Universidade de Évora - Instituto de Investigação e Formação Avançada

Programa de Doutoramento em Engenharia Mecatrónica e Energia

Área de especialização | Mecatrónica

Tese de Doutoramento

Modeling and Development of a Low-Cost Embedded System for MPPT of Hybrid Photovoltaic Thermal System

Md Tofael Ahmed

Orientador(es) | Fernando Manuel Janeiro
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I would like to dedicate this work

to

my late Father ***Md Abu Tayb*** *(1954-2018)*

Abstract

Modeling and Development of a Low-Cost Embedded System for MPPT of Hybrid Photovoltaic Thermal System

Technological improvements and appropriate modeling of solar hybrid PVT systems continue to pose significant challenges. This thesis introduces an improved modeling and implementation approach aimed at improving the effective efficiency of hybrid PVT systems by increasing their overall energy output. It also presents an innovative classification system developed through a comprehensive review of recent literature as well as a parametric analysis model that includes various optimization and performance-based parameters. Parameters characterization, identification and sensitivity analysis are also conducted to assess the sensitivity and overall effect of the system. A mathematical model of both electrical and thermal sections of the PVT system is obtained and incorporated in the simulation model. The simulation model based on the proposed approach is developed using MATLAB environment. An effective efficiency comparison analysis is performed using an appropriate cooling and heat transfer mechanism with different heat exchanger pipes, and the results are discussed. A novel, non-iterative, optimum MPPT technique based on an analytical solution is introduced and compared with the other existing classical approaches. A set of simple low cost instruments and an embedded system is developed for the real time measurement, simulation and optimization purpose. Additionally, a robust monitoring and fault diagnosis system is also presented for the system reliability.

Keywords: PVT, Modeling, Sensitivity, Heat Transfer, MPPT.

Resumo

Modelação e Desenvolvimento de um Sistema Embebido de Baixo Custo para Seguimento do Ponto de Máxima Potência num Sistema Híbrido Fotovoltaico-Térmico

Os avanços tecnológicos e a modelação apropriada dos sistemas PVT híbridos solares continuam a representar desafios significativos. Esta tese apresenta uma abordagem aperfeiçoada de modelação e implementação com o objetivo de melhorar a eficiência efetiva dos sistemas PVT híbridos, aumentando a produção global de energia. Apresenta também um sistema de classificação inovador, partindo de uma revisão aprofundada da literatura recente, bem como de um modelo de análise paramétrica que inclui vários parâmetros de otimização e desempenho. A caracterização dos parâmetros, a identificação e a análise de sensibilidade são também conduzidas para avaliar a sensibilidade e o efeito global do sistema. Um modelo matemático da secção elétrica e térmica do sistema PVT é obtido e incorporado no modelo de simulação. O modelo de simulação baseado na abordagem proposta é desenvolvido utilizando o ambiente MATLAB. É realizada uma análise de comparação de eficiência eficaz utilizando um mecanismo apropriado de arrefecimento e transferência de calor, com diferentes tubos de permutador de calor, e os resultados são discutidos. Uma nova técnica MPPT ótima, não iterativa e baseada em solução analítica é introduzida e comparada com outras abordagens clássicas existentes. Um conjunto de instrumentos simples e de baixo custo e sistemas embebidos são desenvolvidos para fins de medição, simulação e otimização em tempo real. Além disso, é também apresentado um sistema robusto de monitorização e diagnóstico de avarias para garantir a fiabilidade do sistema.

Palavras-chave: Fotovoltaico-Térmico, Modelação, Sensibilidade, Transferência de Calor, Seguimento do Ponto de Máxima Potência.

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Nomenclature and Abbreviations

UNCED	United Nations Conference on Environment and Development
RES	Renewable Energy Sources
PV	Photovoltaic
PVT	Photovoltaic Thermal
DSSC	Dye-Sensitized Solar Cell
PSC	Perovskite Solar Cell
OSC	Organic Solar Cell
MPPT	Maximum Power Point Tracking
GC	Grid Connected
DC	Direct Current
ZnTTBPc	Zinc Tetra-Tert-Butyl Phthalocyanine
RGO	Reduce Graphene Oxide
2D	Two-Dimensional
NTE	Nominal Terrestrial Environment
NOCT	Nominal Operating Cell Temperature
INOCT	Installed Nominal Operating Cell Temperature
CFD	Computational Fluid Dynamics
CCS	Carbon Capture with Sequestration
HTF	Heat Transfer Fluid
TEG	Thermoelectric Generator
PCM	Phase Change Material
LTL	Low Temperature Level
MTL	Medium Temperature Level
HTL	High Temperature Level
CaF	Capacity Factor
FiY	Final Yield
TAC	Total Alternating Current
TPVRP	Total PV Rate Power
PeR	Performance Ratio
ReY	Reference Yield
TESE	Total Effective Solar Energy
RSEn	Standard Conditioned Reference Solar Energy
LCOE	Levelized Cost of Energy
KCL	Kirchoff's Current Law
HBE	Heat Balance Equation
HRF	Heat Removal Factor
MPP	Maximum Power Point
HE	Heat Extraction
I/O	Input/Output
IoT	Internet of Things

Chapter 1: Introduction

1.1 Background

Solar energy is the motivation of continuation and survival of humankind on this earth. Solar energy helps to sustain fundamental processes for life on earth, for example photosynthesis, ecosystem and rain cycle. The history of humankind indicates that solar energy is considered and being used for the betterment of civilization. The use of solar energy implementing modern energy technology is not so old which is exercising for the last 40 years, that is environmentally friendly and free source of energy [1].

The increase of population growth, technological advancement and economic improvement is inherently related to the total global demand of energy. This ongoing demand is mostly covered by using the fossil fuels resources such as oil, coal, gas and other sources. The main problem of using fossil fuels is that they produce an increased amount of CO_2 which is very harmful for the environment. This is also termed as greenhouse gas, and it is one of the main reasons for global warming [2]. In comparison to these resources, it is found that CO_2 is mostly produced by the use of coal and low CO_2 is produced by natural gas. Fossil fuels are non-renewable energy, and they can run out at any moment, besides fossil fuels are also the reason of ozone layer's greenhouse gas presence [3].

The main factor of economic development and industrialization is energy. Economic development and the energy relationship are very strong, which is recognized by historical data also. The increasing human activities have impact on the surroundings that also contributes to the serious environmental problems. These activities are led by the increasing world's population that triggers energy consumption and increasing dependency on industrial products is also associated with environmental pollution. Sustainable energy development and effective integration of renewable energy technology can help to reduce environmental problems and solve energy crisis. In this regard, a long term and sustainable plan is necessary to establish this system. The challenges and problems to achieve sustainable development in the world are addressed by the conference UNCED in 1992 that was held in June 1992. The main focus of this conference was to establish new policies for environmentally friendly energy resources [1].

Mainly industries, thermal energy sectors, electrical power and transportation areas are the main consumers of energy. From the data provided and studied by the International Energy Agency (IEA) it is observed that from 1971 to 2002 the demand for electricity almost tripled. The main reason for consuming more electricity is due to the increased use of modern technology and ongoing transportation facilities. According to the significant growth in China and India, global energy consumption is expected to rise by 3% to 5% annually for the next few years. It may not continue such an increase of energy consumption for a longer period. If it maintains so for example if it continues 2% yearly increase, then the energy demand will be doubled in the year 2037 and tripled in the year 2057. This prediction of energy consumption is an alert to consider and set the strategies and take necessary steps for technological advancements to accomplish the future energy demand [1].

The energy for transportation mostly comes from the oil which is around 95%. So, the future of transportation is dependent on the availability of the oil reserve, rate of productions and prices. Other sources of energy for transportation except oil can be methanol, biogases and ethanol. Another possible alternative is hydrogen that is possible to be economically produced and can be another reliable source of sustainable transportation of energy. Natural gas is used to compensate for the oil production shortage but because it has a higher consumption rate it cannot last longer. The largest reserve available among the fossil fuel is coal but burning of coal produces huge amount of carbon that pollutes the environment. Day by day, the use of coal is increasing in many countries like Australia, China, India including many other countries [1].

The use of fossil and other carbon generated energy resources are creating environmental pollution and also the reason for ozone layer depletion, acid rain and climate change. Acid rain pollutes environment, impact on ecosystems and creates vulnerable environment of excessive acidity which is produced by fossil fuels combustion and the combination of produced SO_2 and NO_x. Proper controlling of the pollutants like SO_2 and NO_x is the solution to stop acid rain issue. The ozone layer is depleting due to the harmful gas emissions and causing environmental issues. It also stops and damages ultraviolet radiation to reach the lower atmosphere level, additional problems to the human body also by the ozone layer depletion like eye damage and skin cancer.

The greenhouse effect is used to describe the warming of the earth's surface that includes clouds with water vapor. Currently it is associated with mostly CO_2 and other gases like N_2O, CFCs, CH_4, ozone and many other gases. It increases the earth's surface's temperature which is increased by the influence of greenhouse gases. Over the last century, the temperature of our earth's surface has increased about 0.6 ºC and sea level also risen by nearly 20 cm due to this effect [4]. These changes will have a significant impact on human life on the earth and will limit the activities and standard of living.

A recent reconstruction for the last 420,000 years of the Vostok ice core from Antarctica was conducted and the obtained data is provided in figure 1.1 [1]. Ice core has the capability to store and trap air bubbles of the previous years. The idea regarding the climatic situation of that time is extracted from the ice core analysis. Mainly two parameters are considered in this case temperature and atmospheric carbon dioxide concentration. It can be seen from figure 1.1 that both parameters have a similar pattern and continue to about 100,000 years.

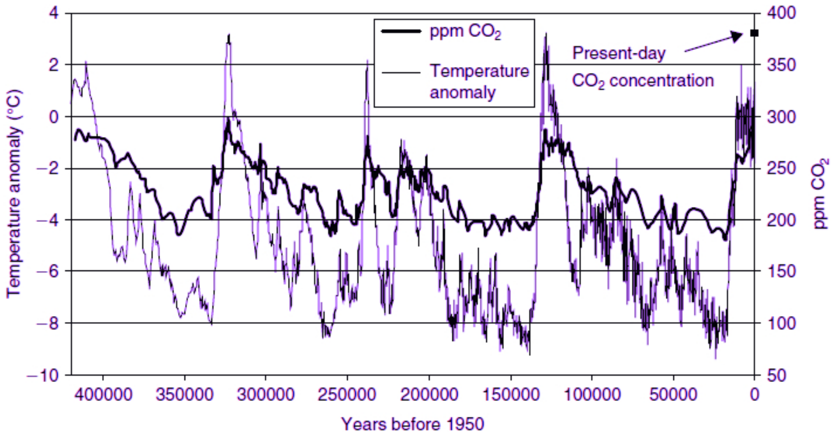

Figure 1.1: Vostok ice core temperature and CO_2 scenario [1].

Renewable energy technology is the type of energy techniques that uses naturally replenished resources to produce usable energy for the consumption. There are several types of renewable technologies like solar, wind, hydro, biomass and many others new system are introducing. Despite having higher energy potential there are challenges related to renewable energies like diffused and fully accessibility restrictions including locations dependency. In recent days, significant development has been achieved to reduce maintenance costs, improve efficiency and performance enhancing renewable energy techniques. Renewable energy installations and operations are mainly benefited by providing pollution decreased environment, energy saving system and provides job availability by creating new job opportunities [1].

