50 °C T_h .

The beneficial effect of implementing an AC system is clearly demonstrated through the analysis of V and I outputs of TEG4 under 3 distinct operating conditions, as depicted in Figures 5.5 and 5.6. The data reveals that the incorporation of an active cooling mechanism significantly enhances the V and I outputs of the thermoelectric generator.

This improvement is in line with the patterns noted in case of TEG3, further validating efficacy of AC systems in optimizing thermoelectric performance. By efficiently managing the temperature differential across the thermoelectric module, the active cooling system not only increases energy output but also facilitates the rapid attainment of stable and reliable voltage and current levels. This ability to quickly

stabilize performance is a critical feature that enhances overall system dependability and efficiency.

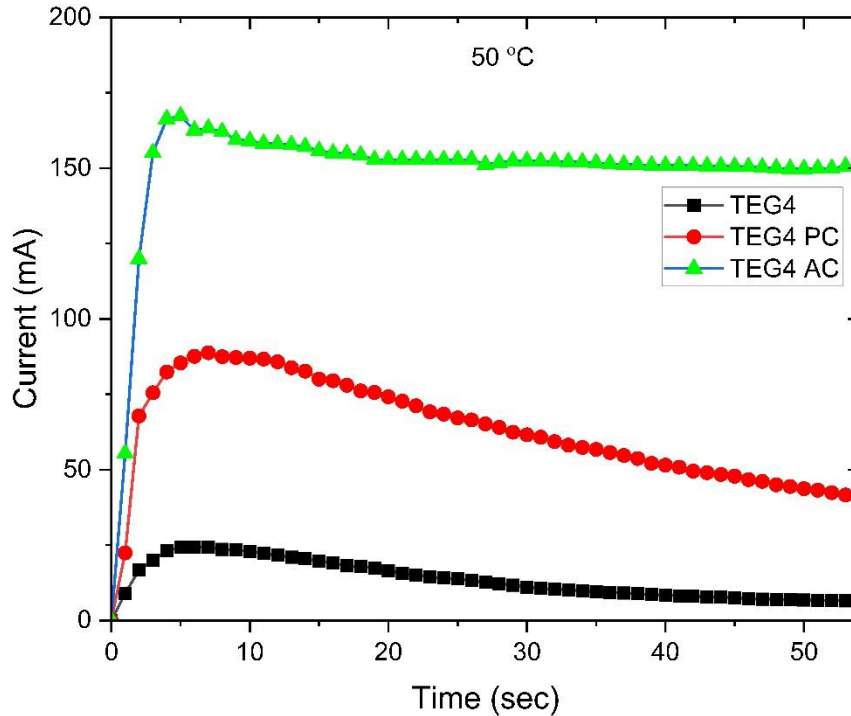


Figure 5.5. Current outputs of TEG4 without cooling system, with PC system and with AC system, under 50 °C T_h .

These findings underscore the active cooling system's pivotal role in advancing commercialization potential of PV-TE systems. By consistently delivering superior electrical output and ensuring operational stability, active cooling mechanisms act as a crucial facilitator for the broader application and scalability of PV-TE technologies in renewable energy solutions.

One significant finding from the performance investigation of TEG4 is that, even with cooling systems installed, it produces more than TEG3. The intrinsic semiconductor properties of thermoelectric generators may be the cause of this performance disparity. These properties, which are governed by the composition of the material and its structural properties of the TEGs, are crucial in determining their effectiveness under varying thermal conditions.

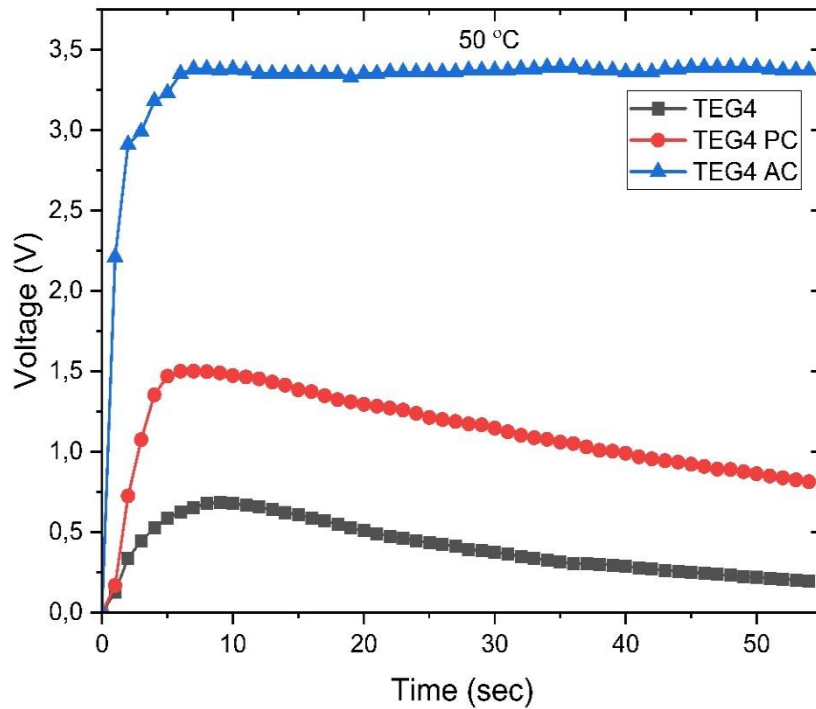


Figure 5.6. Voltage outputs of TEG4 without cooling system, with PC system and with AC system, under 50 °C T_h .

The efficiency of thermoelectric devices is highly dependent on the temperature differential maintained between their cold and hot sides. TEG4's enhanced performance suggests that its semiconductor configuration and material properties are better optimized to capitalize on this temperature gradient, resulting in improved energy conversion. This result emphasizes how crucial it is to choose and tailoring semiconductor materials to maximize the thermal and electrical efficiency of PV-TE hybrid systems, particularly in applications requiring high reliability and output stability.

To enhance temperature differential across thermoelectric module and further improve its efficiency, nanofluids were employed as the cooling medium. In the graphical representations of the experimental results, this approach is denoted as "nAC" (nanofluid-active cooling). Specifically, a Gamma aluminum oxide (Al_2O_3) nanofluid, formulated in the Gamma phase with an average particle size between 20 and 50 nm, was utilized. This advanced cooling medium was selected to achieve higher current, voltage and power outputs from thermoelectric generators.

The decision to use nanofluids as the cooling agent is strongly supported by prior research findings and models, which consistently demonstrate that AC systems incorporating nanofluids significantly outperform those using distilled water in terms of electrical output [201,202]. The superior heat transfer capacities and thermal conductivity of nanofluids aid in the better administration of the thermal gradient across the TE module, thereby maximizing its performance.

These findings highlight the crucial part that innovative cooling strategies in optimizing efficiency of PV-TE hybrid systems. This method, which makes use of the special qualities of nanofluids, is a major breakthrough in the thermal management of hybrid energy systems, opening the door for its further use and improved performance in renewable energy technologies.

Figures 5.7 and 5.8 present the power outputs of TEG3 and TEG4 at a T_h of 50 °C, measured in milliwatts (mW), across four distinct cooling configurations: no cooling, PC, AC and AC utilizing nanofluids (nAC). The results unequivocally demonstrate that both active cooling systems—standard and nanofluid-based—significantly outperform passive cooling in terms of power output. Furthermore, the absence of any cooling mechanism produces the scenario with the lowest performance out of the four.

The data reveal that TEG4 consistently achieves higher electrical output compared to TEG3 across all cooling configurations. This superior performance underscores the influence of TEG4's optimized material composition and structural design, which allow it to capitalize more effectively on the enhanced thermal management provided by active cooling systems. The use of nanofluids in particular amplifies these gains, further highlighting the potential of advanced cooling strategies to increase PV-TE hybrid systems energy conversion efficiency. These results highlight how crucial it is to integrate active cooling mechanisms, particularly nanofluid-based systems, in order to fully realize the potential of high-performance thermoelectric generators.