Integration of renewable energies will reduce environmental pollution and global warming on the earth that will easier our life and enhance development of the industries and other sectors. Figure 1.2 provides long term average of the global surface temperature, and the data is obtained from the NASA website [5]. The analysis of the data shows that the year 2024 was the warmest year according to the recorded surface temperature. Additionally, the average temperature also indicates that the last 10 years were the warmest based on the temperature of our earth's surface. It is not too late to be serious and focus on reducing surface temperature by using sustainable and environmentally friendly energy resources otherwise it will have an extremely negative impact on our human life.

Almost 80% of total global consumed energy is generated from fossil fuels and the depletion of these resources is leading us to think seriously about the smarter integration of renewable energy production [6]. Electricity is one of the fundamentals for human civilization development and according to a statistic it is found that around 770 million people in the world are out of electricity access [7]. In [8], it shows that global energy demand is projected to rise by one-third by 2035. Most of the energy demand is covered by fossil fuels where renewable energy sources (RES) are also participating in global energy demand.

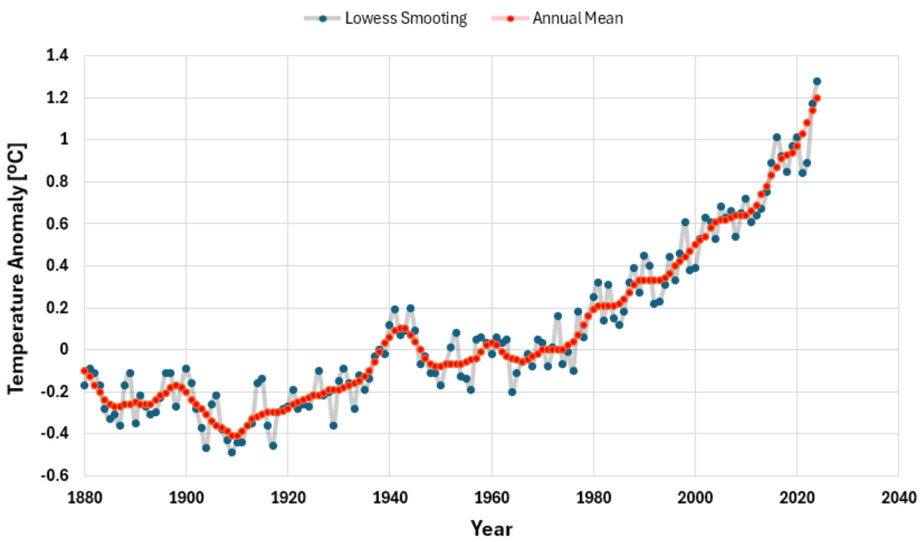

Figure 1.2: Average surface temperature comparison.

Among the renewable energy resources, load demand is increasingly met and adopted by solar and wind. These resources availability and high potential make it more suitable for the energy generation purpose [9]. Therefore, the use of photovoltaic (PV) technology increased recently and installed capacity reached to 488 GW where for wind turbine the capacity of the installed system was achieved to 564 GW [10]. Due to uncertainty and intermittent characteristics, wind and solar renewable energy are considered as weather dependent or intermittent and variable energy sources [11]. The improvement and technological development of these technologies are contributing to the research community and development on a broader scale. Popularity of solar energy is increasing continuously due to its flexible use for both commercial and residential applications, additionally it is also used in automotive industries, airplanes and to power the small spacecrafts also.

Figure 1.3 provides the information regarding global horizontal irradiation overview of the year 2024. It provides the long-term average of global horizontal irradiation of daily and yearly totals. It shows that in some part of Africa, Australia, Middle East and Latina America has the maximum irradiance value which varies from 2264 to 2702 kWh/m^2.

The demand for electricity is growing with the increasing population. It is expected to contribute 27% of total global electricity by 2050 with solar energy where 40% will be covered by solar concentration power and 60% will be covered by the solar photovoltaic system [12]. Global photovoltaic electricity potential by region is provided by the figure 1.4 [13]. It provides PV output power potential of long-term average for daily and yearly totals in this figure. It also indicates that many parts of Africa and middle east have higher PV power potential.

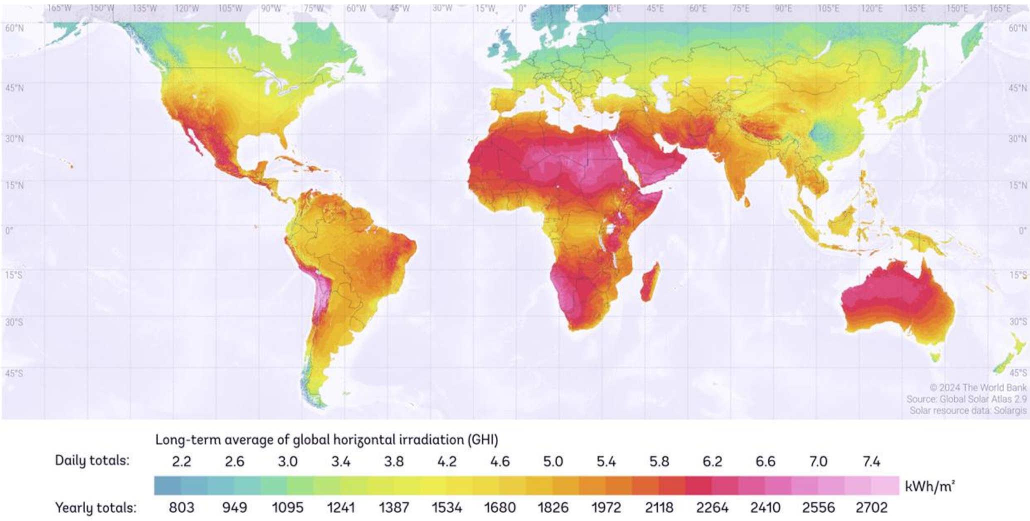

Figure 1.3: Overview of global horizontal irradiation (GHI) of the year 2024 [13].

The installed capacity of the solar system has increased for the last few years. It is provided in the work [14] that in between 2021 and 2022 the installed capacity of solar energy is increased approximately by 22%. The top three countries are in the race of solar installations are US, Japan and China, among these countries China is the biggest installer which installed almost 37% of the total solar system in the year 2022. Figure 1.5 provides solar energy installed capacity by country of the year 2022 [14].

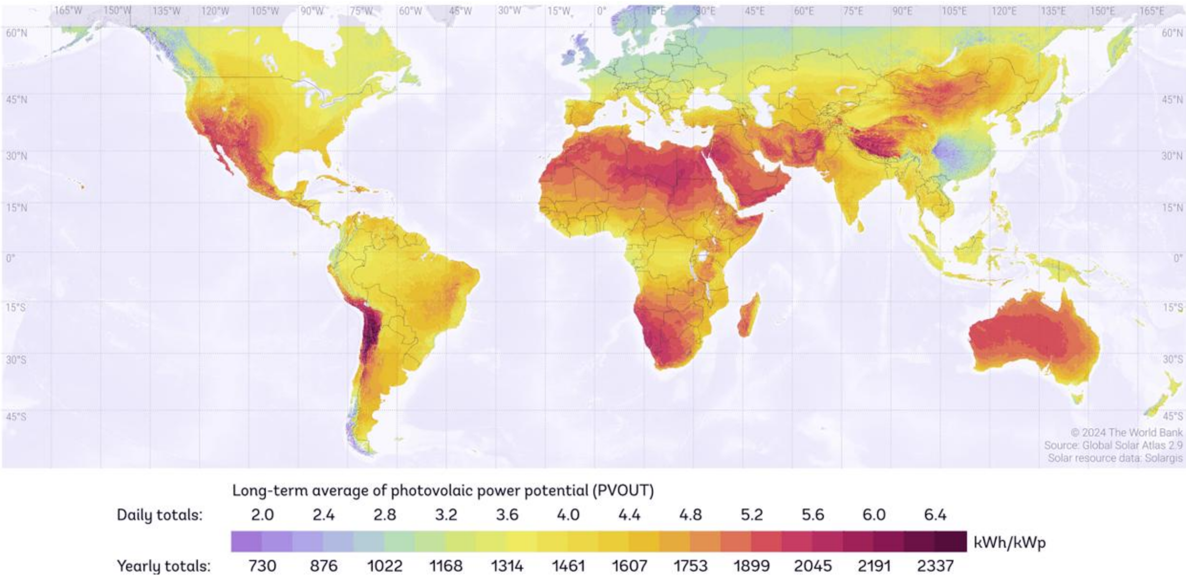

Figure 1.4: Overview of global PV electricity potential of the year 2024 [13].

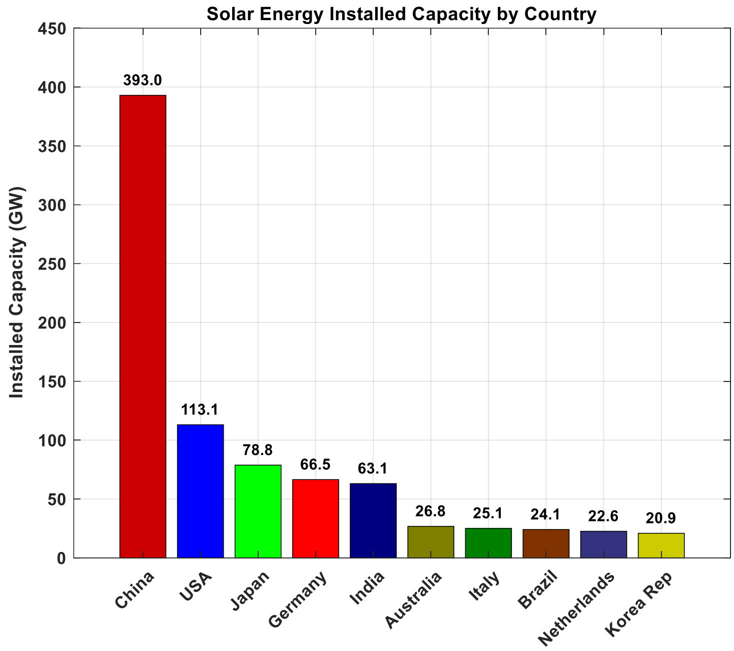

Figure 1.5: Top ten solar energy installers of the year 2022 [14].

Figure 1.5 shows that China is on the top among the installed solar facilities, then USA, Japan, Germany and the other countries. More specifically, the countries that have higher installed capacity of photovoltaic technology are provided by the figure 1.6 [14].

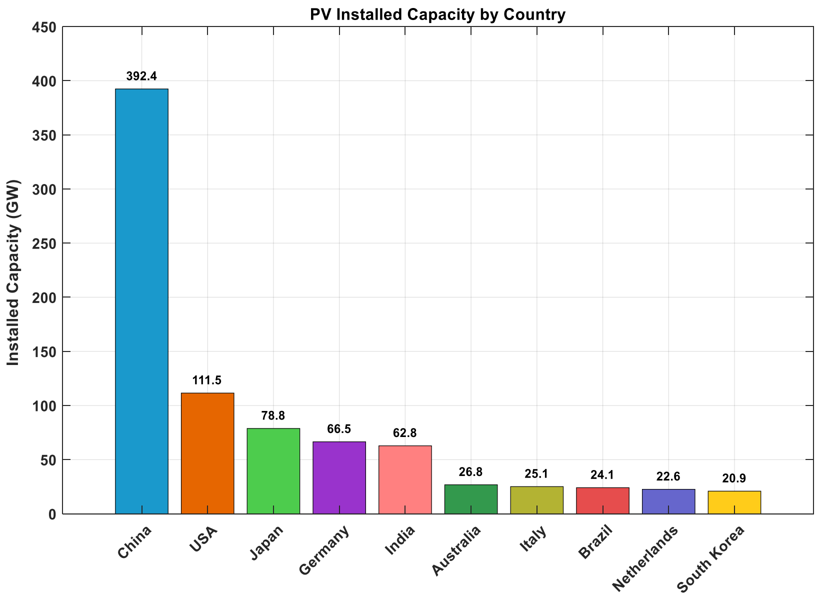

Figure 1.6: Top ten PV installers of the year 2022 [14].