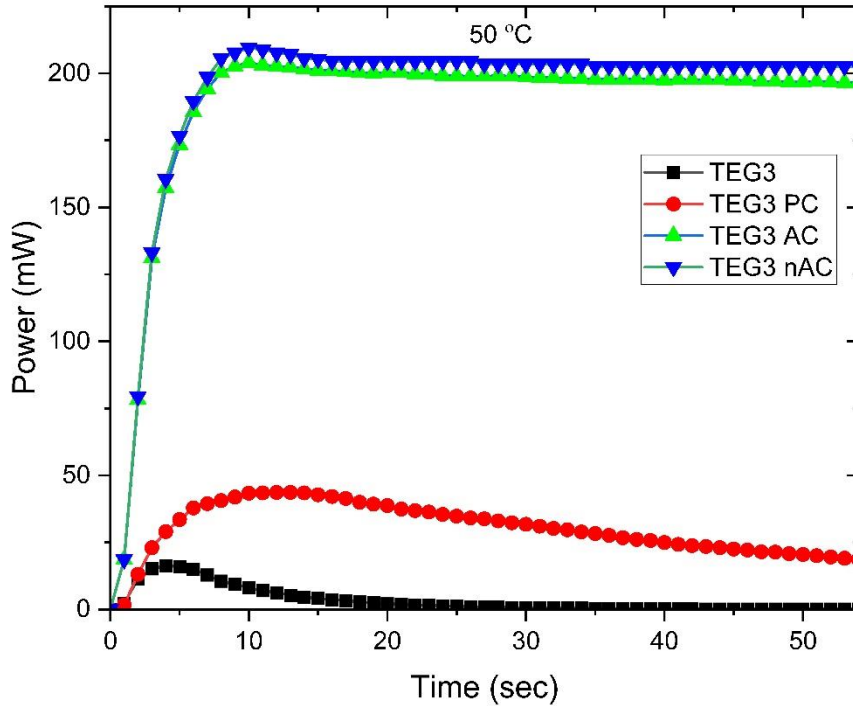


Figure 5.7. Power outputs of TEG3 without cooling system, with PC system, with AC system and with AC system with nanofluid, under 50 °C T_h in mW.

The experimental findings of this research unequivocally demonstrate that PV-TE hybrid systems exhibit superior performance compared to standalone photovoltaic (PV) components. Table 5.1 provides a detailed comparison of power outputs for PV-TE systems incorporating TEG3 under various cooling configurations: no cooling, passive cooling, active cooling with distilled water and active cooling with nanofluids.

The results highlight that among the most successful methods for improving the power output of PV-TE systems is the implementation of active cooling mechanisms. Specifically, when TEG3 operates under steady-state conditions with an active cooling system utilizing distilled water, the power output increases by 3.59%. This improvement is further amplified to 3.69% with the use of nanofluids as cooling medium.

These results highlight the vital role that advanced thermal management in optimizing performance of PV-TE systems. Enhanced heat dissipation and improved temperature gradient facilitated by active cooling systems, particularly those employing nanofluids, significantly contribute to increased efficiency of energy conversion. This illustrates

the possibility of incorporating cutting-edge cooling technologies to maximize the efficiency of operations and scalability of PV-TE systems in renewable energy applications.

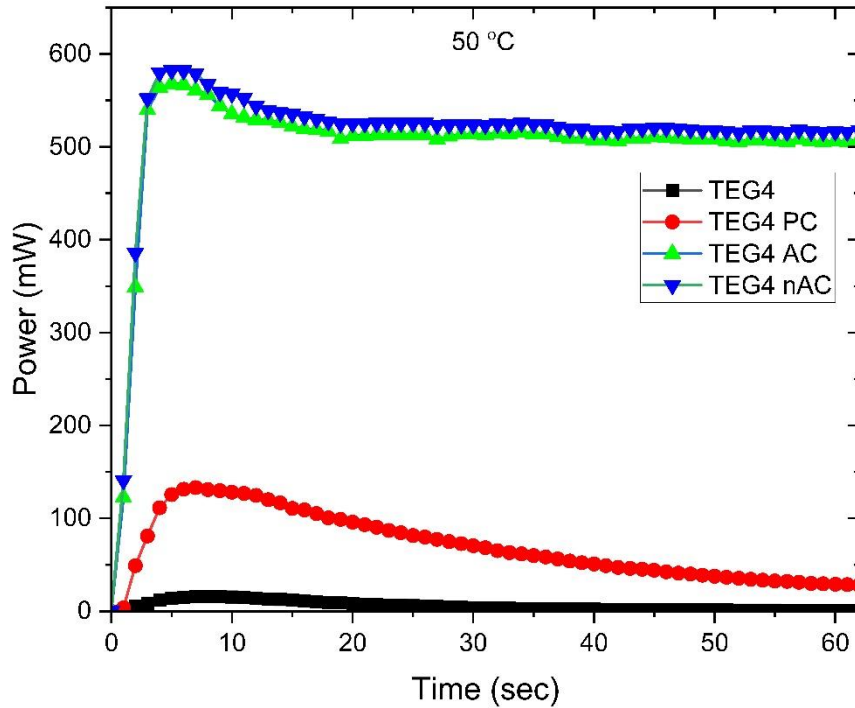


Figure 5.8. Power outputs of TEG4 without cooling system, with PC system, with AC system and with AC system with nanofluid, under $50\text{ }^{\circ}\text{C}$ T_h in mW.