Figure 1.6 provides the list of top 10 countries that shows the highest PV installation for the year 2022. It describes that China is on the top, then USA, Japan and other countries are on the list of installed PV countries. The installation of PV and solar energy structures is increasing every year.

1.2 PV and PVT System Challenges

The use of renewable energy, more specifically PV technology, has become one of the leading global issues as there is an increase in energy consumption where the majority of the energy is produced by fossil fuels on one side and global warming impact in another side [15]. Photovoltaic technology comprises of PV panel, storage, load, inverter and other related components. The energy conversion efficiency of PV system is a major concern nowadays. Currently up to 20% efficiency is obtained by the PV panel using the conventional energy conversion technology [16]. There are several factors, for example availability of solar radiation and energy conversion efficiency and output are directly dependent on each other. Classification of photovoltaic and photovoltaic thermal (PVT) system provides an insight into the system and its operation [17-18]. At a first glance, an appropriate classification is important to analyze the characteristics which can be based on different parameters. Photovoltaic system has different kinds and types that depend on the type of panel, types of metal structure and other phenomenon that is important to be classified before installing it. For PVT system classification are dependent on heat transfer fluid is also important that characterize the type of fluid is used for thermal energy extraction. In both PV and PVT systems, proper classification can help to optimize energy output and overall system efficiency. Various parameters are related to classification and optimization where it is significant to choose and implement appropriate values and parameters for this purpose.

In the PV and PVT systems there are very important parameters that have significant impact on the output and efficiency of these systems. Characterization and parameters sensitivity analysis are very significant in order to enhance performance analysis of the PVT system. In both the PV and PVT systems, there are some parameters that are significantly sensitive to the overall output and efficiency where there are some parameters that are less sensitive to the output. Among the external parameters of the PV and PVT system, irradiance and temperature are the most sensitive. Additionally, the internal parameters, variation and changes also have an impact on the output of the system. Measurement and characterization of various parameters based on their sensitivity are also necessary to be studied in an appropriate manner. A slight alteration or changes can have a higher impact on the overall system output. Due to the inability of full solar energy radiation absorption in the spectrum range the hybrid photovoltaic thermal solar panel is introduced [19 - 22]. The hybrid coupled system is capable of increasing panel efficiency with thermal and electrical energy output by reducing the panel temperature. The extracted thermal energy in the form of hot fluid stream by any heat transfer fluid like phase change material (PCM) or by water flow could be used for water or space heating. An efficient hybrid model using PCM or water is still not developed at an advanced level. Mathematical and thermal modeling with sensitivity analysis of hybrid PVT panel that could be used to estimate and observe parameters simultaneously in real time are not yet developed nor described in literature.

Establishment of a hybrid PVT system model based on mathematical analysis is the first step into the analysis phase. There are already a number of mathematical systems developed for the PV technology. Besides, electrical modeling also takes part in the performance analysis of the PVT system. Excessive temperature of the PV panel degrades the output and efficiency. Solar PVT system mitigates this issue using thermal mechanism and extracting thermal energy. Thermal modeling and management of thermal energy under varying conditions is an important issue to consider during modeling. It is also required to assess the impact of environmental parameters. An innovative, developed and complete modeling for hybrid PVT system is still a challenge due to the characteristics of the system.

In thermal modeling, the use of heat transfer fluid is important as it is the factor that participates in removing excess heat from the panel and extracting the thermal energy. Choosing efficient and effective fluid for heat transfer purpose is also significant for this system. In many cases water is used, phase change material and other type of fluid as heat transfer fluid. It is also necessary to consider related costs, design requirements and user comfort in this case. Heat exchanger pipe which is the most important part of the PVT thermal section that participates in the thermal extraction of this system. The amount of thermal energy also depends explicitly on the heat exchanger pipe. Because, the pipes internal and external parameters, type of metals used, and other properties influence greatly the system's thermal output. Appropriate choice of the heat exchanger pipe is really significant in the context of improved thermal energy extraction.

Efficiency is the main target of the modern energy management system. Photovoltaic technology is still struggling with efficiency, and continuous effort is given to increase efficiency by improving performance. For promoting an increasing efficiency of this system and including operating cost reduction, maximum power point tracking (MPPT) is an important approach [23-24]. If a system can always track the MPP position, then it will be able to provide the efficient output. Integration of an MPPT method into hybrid PVT system is dependent on many parameters. The existing MPPT methods [25-28] are mostly based on iteration, continuous increment and optimization techniques. In the literature different aspects like instrumentation cost, required sensors, effective range and mainly convergence speed are considered for the case of MPPT execution. The challenge is to execute an MPPT method which is non-iterative [29-32], less complex, has high convergence speed and can be obtained by simple analytical solution. The implementation of a non-iterative MPPT method will provide durable, less complex and efficient photovoltaic energy management system.

Nowadays, aging issue is becoming a common phenomenon which is impacting negatively the output of photovoltaic system. This effect of PV panel mainly signifies continuous deterioration and degradation which results in overall energy production reduction and economic loss [33-34]. Additionally, hotspot in the PV module is also affecting the efficiency of the photovoltaic system which is caused due to excessive temperature or weather related problems. Besides, PV system vulnerability and proper maintenance with safe and efficient operation depends on its effective fault identification and monitoring system [35]. Various fault detection techniques by measurement equipment, data-driven [36] and model based are already implemented and presented in the literature that can detect and monitor fault accurately and efficiently in real time [35]. Still there are some issues like specific problem with identified panel's fault detection using low-cost and simplified device is in the improvement stage.

A low-cost instrumentation of PV system for experimentation, monitoring and MPPT observation is an ongoing study [33-36]. Real-time data measurement and characterization [37], modeling and monitoring with low-cost embedded system for hybrid PVT technology is still under development. It provides an efficient way to analyze, study and observe the hybrid PV panel's characteristics with MPPT control and implementation. The low-cost digital signal processing (DSP) units allows integration of other environmental parameters into a mathematical model which allows creation of an automatic instrumentation system. Development of this system for hybrid PVT system will provide an efficient and intelligent energy management system [38-41].

1.3 Motivation and Objectives

The general objective and motivation of this work is to contribute to the development of renewable energy technology "to ensure access to affordable, reliable, sustainable and modern energy for all" (UN sustainable development goal no. 7). The main objective is to dedicate an effective contribution to the solar hybrid photovoltaic thermal technology to increase efficiency by overcoming the limitations identified in the state of the art. The proposed work is composed of classification, parameters characterization, sensitivity analysis, modeling, simulation and both thermal and electrical efficiency analysis, further development and implementation of hybrid PVT technology. The objectives are as follows:

- Classification and parameters optimization provides an insight into the hybrid PVT system. Classification based on several criteria such as designing of the system, heat extraction medium and overall classification is essential for the performance improvement of the system. Additionally, reviewing the recent literature study based on appropriate classification is necessary to establish an updated model. A novel parametric and optimized model of hybrid PVT technology is the key to successful implementation of that system. Providing an updated classification and parametric model considering several factors of PVT system is the primary objective of this work.
- Parameters characterization and identification with sensitivity analysis of hybrid PVT will provide the knowledge to the users and industrial entities about primary conditions regarding parameters of the panel. Characterization will also provide the opportunity to select and perform the operation choosing the best fit parameters. Sensitivity analysis of various parameters

indicates how sensitive a factor to the system during operation and the outcome helps to identify and set optimized value of the parameter for the best output. Variation of several parameters also impact the MPP value which can be identified by sensitivity analysis also.

- The improvement of mathematical model will contribute to predicting the panel's electrical and thermal performance. Electrical model with equivalent electrical circuit analyzes and determines the electrical output of the system. The inclusion of thermal loss model in the form of electrical model provides equivalent circuit of thermal output in the form of electrical energy. Thermal modeling is intended to enhance energy conversion efficiency as it adds total output of the system. Additionally, physical modeling dedicates designing of a solar PVT collector for better irradiance absorption and thermal energy management.
- Thermal regulations for energy balances and spectral analysis for the improvement of electrical and thermal energy production is an important part of the hybrid PVT system. A suitable PCM/ HTF will reduce panel temperature in the acceptance range resulting in increased energy production including addition of thermal energy for the users and storing purpose. A PVT water based system will be able to provide hot water in both residential houses and commercial buildings thus reducing overall electricity consumption.
- Obtaining and tracking MPP of a PVT system is crucial for the efficiency and performance analysis of this system. The main objective of including MPP analysis is to integrate a non-iterative maximum power point tracking system in this work. Implemented MPPT method in this study is based on non-iteration and less complexity which will require simple instruments and fast tracking of maximum power point in the PVT system.
- PV panel degrades with the passing of time and other issues like dust, high temperature and irregular maintenance. The degradation of the module results in decreasing output and efficiency of a system that also negatively impact the economical aspect. Besides, fault in a PVT system may occur for various other reasons. If there is an issue with a single module it impacts total output of the system. So, detection of exact fault in the exact module is necessary for improved efficiency. Real time measurement and simulation using low-cost instruments provide the scope to practical implementation of developed theoretical ideas. An effective automatic low-cost virtual monitoring system with fault identification will increase the proposed system reliability.

1.4 Thesis Organization

This thesis provides a complete overview of the management and performance improvement of hybrid PVT system. It is mainly divided into five main chapters. The first chapter is the present chapter that discusses the general overview of the energy management system, existing energy technologies, and the current situation of renewable and solar energy system in the world. Challenges of developing and performance improvement of photovoltaic thermal system are also discussed and analyzed here. A brief analysis on motivation and objectives of this thesis is also described at the end.

Chapter 2 provides a general overview of the photovoltaic and photovoltaic thermal system. Principles of photovoltaic technology including design configuration, cell classification, PV system infrastructure and classification are also discussed. Study of PV system modeling, temperature effect analysis and existing cooling technologies are also discussed. Hybrid PVT system subsection includes classification analysis based on several criteria and discussion of parametric optimization. Finally, obtained classification of hybrid PVT system based on parametric analysis and optimization system is significantly provided.

Chapter 3 discusses detailed modeling and development of hybrid PVT system. A brief introduction to PVT system provides an enhanced idea regarding this technology. An extensive study and analysis regarding classification of PVT system is also provided here. Discussion of its application in various sectors provides its importance for developing this system. PVT systems modeling includes brief overview of performance study, electrical modeling, thermal modeling, thermal loss modeling and optical modeling of the hybrid PVT system. Modeling of parameters and sensitivity analysis are also discussed in this section. MPPT modeling analysis includes discussion of existing iterative methods and a developed non-iterative method. At the end, a subsection is dedicated to modeling PVT system monitoring and Fault detection to obtain real-time observations.

Chapter 4 is dedicated to describe and present the results obtained using the developed PVT system. Results obtained by the parameters and sensitivity analysis are also presented here. The results developed by the effect of the most important parameters, namely irradiance, temperature, wind speed and humidity are studied in this section. It also discusses and provides outputs of the developed innovative thermal loss model. An extensive simulation model of hybrid PVT system is modeled and provided in this section. A brief discussion on provided simulation model and related input parameters are also discussed here. Simulation results analysis subsection provides obtained output and performance analysis of the system. Input and output analysis including efficiency comparison of the simulation model using three different types of heat exchanger pipes are discussed and analyzed in this part. Results obtained using non-iterative MPPT model are provided and compared with the iterative models. Finally, observation and results of real-time monitoring and fault detection system are discussed.