Among all the thermoelectric generators (TEGs) evaluated in this study, TEG4 consistently demonstrated highest electrical output under both PC and AC configurations, as demonstrated by the findings of our experimental analyses. Table 5.2 gives a thorough comparison of power outputs for various configurations, including a standalone photovoltaic (PV) system, PV-TE systems incorporating TEG4 without any cooling, with PC and with AC using purified water and nanofluids.

Table 5.1. Power outputs and performance increase of pure PV, PV-TE with TEG3 without cooling, PV-TE with TEG3 with PC and PV-TE with TEG3 with AC by using distilled water and nanofluid. ($T_a = 25$ $T_h = 50$ $T_c = 10$).

Product Test in 50 °C T_a	Power in W	Performance Increase
PV	5.48	
PV-TE TEG3	5.480107	0.00%
PV-TE TEG3 PC	5.504732	0.45%
PV-TE TEG3 AC	5.676746	3.59%
PV-TE TEG3 nAC	5.682654	3.69%

Table 5.2. Power outputs and performance increase for pure PV, PV-TE with TEG4 without cooling, PV-TE with TEG4 with PC and PV-TE with TEG4 with AC by using distilled water and nanofluid. ($T_a = 25$ $T_h = 50$ $T_c = 10$).

Product Test in 50 °C T_a	Power in W	Performance Increase
PV	5.48	
PV-TE TEG4	5.480149	0.00%
PV-TE TEG4 PC	5.503771	0.43%
PV-TE TEG4 AC	5.987822	9.26%
PV-TE TEG4 nAC	5.997978	9.45%

The superior performance of TEG4 across all cooling scenarios highlights its optimized material properties and structural design, which enable it to effectively leverage thermal management strategies to enhance energy conversion efficiency. The data underscore the pivotal role of advanced cooling techniques in amplifying the electrical output of PV-TE systems, particularly when active cooling systems, such as those utilizing nanofluids, are employed. These results offer insightful information about the possibility of integrating high-performance TEGs like TEG4 with innovative cooling mechanisms to maximize the hybrid renewable energy systems' dependability and efficiency.

5.1. Results

This research offers a thorough investigation of PV-TE hybrid systems, focusing on optimizing thermoelectric generator (TEG) performance, material efficiency and cooling mechanisms. By examining 7 distinct TEG configurations under various operational conditions, we achieved significant advancements in understanding the

interplay between material properties, thermal management strategies and hybrid system integration.

About the performance of thermoelectric Generators (TEGs) our experimental results underscore the critical importance of TEG material composition and structural design in achieving optimal system efficiency. Ceramic-based TEGs consistently demonstrated superior performance over graphite-based alternatives, especially under elevated operating temperatures.

Our experimental results show us about the material properties and heat transfer dynamics, that graphite, despite its high Seebeck coefficient and electrical conductivity, exhibited limited thermoelectric efficiency due to its excessive thermal conductivity, which negatively impacts its ZT value. This high thermal conductivity allowed heat to dissipate inefficiently, reducing temperature gradient across TEG, a critical parameter for effective energy conversion.

Ceramic TEGs, in contrast, exhibited rapid thermal equalization and effective heat dissipation. Their intrinsic properties allowed them to maintain a stable temperature gradient, optimizing energy conversion efficiency and demonstrating robustness under fluctuating thermal loads.

With the help of our experimental results we get important criteria about the selection of material and structural properties of TEGs. The selection, assessment and structural characteristics of TEG materials served as the basis for this research. The performance of TEGs, categorized into ceramic (Al_2O_3) and ceramic and graphite based plates, highlighted significant disparities.

The experimental results of our study show the material influence to the TEG efficiencies. Ceramic-based TEGs (TEG1–TEG5) consistently demonstrated superior performance, attributed to their enhanced thermal conductivity and rapid temperature equalization. These properties facilitated better energy conversion and stability under varied thermal loads.

Graphite and Ceramic mixed based TEGs (TEG6 and TEG7), while exhibiting moderate efficiency, were hindered by their higher thermal conductivity, which disrupted the maintenance of optimal temperature gradients. Notably, TEG7, composed of a Pb-BiTe alloy, exhibited unique characteristics but lagged behind ceramic-based TEGs in overall output.