Chapter 5 is reserved for the concluding remarks of the work developed in this thesis. It also discusses ongoing development and future works which are the continuation of this doctoral thesis.

Chapter 2: Photovoltaic and Photovoltaic Thermal System

2.1 Solar Energy and Photovoltaic System

Solar Energy

Solar energy is a form of electromagnetic radiation produced by the fusion processes occurring at the core of the Sun. The value of intensity of solar radiation is obtained roughly equal to 1370 Wm^{-2} considering the outside atmosphere of the Earth. But, in reality due to atmospheric friction, it does not reach to that highest level to the Earth which ranges around 0 to 1100 Wm^{-2}. This incident of solar energy even in a small portion is far greater than the total consumption. It is important to capture this incident of energy on the Earth in order to reduce dependence on fossil fuel resources. Advanced solar energy systems are becoming more affordable due to technological development, cost reduction and environment friendliness. The fact is that the Earth's atmosphere sends back by reflection about 25% of this energy which is not received by the Earth in reality. The Earth's surface receives just 47% of the energy as it is the same amount that is able to pass through its atmosphere. This energy makes life on earth possible and providing a source of energy for plants. Among this radiation 18% is held by atmospheric particles. Eventually, all of the irradiance that is captured by the earth goes back to space in the form of converted heat [42]. The percentage of the radiation that is absorbed/reflected depending on several parameters are provided in the figure 2.1.

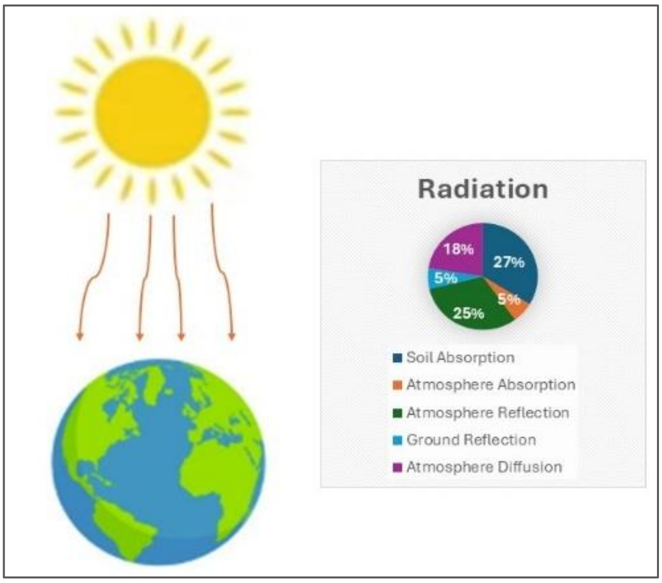

Figure 2.1: Earth and atmospheric Solar energy flow percentage [42].

Figure 2.1 shows that the soil absorbs 27% of incoming energy, atmosphere absorbs 25% of the energy, atmosphere reflects 5%, atmosphere diffuses 18%, ground reflects 5% of the energy.

The use of solar radiation into energy production technology is advantageous due to its limitless and non-depletion characteristics despite the recycling issues and waste management. Additionally, this technology is also a feasible choice for everyone as the sunlight reaches almost everywhere. Use of solar energy technology is desirable because of their practicality for household installations and relative light weight properties. There are two parts of solar energy, namely extraterrestrials which lie above atmospheric level, and the other one is global that stays under the atmospheric level. Both diffuse and direct radiation may be present in the global type of solar energy which falls on the horizontal surface. The usual components to measure direct beam type of irradiance is by using pyrheliometer and diffuse type by using solarimeters, actinography and mainly pyranometers. The development of solar energy models to study and establish the mathematical relationships between energy and meteorological factors like ratio of sunlight, outside temperature, humidity, wind speed is possible to determine using the measured values. This type of established model can be utilized for diffuse and direct data prediction analysis using provided meteorological data of the system [43].

In the past, linear models and nonlinear models were considered as the foundation for the mostly used types of solar energy models [44]. The main purpose of these models is to provide a link between a few climatic parameters and solar energy on the horizontal surface. In linear models, simplified linear functions are used and in the nonlinear models third/fourth degree polynomial functions are considered. It is possible to obtain global solar output by means of total sunny hours using either linear or nonlinear models. From the perspective of extraterrestrial energy output, the well-known linear model to illustrate global solar output is obtained by [45]

$$\frac{E_T}{E_{Extra}} = a + b\frac{S}{S_o}\ , \tag{2.1}$$

where S is day length and S_o is total sunny hours, a and b are model coefficients, E_T is total solar energy and E_{Extra} is extraterrestrial energy from the sun. Instead of taking account of the sunshine hours and the solar radiation that first reaches the ground, the Angstrom model is considered using a modified day-length applied to measure the solar radiation while considering atmospheric and cloud conditions to create an improved model of global solar energy. The specific quadratic model [46]**,** is obtained by adding a nonlinear element to the Angstrom model

$$\frac{E_T}{E_{Extra}} = a + b\frac{S}{S_o} + c\left(\frac{S}{S_o}\right)^2\ , \tag{2.2}$$

where c is the coefficient. This model is obtained using the popular Angstrom model. There are some other simple models like regression that can be provided for global solar energy based on diffuse indices including clearness. Relative humidity, temperature of the ambient, daily sunny hours are the main parameters of the global irradiance.

Modeling of diffuse solar energy is also significant in relation to solar technology development. Direct meteorological data or an empirical correlation can be used to determine the relationship between the sky clearness index and the mean daily irradiation of diffuse and global incident with respect to a horizontal surface [47]. The relationship of $\left(E_d / E_T\right)$ where the clearness index is K_T used in several numerical models in order to obtain diffuse solar output is determined by

$$\frac{E_d}{E_T} = a + bK_T \tag{2.3}$$

In the provided equation, global/total solar power is E_T and diffuse solar power is E_d where clearness index K_T. This linear equation of diffuse solar output is developed based on clearness index of the surroundings and total/global solar power. This type of equation is implemented to model diffuse radiation in many works [43]. Nonetheless, the given non-linear model can provide the same link between the parameters diffuse and global solar power and the clearness index. The described non-linear model is obtained as

$$\frac{E_d}{E_T} = a + bK_T + cK_T^{\,2} + dK_T^{\,3} \ . \tag{2.4}$$

This model is related to the relative humidity, atmospheric temperature, irradiation, ratio of sunlight and clearness index. But there are other models based on linear and non-linear system that did not consider the parameters humidity and related temperature.

There are also challenges to be considered during the modelling of solar energy. The data precision of predicted value is the most crucial factor in solar power modeling though heuristic optimization techniques are employed to solve this issue nowadays as it shows appropriate result than other optimization techniques based on linear and non-linear system. Model simplicity also needs to be considered for solar modeling purpose that will enhance accuracy and non-complexity. There are other challenges that appears in the modeling of solar energy for example data availability, complexity in artificial intelligence-based modeling [41].

Photovoltaic Technology

It has been proved that the use of sunlight to generate electrical energy is one of the most potential ways to address global energy challenges. Photovoltaic panel is the type of semiconductor device constructed with several solar cells that are able to convert irradiance into electricity.

PV Cell

The key component of solar energy production unit that transforms sunlight into electrical energy is a photovoltaic cell which is constructed based on p-n junction. Positively charged holes produced by acceptor impurity atoms are referred to as p-type, whereas negatively charged electrons provided by donor impurity atoms are referred to as n-type. The operation principle of a solar cell based on incident photon is provided in figure 2.2.

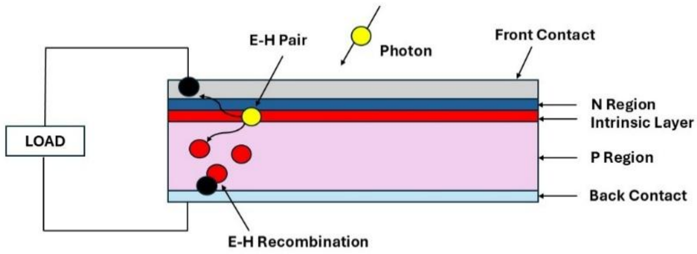

Figure 2.2: PV cell operation [48].

Solar cell in a PV system operates based on the effect of photovoltaic conversion. Inside the solar cell, in the semiconductor's p-n junction photons are absorbed to produce charge carriers are also defined as electron-hole pairs. From the valence band to the conduction band using the photon energy which overcomes the bandgap energy of the doped semiconductor material that creates a void is named as hole and it is obtained by exciting the electron. The extra photon energy provides the electron or hole with additional kinetic energy and generates electron-hole pair [48]. In the semiconductor, the extra energy is released as heat [49]. As a result, the charge carriers produced by the light are subsequently separated. In an external solar circuit, electrons can go out over the n-region and travel the circuit before recombining the holes, while the holes can move away using p-region from the junction. An electric circuit can be powered by the split electrons, and it will recombine with the holes as soon as they travel across the circuit. Most importantly, it is necessary to design the n-type finer in comparison to p-type. As a result, the electrons can quickly move across the circuit and produce current before joining the holes again. In addition, to improve light transmission to the semiconductor material and minimize surface reflection, anti-reflective coating is also added in the n-layer of the PV cell.

Photovoltaic System

Photovoltaic panel is a combination of series and parallel cells to produce power output considering certain internal and external parameters. Many solar cells are coupled to one another in parallel or series to boost the power output. This kind of design is referred to as a PV module or solar cell module. Additionally, solar panels are produced with the appropriate voltage and current levels. The power generated by the module connections ranges from a few watts to megawatts, depending on the demand. An overview of the PV system design configuration is shown in figure 2.3.

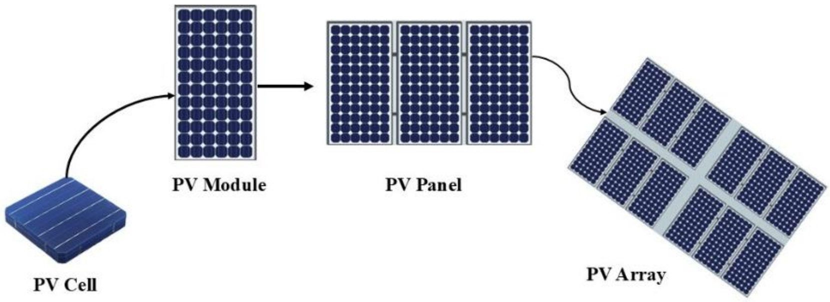

Figure 2.3: Design configuration of photovoltaic system.

The physical configuration of photovoltaic system generally starts with PV cell which forms PV module, adding modules form panels and finally it is transformed into array. With this described technology, solar irradiance is directly converted into electricity without the need for a conversion medium. Consequently, these devices are designed to be operated efficiently without complexity [50]. Use of this technology is an advantage because it produces higher outputs in less inputs. That is why PV technology is becoming popular not only for clean energy production but also for its technological simplicity. Nonetheless, this system needs to be improved in many contexts like efficiency and better overall output for higher performance.

Silicon is a typical semiconductor material used in photovoltaic devices to generate power. The device works on the principle of activating electrons by providing more energy. The way this device operates is based on the idea that electrons are activated from lower energy levels to higher energy level by solar energy input. Electricity is produced by the number of holes and free electrons created by this activation mechanism in these semi-conductors [51]. The most frequently utilized semiconductors in photovoltaic system includes monocrystalline, microcrystalline, polycrystalline silicon, along with cadmium telluride, indium diselenide and copper. But a variety of factors influence the choice of these materials. PV systems use a variety of components including arrays, modules, and cells for producing power. In order to improve operational efficiency, a variety of methods are employed to regulate and control which structures include electronic devices, electrical connections, and mechanical equipment [52].