Our experimental results also show the importance of the thicknesses of p-n junctions. One important factor influencing performance was found to be the p-n junction's thickness. TEG4, with the thinnest junction (1.81 mm), consistently outperformed other TEGs, underscoring how crucial it is to optimize this value for enhanced thermal and electrical efficiency.

The effects of the cooling mechanism to the efficacy was also seen from the results. Cooling strategies emerged as fundamental to enhancing both TEG and PV performance. The study systematically evaluated passive cooling (PC) and active cooling (AC) techniques, revealing key information about their efficacy and suitability.

The different cooling conditions has also changed the efficiency of TEGs. This could be easily seen from the results. The experimental results revealed the profound impact of cooling mechanisms on system efficiency, with active cooling outperforming, passive cooling and without cooling configurations:

By the tests with Passive Cooling (PC), Aluminum heat sinks facilitated efficient heat dissipation, stabilizing the operational temperature of TEGs. This strategy is very beneficial for cost-sensitive applications where simplicity and reliability are prioritized.

Passive systems provided consistent improvements in energy production without requiring further facilities, making them an accessible solution for retrofitting existing systems.

By the tests with Active Cooling (AC) with distilled water condition we got: increased thermal management efficiency, lowering the device's operating temperature of TEGs and enhancing their electrical output. However, its scalability for larger systems remained a concern.

By the tests with Nanofluid-Active Cooling (nAC), the use of Gamma aluminum oxide (Al_2O_3) nanofluids introduced a substantial improvement in cooling efficiency. These nanofluids, with particle sizes between 20 and 50 nm, increased thermal conductivity and reduced temperature gradients more effectively than water-based cooling systems. As a result, TEG4's power output rose by 9.45%, demonstrating the transformative potential of nanotechnology in hybrid systems.

If we make a comparative performance comment about the TEGs by using our experimental results, the V and I outputs of the TEGs under varying thermal conditions highlighted significant differences:

At 50 °C Th, TEG2 and TEG3 exhibited strong voltage and current outputs, surpassing other TEGs with comparable structural configurations.

At 70 °C Th, the performance of TEGs with ceramic plates continued to excel, maintaining stability and higher output levels. TEG4 consistently outperformed all others, affirming the advantages of its optimized p-n junction thickness and material composition.

Figures 5.3 to 5.8 illustrate the comparative performance of TEG3 and TEG4 under varying cooling conditions. These outcomes confirm that active cooling systems are effective in enhancing both voltage and current stability, critical for reliable and scalable energy solutions.

PV-TE system is an integration of PV and TE Systems and with our experimental results we could easily show outputs of this system. The integration of PV and TE systems demonstrated a synergistic effect, leveraging waste heat from PV modules to generate additional energy through TEGs. This dual approach not only enhanced overall system efficiency but also mitigated the thermal challenges associated with photovoltaic operation. The hybrid integration of PV and TE components proved to be synergistic, leveraging waste heat from PV cells to generate additional energy through TEGs:

From the side of energy harvesting and utilization, TEGs directly attached to the rear of PV modules effectively converted thermal energy into electrical power. This arrangement optimized the utilization of solar spectrum energy, allowing low-energy photons to contribute to power generation.

The dual utilization of high-energy photons for photovoltaic conversion and low-energy photons for thermoelectric conversion optimized the solar spectrum's energy usage.

Active cooling systems further amplified this effect, with nanofluids enabling the most significant improvements.

The Seebeck effect was exploited to achieve efficient energy conversion, with the heat generated by PV cells directly contributing to the temperature gradient required for TEG operation.

Our experimental results prove the thermal regulation and system stability. By reducing the operational temperature of PV cells, TEG integration improved photovoltaic efficiency and longevity. This highlights the dual benefit of energy augmentation and thermal regulation in hybrid PV-TE systems.

By mitigating the temperature increase on the PV module's backside, the integration of TEGs improved both photovoltaic efficiency and lifespan.

From the economic viability and optimization side, this study emphasized the significance of balancing performance with cost to ensure commercial viability of PV-TE systems. While TEG4 exhibited highest power output, its elevated production cost presents a challenge for widespread adoption. Conversely, TEG3 emerged as a promising alternative, offering nearly equivalent voltage output at a significantly lower cost.

Tables 5.1 and 5.2 present quantitative insights into the power outputs and performance enhancements of PV-TE systems under different cooling conditions:

The TEG3 results show a Passive cooling improved power output by 0.45%, while AC with distilled water and nanofluids increased it by 3.59% and 3.69%, respectively.

The TEG4 Results show a Passive cooling yielded a 0.43% improvement, with distilled water-based active cooling increasing output by 9.26% and nanofluids delivering a remarkable 9.45% boost.

These findings emphasize the economic viability of integrating advanced cooling systems and optimized TEG designs into commercial PV-TE systems.

About the design parameters our results show one important factor affecting the thermal and electrical performance of TEGs was found to be the thickness of the p-n junction. Thinner junctions, as observed in TEG4, facilitated superior heat transfer, emphasizing the need for precision engineering in TEG design.

This study also gives a bright proof of the material for the market consideration. The integration of BiTe alloy-based TEGs and cost-effective cooling solutions provides a feasible pathway for scaling hybrid systems in commercial applications.

For the energy and PV future our study gives a light to the path and for the wider consequences a key. This study lays a strong basis for advancement of PV-TE systems in the future by highlighting their potential to improve sustainability and energy efficiency globally.

One powerful side of PV-TE system is its scalability and implementation. Proposed hybrid systems can easily be integrated into working photovoltaic infrastructures, offering a scalable and cost-effective pathway to enhance energy output, enabling energy augmentation with minimal disruption. This scalability ensures their applicability across diverse geographic and climatic conditions.





6. CONCLUSION AND FUTURE WORK

In my comprehensive research for this thesis, we focused into optimizing PV-TE systems, focusing on enhancing performance through advanced cooling techniques and the composition of TEGs. Our research shows that because of their quick temperature equalization, ceramic-plate TEGs function better than their graphite counterparts, especially at high temperatures.

With the results of the examinations of the materials for this research, this study represents a significant milestone in the ongoing advancement of PV-TE systems, shedding light on interplay between material selection, cooling methodologies and system integration. The research provides a detailed examination of how innovative material properties and advanced thermal management techniques can collectively optimize performance of hybrid PV-TE systems.

At room temperature, graphite is renowned for having high Seebeck coefficient and high electrical conductivity. Its thermal conductivity, however, is noticeably high from a thermoelectric standpoint, which therefore restricts its ZT .

Because of the characteristic properties of micromaterials, the surfaces of the graphite mixed TEGs collect the heat but dont give it up very easily. The ceramic ones can easily give the heat outside but graphite ones dont give it. Following the studies, it was discovered that the graphite-coated ones had a higher temperature than the ceramic ones.

The efficiency of the TEG modules with high average ZT -based BiTe alloys is 15% higher than the values published in the literature and 40% higher than that of commercial crystalline materials. In BiTe alloy-based modules, a record 2.1 W/cm² power density and 8% conversion efficiency were attained. Also BiTe alloys are cheaper when compared to other alloys. Today in the market BiTe alloys are dominant and TEGs produced with BiTe alloys. Nearly all TEG manufacturers use BiTe alloys for TEG production so it has nearly been a standard material for TEG applications.

By combining PC and AC systems, this superiority is further highlighted. Nanofluids in TEGs provide notable increases in efficiency and power production. The outcomes demonstrate the potential of nanofluids in upcoming PV-TE applications, providing opportunities to increase system efficiency.

Additionally, my research demonstrates the function of cooling systems in PV-TE hybrid configurations. Due to the different characteristics of micro- and nanoparticles, we found that TEGs with ceramic plates have better heat transmission and energy output than those based on graphite. Furthermore, a significant improvement in system performance and design is represented by the addition of an aluminum heat sink and Gamma aluminum oxide nanofluid to active cooling systems. Despite having the highest power output, TEG4 may not be widely used due to its greater cost. On the other hand, TEG3, which has almost the maximum voltage output and is less expensive, becomes a more practical option.

The significance of selecting TEG materials is demonstrated by this thesis research, which favors ceramic plates over graphite for increased efficiency and possible cost-effectiveness. We looked into the effect of p-n junction size in TEGs nearby and discovered that a thinner junction, like the one in TEG4, improves heat transfer efficiency. And shows importance of optimizing p-n junction size to maximize TEG cooling capacity, with significant design and performance implications.

About the Material Performance and Thermoelectric Efficiency, these findings unequivocally demonstrate that ceramic-based thermoelectric generators (TEGs) outperform their graphite-based counterparts, particularly under high-temperature operational conditions. The main cause of this performance disparity is the superior thermal conductivity and heat dissipation properties of ceramics, which enable rapid temperature equalization. Conversely, graphite, despite its high Seebeck coefficient and electrical conductivity at ambient conditions, is hindered by excessive thermal conductivity. This characteristic undermines its thermoelectric efficiency (ZT), as evidenced by experimental observations where graphite-mixed TEGs retained heat, thereby limiting energy conversion efficiency.