PV technology has been the subject of many research efforts to enhance their efficiency for a long time, and it's crucial to remember that this is a rapidly expanding technology that doubles its output every two years, with an average increase of 48% since 2002 [52]. A classification of PV system solar cell based on various components is provided by the figure 2.4.

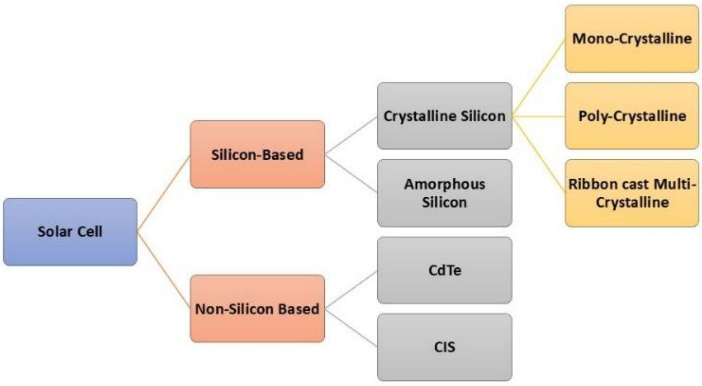

Figure 2.4: Classification of solar cell [53].

Generally, solar cells of photovoltaic system are divided into two main parts silicon-based and non-silicon based. In crystalline silicon there are several other subparts like mono-crystalline, poly-crystalline and ribbon cast multi-crystalline. Among all of these, crystalline silicon is significantly more commonly used than other solar cell technologies due to its excellent efficiency and lower cost [53]. Recent studies have shown that multi-crystalline technology may reach up to a bit higher efficiency [54]. The research article [55] provides an explanation of the latest photovoltaic production technique and its uses. Additionally, it assesses the most current research on photovoltaic power, its applications, and building integration in the research work provided in [56]. Analysis of types and properties of cell technologies is also very significant in terms of energy and efficiency study.

Among many of the semiconductor types, Gallium arsenide (GaAs) is a composite semiconductor which is made of a combination of gallium and arsenide components. To increase efficiency, it may be possible to combine with other elements like phosphorus, aluminum and antimony. The drawback of using GaAs is that it is very costly and that is why it has less attraction to the industries. Dye-sensitized solar cell (DSSC) technology was discovered in 1991 by Brian Oregano and Micael Gretel. A photo-sensitized anode and an electrolyte are used to form this semiconductor. Recent photovoltaic development technologies have attracted attention due to its lower production costs, increased efficiency, and ability to interact with low radiation levels. It is also known that some dye-sensitized materials, like those based on dyes containing polythiophene and porphyrins, that help to increase power conversion efficiency and stability in commercial applications [57].

The purpose of developing perovskite solar cells (PSC) is to create efficient and less costly solar cells. PSC can be produced with either thin-film architecture or mesoporous architecture. Despite being produced using a straightforward chemical process, PSCs possess an impressive power conversion efficiency of about 22.1% [58]. The newest and most popular technology is the Organic Solar Cell (OSC), which has conversion efficiency about 9% and it is inexpensive also. However, further efficiency improvement is required if it is to be used for commercial applications. A p-n junction is necessary for semiconductor production, whereas a donor electron with acceptor materials is required for OSC [56].

Several investigations have shown that geographical differences, whether in urban or rural areas, are related to the implementation of an effective photovoltaic system. In addition to changes in wind speed, moisture content, dust, and the buildup of air pollutants on PV panel, variations in geographic location also have a direct influence on the intensity of solar radiation. Because of each of these factors, PV can face low productivity and performance fluctuations [59]. Numerous research studies examine and evaluate how climate conditions affect PV. Continuous high temperatures and intense solar exposure have been observed and results in significantly affecting PV output. Additionally, the panel temperature effect was investigated and found to be unchanged by the wind impact in [60]. As the temperature of the air rises, the voltage decreases significantly while current increases very little, which leads to a large reduction in power output [53].

The solar cell market is dominated by crystalline silicon, however thin film or other technology such as amorphous technologies are also widely integrated in the PV applications. Unlike silicon-based PV cells, that are polycrystalline and mono-crystalline, it is inefficient and does not change much with temperature. However, it has some disadvantages over crystalline silicon, such as decreased efficiency and a shorter lifespan. However, generating electricity using PV technology is significantly more expensive than generating heat energy. Therefore, the ability of photovoltaic applications to generate heat energy is of great interest to academics. The fact that current PV technology does not have the capability to collect energy from the whole spectrum is a limitation. In the PV panel, electrical efficiency reduces due to the temperature induced on it which is because of absorbed sunlight [61].

Decentralized power is described by power generation that is closer to the centers of demand and primarily focuses on supplying local energy demands. The extent of decentralization determines whether decentralized energy systems are implemented. In villages, decentralization involves local participation in system management and provides energy to fulfill local energy demands. The grid may receive the excess power from this type of installments in some cases. Additionally, whether the system functions in stand-alone (SA) or grid-connected (GC) mode depends on the degree of decentralization. The photovoltaic system is divided mainly into two parts, name grid-connected and standalone system.

An autonomous decentralized power system coupled with an electrical transmission and distribution network is known as a grid-connected energy system. This type of system is convenient to use near grid facilities. The source of supply in this system determines the operational capacity and only in the presence of the supply sources is the system able to operate. When supply sources are unavailable, the system itself has to put aside local demand due to its supply-driven operation. Alternatively, the system might just exist to supply the grid with extra energy, or it might be used to meet local demand. Grid connectivity makes it possible to build up systems on a reasonably big scale, which increases the operation's economic sustainability by allowing them to run under high plant load factors. In this type of PV system, the grid functions as a battery utilizing infinite reserve capacity and helps to load variations due to several reasons. The produced electricity can continuously be captured and stored, and surplus output does not get wasted as the storage is almost limitless. Consequently, a grid-connected system's overall efficiency will be greater than that of a standalone system. Apart from the system's initial cost, there are further expenses for the system's grid interface [62].

The term "stand-alone" refers to systems that generate electricity separately from the utility grid. These are better suited for the most isolated areas without access to the grid and without any alternative energy sources. Most photovoltaic installations in distant parts of the world are stand-alone systems since they are frequently the most economical option for applications located beyond the utility grid. This type of system experience issues of intrinsic drawbacks such as reduced capacity factor, high battery expenses and limited ability to hold electricity necessitating the disposal of the additional energy produced. The operational capacity of these energy systems corresponds to the demand. The demands of the local area are given prior consideration. In remote areas where the system has to function at lower level of load demand, these systems are suitable. Due to the fact that most stand-alone systems rely on renewable energy technologies, such as solar PV which are not always accessible, and operation is generally seasonal. It is mainly focused on small scale usage and does not require excessive demand from existing renewable energy resources. Due to their lack of utility grid connectivity, these systems must store electricity generated during off-peak demand hours using batteries, which adds the cost of batteries and storage; otherwise, the excess power must be released [62]. An overview of a grid-connected system with its related parameters is shown in the figure 2.5.

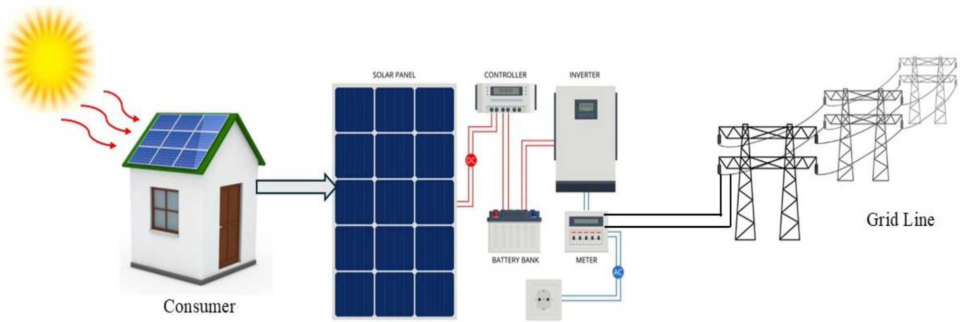

Figure 2.5: Grid-connected photovoltaic system example.

Grid connected renewable energy system generates electricity and provides the surplus electricity to the grid. For a PV grid-connected system, the generated DC power is converted to AC power by an inverter, which then supplies energy to both the connected load and the grid. Among the various components, photovoltaic module is inherent, and it can be based on monocrystalline, polycrystalline or any other type. The junction boxes are utilized where all of the PV strings are connected to the power converter. The device that transforms DC power into AC power is an on-grid inverter. One of the most necessary components of a PV system to connect to the modern electricity industry is this type of converter. There are several different kinds of inverters on the market, ranging in rating from low kVA to higher kVA. Currently, present inverters have a larger input Vdc range and MPPT enabled.

The electrical system cannot be interconnected with the electrical power grid until the main panel is in place. In the purpose of disconnection of the solar power plant from the grid, electromechanical devices are typically utilized. Monitoring the flow of electricity from the electrical power production facility to the electric utility grid is accomplished with a device called a net meter. This allows excess energy produced by solar systems to be supplied to the utility. The electric grid is a network of electrical power sources that connects energy suppliers and load centers. It is a key component of the electrical power system network, serving as a link connecting distribution lines, power transmission lines, and power producing plants. Electric power generated from any source, renewable or non-renewable, is sent to desired location and then distributed to customers based on their needs [63]. A classification of solar PV system is provided in figure 2.6.

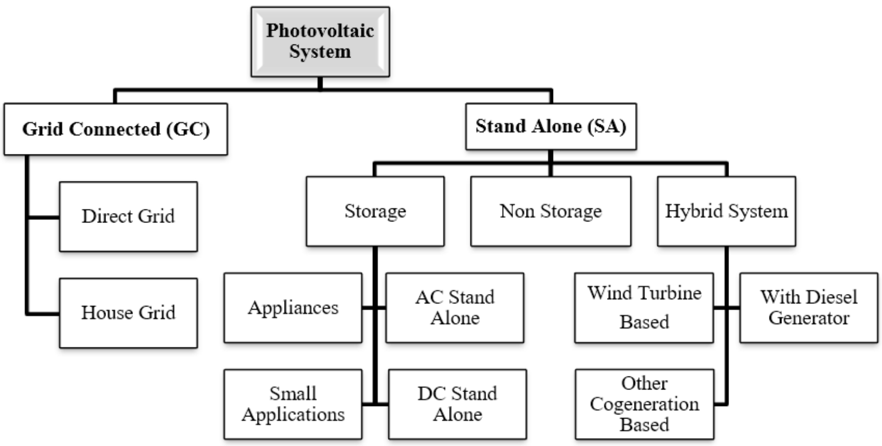

Figure 2.6: Classification of solar PV system.

Photovoltaic System Modeling

PV energy harvesting and conversion to electricity for daily use and also to provide in the grid is not only useful but also a substitute for burning fossils. Nevertheless, there are issues and limits with this technology that need to be resolved before PV energy is expanded for extensive utilization. These issues are mostly being faced by PV system modeling, and precise characterization which is necessary for system design [64]. The significance of PV modeling in determining and calculating PV system parameters for all weather circumstances has made it one of the most crucial steps in the PV power combining process [65]. Parameters extraction and modeling accuracy are found to be the most significant aspect in this case. Additionally, the accuracy of the PV model is strongly correlated with the variety of PV parameters considered; the five-parameter model is perhaps the most precise of these models [66-67]. An equivalent ideal four parameter equivalent electric circuit model of a PV cell is provided in the figure 2.7 [68].