Furthermore, the study highlights the crucial part that BiTe alloy-based TEGs, which exhibited a groundbreaking 8% energy conversion efficiency and a power density of 2.1 W/cm². These performance metrics mark a substantial leap from conventional

crystalline materials, demonstrating up to 40% higher efficiency. BiTe alloys, already prevalent in business settings because of their affordability and consistent performance, underscore their importance as the de facto standard material for thermoelectric systems.

About the cooling techniques and system integration, a critical progress in this research is the incorporation of passive and active cooling systems, which collectively enhance the efficiency of TEG modules. The deployment of nanofluids, particularly those based on Gamma Aluminum Oxide, coupled with aluminum heat sinks, significantly optimized heat transfer and system stability. These cooling solutions not only mitigate thermal inefficiencies but also clear the path for long-term performance under varying operational conditions.

While TEG4 demonstrated the highest power output among the configurations tested, its high production cost presents a barrier to mass adoption. On the other hand, TEG3, offering nearly equivalent voltage output at a lower cost, emerged as a practical alternative for commercial applications. This trade-off between cost and performance emphasizes how crucial economic factors are when implementing hybrid PV-TE systems.

Another novel contribution of this research about optimization of design parameters, lies in its exploration of p-n junction dimensions in TEG modules. The findings indicate that thinner p-n junctions, as exemplified in TEG4, significantly enhance heat transfer efficiency. This discovery underscores the importance of precise design optimization to maximize both thermal and electrical performance in hybrid systems. By refining junction dimensions, it is possible to achieve superior energy output without compromising cost-effectiveness, making this an essential focus for future studies.

Integrating PV-TE systems into existing photovoltaic infrastructure offers a promising pathway to improve sustainability and energy efficiency. By strategically placing TEGs beneath photovoltaic cells and employing advanced cooling mechanisms, current energy infrastructures can be retrofitted with minimal disruption. This method not only increases energy production but also aligns with global efforts toward transitioning to more sustainable energy systems.

In order to fully utilize the potential of PV-TE systems, further research is essential, particularly in real-world applications. Long-term performance analyses, coupled with life-cycle assessments encompassing economic, environmental and operational metrics, will be critical. Additionally, developing predictive models to correlate TEG and PV module characteristics with hybrid system performance will provide invaluable insights for optimizing system design and scalability.

Productivity can be raised by integrating PV-TE systems into already-existing PV power facilities. We may be able to modernize existing energy infrastructures with little disturbance if we install TEGs below each solar cell and integrate cooling block heat sinks with an active system. These findings not only advance scientific knowledge but also offer helpful guidance for future research and commercial applications.

In conclusion, our in-depth study explores photovoltaic–thermoelectric (PV-TE) system optimization, emphasizing performance gains attained by sophisticated cooling techniques and thermoelectric generator (TEG) material composition. Because of the quick temperature equalization, it is found that ceramic-plate TEGs operate noticeably better than graphite TEGs, especially at higher working temperatures. By combining passive and active cooling systems, this superiority is further increased and nanofluids significantly boost TEG power production and efficiency.

Cost-effectiveness is another important component for these systems' economic success. Even though TEG4 produced the most power, its greater price may prevent it from being used commercially. On the other hand, TEG3, which is less expensive and has almost the maximum voltage output, turns out to be a more practical choice.

According to test results, ceramic plates are preferred over graphite when choosing TEG materials due to their possible cost-effectiveness and high efficiency. Our study also looked at the impact of the p-n junction size in TEGs and found that a thinner junction, like the one seen in TEG4, improves heat transfer efficiency. This suggests that increasing the cooling capacity of TEGs requires optimizing the p-n junction size, which has important design and performance ramifications.

These findings show how promising nanofluids are for improving system efficiency in upcoming PV-TE applications. Additionally, our scientific study highlights how important cooling systems are to PV-TE hybrid systems. Because of their distinct qualities of micro- and nanomaterials, we discovered that TEGs with ceramic plates

exhibit more effective heat transmission and energy output than TEGs with graphite plates. Furthermore, the design and functionality of active cooling systems were very enhanced by inclusion of an aluminum heat sink and Gamma aluminum oxide nanofluid.