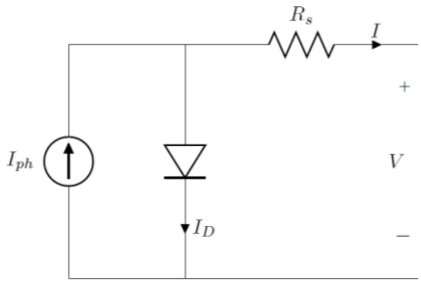

Figure 2.7: Electrical equivalent circuit (Four parameter Model).

Current-voltage (I-V) relationship obtained using this four parameter model is described as [68-69]

$$I = I_{ph} - I_D = I_{ph} - I_s\left(\exp\left(\frac{qV + qR_sI}{NKT}\right) - 1\right), \tag{2.5}$$

where photo current symbol is I_{ph} and it is irradiance proportional, reverse saturation current of the diode is I_s, R_s is series resistance, thermal voltage of the diode is $V_t = {NKT}/{q}$, ideality factor of the diode is N, q is charge of electron value, K is Boltzmann's constant, temperature of the cell is T which is thought to be equivalent to the P-N junction's temperature. Short circuit current, open circuit voltage, and diode ideality factor all have a significant impact on the solar cell's characteristics.

An electrical equivalent circuit model based on single diode is illustrated in figure 2.8. A constant current source and a diode connected in parallel from this type of equivalent circuit where in the space charge area ideality factor is considered for recombination [70].

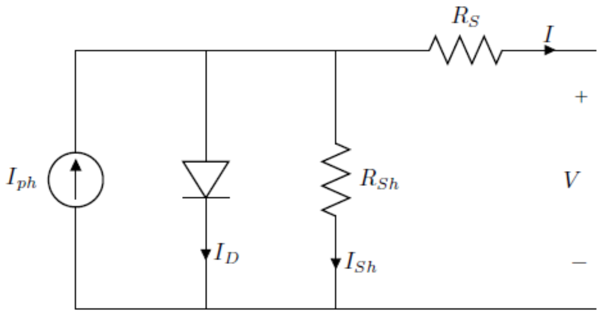

Figure 2.8: Electrical equivalent circuit (Five Parameter Model).

This is also known as a full model using single diode, detailed model or single-exponential model. This model is constructed with parallel resistance to increase its accuracy.

Additionally, it considers the losses resulting from leakage current in and within its cell due to impurities, including crystal deficiency. The current equation based on this model and relationship with other parameters can be shown as [68]

$$I = I_{ph} - I_s\left(\exp\left(\frac{qV + qR_sI}{NKT}\right) - 1\right) - \frac{V + R_sI}{R_{sh}}. \tag{2.6}$$

The induced voltage equation at the load is [27]

$$V = I_{ph}R_{sh} - IR_s + I_s\left(\exp\left(\frac{qV + qR_sI}{NKT}\right) - 1\right) - IR_s, \tag{2.7}$$

where the PV cell's maximum current under particular temperature and irradiation conditions is defined as short circuit current (I_{sc}) of the circuit. It is equivalent to having zero output power and zero output voltage. Shunt resistance is R_{sh}. The highest voltage potential that the PV cell produces under particular temperature and irradiance condition is defined as open circuit voltage (V_{oc}). It is also equivalent to zero current output and zero output power. The maximum value obtained for current at specific environmental conditions for this given model is the current at maximum power (I_{mp}). This current represents as a PV cells rated current. The obtained voltage under specific circumstances and environmental conditions of maximum power is defined as the voltage at maximum power (V_{mp}). This value is considered as the rated voltage of the PV system [68].

It is assumed that there is less impact in depletion region due to recombination loss in the five parameter or single diode model. However, an operational solar cell must account for such recombination loss and the double diode model was introduced for this particular reason [71]. The single diode model provides satisfactory accuracy level, but in real-world scenarios, PV cell saturation current arises due to the combined effects of charge diffusion and recombination within the depletion region [72]. Despite being rather complex and having a slow computing speed, this model can be recognized by its precise accuracy. When compared to the single diode model, it has been demonstrated that this model shows accurate behavior of a PV system at low irradiance values. The electrical equivalent circuit for a double diode model is represented as [68]

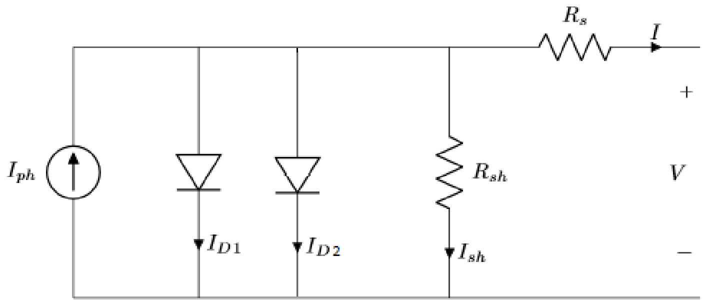

Figure 2.9: Electrical equivalent circuit (Double Diode Model).

This type of model is also referred to as double exponential model and it is constructed by adding an additional diode with the single diode model. In this type of model, diffusion current is produced by the first diode. The current-voltage (I-V) curve is determined by the following equation

$$I = I_{ph} - I_{D1} - I_{D2} - I_{sh} \quad (2.8)$$

The reverse saturation current for both of the diode is obtained as [68]

$$I_{D1} = I_{s1}\left(\exp\left(\frac{qV + qR_s I}{N_1 KT}\right) - 1\right), \quad (2.9)$$

and,

$$I_{D2} = I_{s2}\left(\exp\left(\frac{qV + qR_s I}{N_2 KT}\right) - 1\right), \quad (2.10)$$

where load (I) current equation of this double diode model is described as [68]

$$I = I_{ph} - I_{s1}\left(\exp\left(\frac{qV + qR_s I}{N_1 KT}\right) - 1\right) - I_{s2}\left(\exp\left(\frac{qV + qR_s I}{N_2 KT}\right) - 1\right) - \frac{V + R_s I}{R_{sh}}, \quad (2.11)$$

where ideality factor for the first and second diode is N_1 and N_2 respectively, I_{s1} and I_{s2} are the reverse saturation current for both diodes. In comparison to a single diode model, it is obtained that the double diode model is capable of attaining improved accuracy, especially while it receives low irradiance rates and under partial shadowing scenarios. Although the number of calculated parameters is increased by adding another diode, the double diode model has improved accuracy for overall parameters characterization. This type of model was adopted to increase accuracy and improve shortcomings of five parameter model. But the key concern is simulation time for double diode model which takes longer during parameters estimation [68].

It is fundamental to describe the important parameters related to PV system in order to understand the behavior of the system. It is also essential to understand how the parameters vary depending on the standard operating environmental parameters.

- *Photo Current (*I_{ph}*)*

There are two main processes of this current generation, and it is called as photo current or current from light/light generated current. It is temperature and irradiance dependent; the equation is obtained as [68]

$$I_{ph} = I_{ph,ref}\left(\frac{I_{Irr}}{I_{Irr,ref}}\right)\left[1+\alpha'_{T}\right], \tag{2.12}$$

where the photocurrent under standard conditions is denoted by $I_{ph,ref}$, with regards to temperature its short-circuit current relative temperature coefficient represents the rate at which the current changes. Solar irradiance is I_{Irr} and irradiance at reference is $I_{Irr,ref}$. The short circuit current relative temperature is α'_{T} . The relationship can be established by using the following formula

$$\alpha_T I_{sc} = \alpha'_{T} I_{ph,ref} . \tag{2.13}$$

- *Temperature of PV Cell (*T*)*

The efficiency of a PV cell is largely dependent on the temperature of that PV cell including panel. The fluctuation of temperature is triggered by solar irradiance variation and related temperature of the outside environment. The produced temperature of the cell is determined by [73]

$$T = T_{amb} + \left(\frac{NOCT - 20^{\circ}C}{0.8}\right) I_{Irr} \tag{2.14}$$

where solar irradiance and ambient temperature are represented by I_{Irr} and T_{amb} respectively. NOCT represents Nominal Operating Cell Temperature which is defined by the manufacturers.

- *Ideality Factor (N)*

It is found that there are various moving carriers that are present across the diode junction. These moving carrier’s operations are run by the diode ideality factor. Depending on its properties, the diode ideality factor’s value changes. The value of ideality factor is considered as 1 if its movement process is mainly diffusion, and the value is close to two when there is primary recombination in the depletion region. Operating parameters have no influence on diode ideality factor value, it is always the same value defined at standard conditions.

- *Diode Saturation Current (I_s)*

The following formula can be used to define how there is variation of cell temperature with diode saturation current

$$I_s = I_{s,ref}\left[\frac{T}{I_{ref}}\right]\exp\left[\frac{E_{g,ref}}{kT_{ref}} - \frac{E_g}{kT}\right], \tag{2.15}$$

where $I_{s,ref}$ is reference cell temperature current for the diode, I_{ref} is reference current, T_{ref} is reference temperature, the band gap energy is E_g, reference band gap is $E_{g,ref}$.

- *Series Resistance (R_s) and Shunt Resistance (R_{sh})*

The two important parameters that take parts in the output analysis are series resistance and shunt resistance. Shunt Resistance is commonly referred to as parallel leakage resistance. The shunt resistance is provided by [74]

$$R_{sh} > \frac{10V_{oc}}{I_{sc}}. \tag{2.16}$$

The correlation between shunt resistance and irradiation under typical operating conditions is established by [75]

$$\frac{R_{sh}}{R_{sh,ref}} = \frac{I_{Irr}}{I_{Irr,ref}}. \tag{2.17}$$

And series resistance is obtained by [75]

$$R_s < \frac{0.1V_{oc}}{I_{sc}}. \tag{2.18}$$

It is described in [75] that, under all circumstances, series resistance is independent of temperature and irradiation

$$R_s = R_{s,ref}. \tag{2.19}$$

According to the equation above, it is clear that the series resistance in the reference conditions is equivalent to series resistance of the system.

A typical solar cell's current -voltage curve (I-V) is provided in the figure 2.10 below. It is generated using the values given by the manufacturers and the parameters considered as ambient temperature, irradiance and other related parameters.

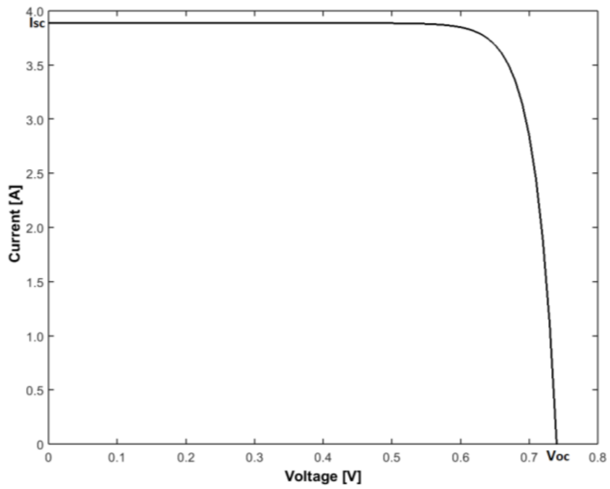

Figure 2.10: PV module's current-voltage (I-V) curve [68].

Figure 2.10 illustrates how the current behaves in relation to its voltage. The analysis of this given result is obtained by simulation, and it shows that at lower voltage PV cell behaves as a constant current source which is nearly equal to the short circuit current of the system. The value of current is maximum at short circuit current and minimum at open circuit voltage, on the other hand, the value of voltage is maximum at open circuit voltage and minimum at short circuit current. Obtained power-voltage (P-V) curve of a PV cell is provided in figure 2.11.

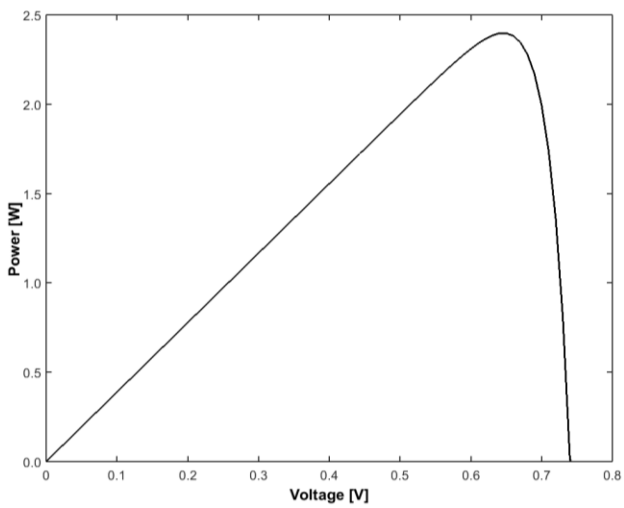

Figure 2.11: PV module's power-voltage (P-V) curve [68].

The power of a PV cell is obtained using the current value and voltage value in a PV system. The main purpose carries by a P-V curve are to illustrate the output behavior of a PV system. Additionally, the I-V and P-V curve also can be used to illustrate the electrical properties of solar cells.

Maximum power point (MPP) for a PV module is the point at which the module's power is at its highest point obtained by power-voltage characteristics. Tracking and capturing MPP is in reality one of the most important and difficult tasks in a PV system. There are several ways and methods to fulfill MPP tracking that exist in many studies. However, the MPP value fluctuates when a PV systems internal and external factors vary in relation to ambient conditions. The MPP curve that was generated using standard values is provided in the figure 2.12.

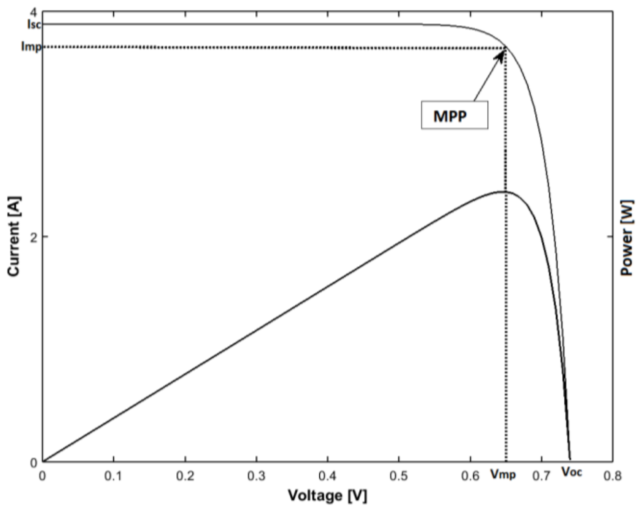

Figure 2.12: Maximum power point of a PV system [68].

The amount of sunlight varies during the daytime and is not a continuous source of energy. The photo-current of the PV cell is dependent on temperature and irradiance characteristics. Photo current of a PV cell is determined by [68]

$$I_{ph} = \left[I_{sc} + k_i \left(T - 298 \right) \right] \frac{I_{Irr}}{1000}, \tag{2.20}$$

According to the equation described, it is observed that the photocurrent is primarily dependent on temperature and irradiance. Additionally, it is also dependent on the temperature coefficient and short circuit current of the system. As it was already mentioned that due to non-uniformity of irradiance there is variation in the output also.

Obtained current-voltage (I-V) curve due to irradiance variation [76] is provided in the figure 2.13. It is evident from the figure 2.13 that both the open circuit voltage and short circuit current increases with the increasing irradiance value. However, compared to the voltage value at open circuit, the current value at short circuit increase is significantly higher as there is slight increase of the voltage. Output obtained due to irradiance variation is provided in table 2.1.

Table 2.1: Output I-V values comparison due to irradiance variation [68].

Irradiance [Wm^{-2}]	(I_{sc}) [A]	(V_{oc}) [mV]	Difference [A]	Difference [mV]
500	2.05	720	n/a	n/a
750	3.07	735	1.02	15
950	3.88	740	0.81	5

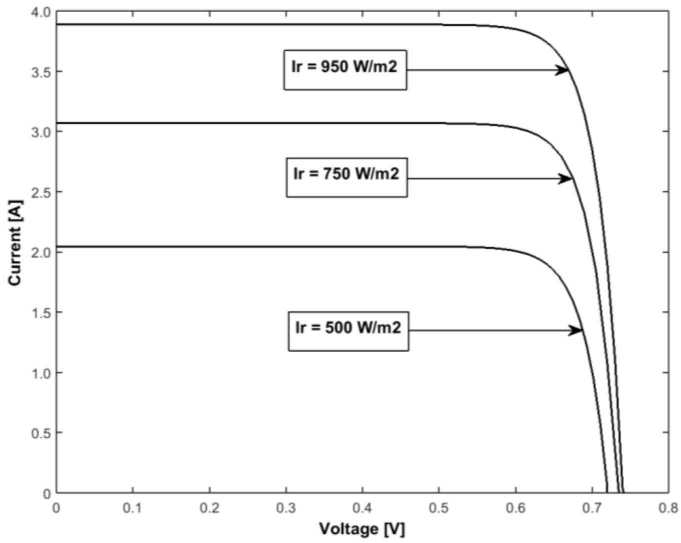

Figure 2.13: Current-Voltage curve variation for various irradiance [68].

The results obtained due to irradiance variation of a PV cell shows that increasing irradiance value has positive impact on the PV system as it increases overall output. Due to the variation in irradiance, there is an impact in the power-voltage (P-V) characteristics is demonstrated in the figure 2.14.

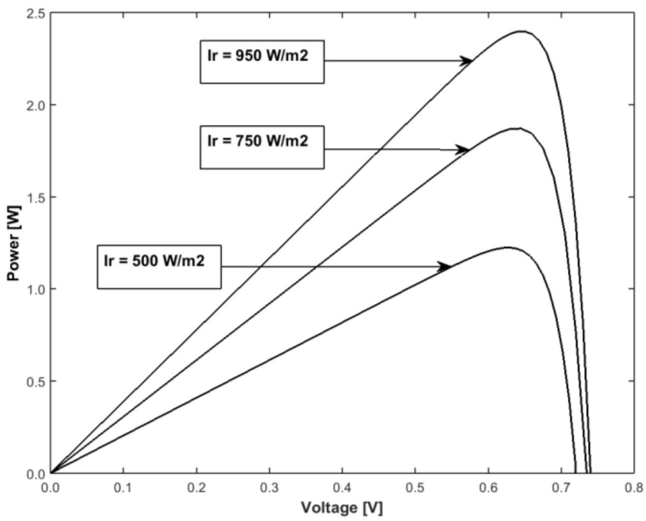

Figure 2.14: Power-Voltage curve variation for various irradiance [68].

With the rising value of irradiance there is increasing tendency in the P-V curve of this system which results in overall output also. The results variation due to these parameter changes and impact is provided in table 2.2. With the increasing irradiance, the value of short circuit current and open circuit voltage increases, which returns positive impact in the maximum power point.

Table 2.2: Output P-V comparison due to irradiance variation [68].

Irradiance [Wm^{-2}]	(I_{sc}) [A]	(V_{mp}) [mV]	MPP [W]	MPP Difference [mW]
500	1.94	630	1.22	n/a
750	4.83	387	1.87	647
950	3.68	650	2.39	527

Solar PV system still faces the problem of low efficiency, despite the fact that it may be a possible and sustainable substitute for fossil fuels. The maximum efficiency is about 29% in the industrial PV module, which is theoretically achievable, but in reality, this number only rises to a maximum of 26% [77]. A number of internal and external factors, including PV construction, PV operation, system maintenance, and the environment, are the reason for an overall decrease in the panel efficiency. Even though the PV designing and installation procedures are being improved progressively, dealing with environmental variables represents barrier in improved efficiency [78].

PV modules are capable of efficiently receiving the spectrum and intensity of sunlight. Nevertheless, any form of shadowing by natural or human made such as snowfall, dust, shadow by any obstacle may restrict the module's exposure to sunlight. Furthermore, humid air absorbs dust and other air pollutants, which leads to module soiling and decreased irradiance, which provides a decrease of PV power output. The internal and external parameters that are interrelated with the PV systems operation are provided by the figure 2.15.

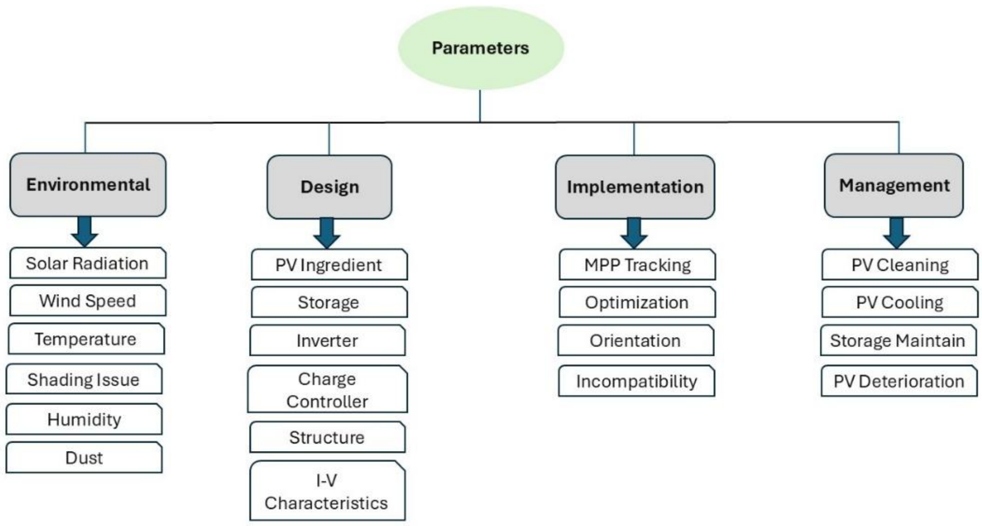

Figure 2.15: Factors that impact the PV panel efficiency [78].

It is considered several parameters in the figure 2.15 which are based on environmental characteristics, design parameters, implementation of PV and the systems management [78]. It is also studied and analyzed irradiance, wind speed, temperature of the environment, shading by obstacles, humidity impact on PV, dust issues regarding the environmental impact on PV in [78]. Design parameters of the photovoltaic systems are also considered in terms of used components for PV, storage or battery design, inverter used, charge controller of the system, structure of that system and current-voltage characteristics. In the implementation part maximum power point tracking, optimization of the system, orientation of the module and other related incompatibility is discussed. They also consider operational management as an important part of the system like cleaning of PV panels, cooling of the system due to heat issues, maintenance and upgrading of used storage, and other reasons of PV deterioration.