Another crucial factor for these systems' commercial success is cost-effectiveness. Despite having the highest power output, TEG4, because of its expensive cost, it might not be used much. Otherwise, on the other hand, TEG3, which is less expensive and has almost the greatest voltage output, it ends up being a wiser decision. According to our research, ceramic plates are a better option than graphite when choosing TEG materials because of their increased efficiency and possible cost-effectiveness. A thinner connection, such that found in TEG4, improves heat transfer efficiency, according to our test results of p-n junction's effects, size in TEGs. This suggests, increasing the cooling capacity of TEGs requires optimizing p-n junction size, which has important design and performance ramifications.

One approach that shows promise for increasing overall efficiency is the integration of PV-TE systems into already-existing PV power plants. It may be possible to change existing energy infrastructures with little disturbance by affixing TEGs beneath each solar cell and adding cooling block heat sinks with an active system.

Those discoveries not only advance our knowledge of PV-TE systems scientifically, also provide useful recommendations for further study and commercial applications.

To investigate these systems' long-term performance and scalability, more research is required, particularly in real commercial settings. In order to fully utilize PV-TE systems for sustainable and simultaneously efficient energy future, this further research will be essential.

One approach that shows promise for increasing overall efficiency is the integration of PV-TE systems into already-existing PV systems. We may be able to modify existing energy infrastructures with little disturbance by affixing TEGs beneath every solar cell and adding cooling block heat sinks with an AC system. These results offer useful direction for next studies and commercial applications in addition to advancing our scientific meaning of PV-TE systems. The scalability and performance of these systems over time require more research, especially in actual commercial

environments. In order to fully utilize PV-TE systems for sustainable and effective energy future, this further research will be essential.

Obtaining maximum efficiency, with a research PV cell, was not one goal during the research for this thesis, TEGs, sold in the market, are used and also the PV Modules which, found in market and their simplicated forms are used. So a better result which able to be applied to straight conversion of PV Solar Systems to PV-TE Solar Systems is found.

Otherwise the research could only be used by the academic people and can not be used directly at the PV market. But with the results we know now, when a PV module with the information of the power and with which TEG with the information of the characteristic information of the TEG, we can predict the increase of PV-TE system compared to PV system.

To ensure the commercialization of hybrid PV/TE systems, more research on PV/TE systems is required, with emphasis on energy performances, economics, environmental sustainability on long-term operation.

6.1. Future Research

While this study provides actionable insights for improving PV-TE systems, several avenues for future exploration remain.

This study showed the importance of material innovation for PV-TE systems. Exploring alternative thermoelectric materials with enhanced ZT values, cost-effectiveness and durability under varying environmental conditions. Also exploring novel cooling technologies, including hybrid nanofluids, to further optimize thermal management. Investigating advanced nanofluids and hybrid cooling solutions to further optimize thermal management.

Conducting long-term performance assessments in real-world settings to validate the reliability and Conducting comprehensive cost-benefit analyses to facilitate commercial adoption.

In the energy and PV market, PV-TE systems will have scalability and market integration. Assessing the scalability of hybrid systems and their compatibility with existing PV infrastructure.

Like the PV simulation programmes PV-TE systems should also have a predictive modeling. Developing advanced simulation tools to predict system performance based on material and environmental variables.

In conclusion, this study advances our knowledge of the variables affecting PV-TE system performance. The superiority of ceramic-plate TEGs, combined with the efficiency gains enabled by BiTe alloys and innovative cooling strategies, establishes a strong foundation for the next generation of hybrid energy solutions. By addressing material limitations, optimizing design parameters and exploring scalable integration methods, this study offers a roadmap for transforming the renewable energy landscape. Continued interdisciplinary research in material science, thermal engineering and system integration will be instrumental in achieving a sustainable and energy-efficient future.



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CURRICULUM VITAE

Name Surname : Selçuk BULAT

EDUCATION:

- **Undergraduate** : 2004, Technical University of Berlin, Electrical and Electronics and Information Sciences Faculty, Electrical and Electronics Engineering Department
- **Graduate** : 2011, Technical University of Berlin, Electrical and Electronics and Information Sciences Faculty, Electrical and Electronics Engineering Department, Electrical and Electronics Engineering

PROFESSIONAL EXPERIENCE AND AWARDS:

- He worked as engineer at the Turkish Standards Institution 2013-2024.

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- Bulat, S.; Büyükbicakci, E.; Erkovan, M. Efficiency Enhancement in Photovoltaic–Thermoelectric Hybrid Systems through Cooling Strategies. *Energies* **2024**, *17*, 430. <https://doi.org/10.3390/en17020430>