Temperature Effect Analysis

Power generation efficiency is highly dependent on a photovoltaic panel module temperature. Because the PV modules effectively convert 20% of sunlight into electrical energy while 80% to heat, as a result electrical efficiency drops while temperature increases in the module [79]. The PV cell material's bandgap energy and module temperature are closely related to each other. In general, bandgap energy decreases under high operating temperature circumstances. It allows the cell to absorb photons with greater wavelengths and usually extends the minority carriers' lifespan. Despite this there is an increase in photo current and decrease in open-circuit voltage which results in fill factor value reduction. In general, the number of series and shunt resistance in the system is measured by the fill factor. Maximum power of a PV system depends on its open circuit voltage and short circuit current, and it is determined as [80]

$$P = V_m \times I_m = (FF) \times V_{oc} \times I_{sc}, \tag{2.20}$$

where fill factor is FF (maximum obtainable power), voltage at maximum power is V_m and current at maximum power is I_m. In many of the research it is described that module temperature is determined by external parameters like ambient temperature, irradiance [81], wind speed [82] and other material of PV such as glass transmittance [83]. In this regard, the temperature of the PV module is described as [84]

$$T_{Panel} = T_{Amb} + Irradiance \times \exp(-a - b \times WS) + \Delta T \times \frac{Irradiance}{1000}, \tag{2.21}$$

where the constants are ΔT, a and b, wind speed is represented by WS. It is also obtained that the operating temperature of the single crystal silicon solar cell has a significant impact on its efficiency.

A comprehensive review of temperature effect on a PV cell based on microscopic and macroscopic is extensively discussed in [85]. It is already established that PV modules are normally prepared under standard test conditions even so there is deviation in the actual operating conditions like the temperature of the module [86]. The temperature of the solar panel is considered one of the key elements and has a significant impact on their performance. Additionally, different cell types respond to temperature in different ways. Additionally, a variety of elements influence these cells' temperature coefficient. For example, thin film type cells have lower sensitivity to temperature than crystalline silicon [87]. The active layer with aging will have an impact on the polymer cells' temperature coefficient [88]. Other type of temperature like annealing, substrate and processing also show impact on the solar cell.

Micro level temperature effect

A solar cell of a PV module is a component that uses the PV effect principle to directly transform incidence photon to DC electrical energy. Current and voltage are generated when photons with energy above the cell material's band gap are absorbed and excite charge carriers. Solar cells microscopic parameters and temperature effects on PV cell are interconnected and related in many aspects.

- *Temperature Effect on Band Gap of Solar Cells*

One of the key variables that influences loss and cell conversion efficiency is the band gap, also referred to as energy gap or energy band gap. The PV effect can only be produced by photons with energy greater than the forbidden band width, which also establishes the upper limit of the wavelength that cells may absorb in order to generate electricity [88]. Additionally, the temperature dependency of the cell parameter decreases with increasing material energy gap [89]. There are fluctuations in bandgap energy of cell when external energy sources like photons, temperature, electro-magnetic field, pressure interact with it. The atom's bond energy within the cell is reflected by the band gap. The electron moves to the conduction level from the valence level when the temperature increases, and it occurs modifying the chemical bond [90]. The dependency on the band gap temperature and the impact by incident spectrum over the short-circuit current's temperature sensitivity is demonstrated in [91]. Additionally, they also illustrate the cells' conversion loss mechanism which is depicted in the following figure 2.16.

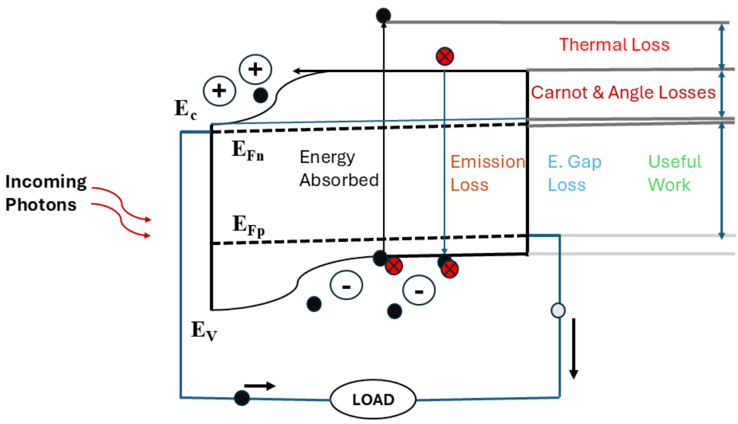

Figure 2.16: Solar cell conversion loss process [91].

It is discovered that the unique temperature sensitivity of cells at the radiation limit occurred by the band gap anomalous behavior of perovskite semiconductor substances. The cell's band gap decreases with increasing temperature, resulting in a longer cut-off wavelength and an expanded spectral spectrum of absorption [91-92]. Nonetheless, a smaller band gap results in better visible light absorption, which enhances photons and, consequently, photocurrents. Keeping in consideration about light, an elevation in temperature which is advantageous for PV power generation since it will, to a certain level, enhance the free electron–hole pairs produced by the PV effect in the cell. Nevertheless, the overall output of a PV system is not improved by an excessive amount of temperature rise. At the same time, the increased temperature has an impact on the movement of carriers within the cell [93].

- *Temperature Effect Analysis on Carrier Mobility*

Carrier mobility is regarded as an essential feature of organic solar cell components since it influences kinetics recombination and energy extraction. Increased mobility reduces the duration that the charge carriers are inside the device and lowers the chance of recombination [94]. Carrier mobility is often calculated by the constrained current of the steady state space. The study and findings in [95] demonstrated that altering the temperature to modify mobility is a useful technique for figuring out the material's loss and optimization potential. The ZnTTBPc-RGO heterojunction's carrier mobility was experimentally investigated in [96] at various temperature level. With the increasing temperature there is an increase in the PV cell's mobility carriers, which is illustrated in the figure 2.17. A (black) is considered as 0.25 RGO fraction, B is 0.33 RGO fraction and C is 0.50 RGO fraction.

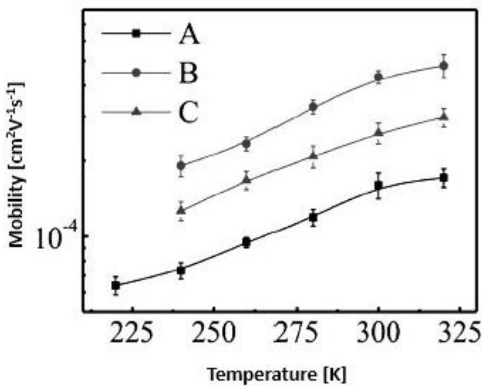

Figure 2.17: Error bars and carrier mobility for various temperatures value of ZnTTBPc-RGO [95].

It is also obtained that with the increasing temperature value there is a decrease in the mobility carriers. It results in a reduction in conversion efficiency which means that the output also decreases with overall performance degradation. Additionally, lowering carrier mobility also lowers its diffusion radius, making it more difficult for free carriers to move to an external circuit and create current. It can be concluded after the analysis that there is a negative impact on carrier's drift effect of solar cells while there is temperature increase inside of it [95].

- *Temperature Effect on Carrier Lifetime in Solar Cell*

It is already established that carrier lifetime is affected by the temperature, not only that but also influences the carrier's longevity. In a PV system, the lifetime of the carrier is significant. It is the average amount of time it takes for various recombination to bring excess minority carriers back to equilibrium [97]. Within the cell, the recombination center created by flaws or impurities will continually capture free carriers when the cell is exposed to irradiance to produce photo-generated carriers. Due to this issue a long-term impact and reduction in numerous carriers resulted in [98]. The diffusion length and carrier lifetime of solar cells are proportional to each other. The diffusion length increases proportionally with the lifetime of the minority carrier [99].

Microscopic studies have demonstrated the interdependence of temperature's impacts on solar cells microscopic characteristics. Additionally, the temperature dependency of the cell parameter decreases with increasing material band gap. Furthermore, inside the cell there is an indirect impact of the restricted band width in the carrier's transportation while it affects carriers' diffusion radius and mobility also. Additionally, the diffusion radius and carrier lifetime are exactly proportionate. So, it can be concluded after microscopic analysis that the increase of high level of temperature in a PV cell has negative impact in its output.

Macro level temperature effect

In the perspective of macro level analysis, it is important to receive continuous irradiance from the sun in order to produce electricity. Additionally, the PV panel should be able to handle high temperature also [100]. Induced high temperatures in a PV panel has negative impact on the PV modules performance is obtained in many studies [101]. Additionally, other environmental factors like climatic parameters [102], dust accumulation [103] have impact on PV panels. Aging of the PV panels occurs when its productive life shortens, which also significantly affects the panels temperature effect [104]. Solar cells temperature coefficient is described by using its efficiency, fill factor, current density, short circuit current, open circuit voltage [105]. The effect of temperature and other parameters in macroscopic level is shown in table 2.3.

This table provides macro level impact of temperature and related efficiency analysis. They considered analyzing temperature effects based on two grounds are external environment and nonuniform temperature of the system. In the external environment light intensity, accumulation of dust, outside wind and location are studied. It is obtained that with the increase of temperature, open circuit voltage decreases and short circuit current increases slightly, as a result power in total the efficiency decreases. It is also found that with the increasing dust accumulation and temperature overall efficiency decreases. For the case of outside environment, while wind speed increases then temperature decreases resulting efficiency of the system increases. Other parameters like uneven irradiance, wind direction, inclination, wind azimuth has also great influence in the output. The study reveals that temperature and azimuth increase decreases efficiency [85].

Table 2.3: Macro level temperature effect analysis [85].

Macroscopic Level Parameters		Parameters	Observation	
	Description		Increase	Decrease
Environment (External)	Intensity of Light,	Temperature ↑ Irradiance ↑	Voltage	Current, Power, Efficiency
	Dust Accumulation	Accumulation ↑ Temperature ↑		Efficiency
	Outside Wind, Location	Temperature ↓ Wind Speed ↑	Efficiency	
Temperature (non-uniform)		Uneven irradiance, wind direction, inclination, installation, wind azimuth	Greater Impact	
	Azimuth, Temperature (Increase)		Efficiency	

- *Outside Environment*

One of the main elements that influences solar cell performance is the light intensity. Continuous exposure to sunlight will cause solar cells temperature to elevate notably. PV cells may experience varying effects from different radiation bands. The impact of various spectra and irradiance level on PV cell has been investigated in many research work. Operating temperature and irradiance impact on PV cell is studied and described in [106]. According to the results it is obtained that with the light intensity increase, open circuit voltage increases, and there is decreasing tendency in short circuit current resulting overall maximum power decrease. There is an increase in output current with the irradiance increase before the temperature disruption that drops it again.

Solar cell efficiency is measured by the proportion of total irradiance and output power of the system. Environmental circumstances and cell characteristics combinedly responsible for power output in which the system’s total performance is dependent [107]. While there is continuous increase in the intensity of light then the surroundings temperature including PV cell inside temperature will also rise continuously. The cell performance and eventually its efficiency will be significantly impacted by this phenomenon. The output power of specific system has dependency on incident light and its operating temperature [108]. PV system efficiency will differ in real-world operating conditions and in the experimental setup conditions. It is because solar cell has sensitivity to its surrounding environment conditions. Most PV systems are significantly impacted by climate factors that reduce performance and initiate aging process. Lime soil deposition also increases panel temperature which decreases efficiency of the system. It is also obtained in [109] that with the increasing wind speed the panel temperature decreases.

A model that is capable of measuring the temperature impact of PV panels mounted on automobiles in actual weather circumstances was developed in [110]. It is obtained in [111] that with the increasing wind speed from 0.5 ms^{-1} to 6 ms^{-1} the temperature of the panel reduced, and its overall efficiency improved. It is also observed that efficiency improved with the temperature drop due to the change of inclination value from 0º to 90º. Additionally, changes of irradiance from 200 Wm^{-2} to 1000 Wm^{-2}, there was an increase in cell temperature, but efficiency also increased due to an increase in irradiance value. The impact of partial shadowing on the properties of Dye-sensitized solar cells was investigated in [112]. The study reveals that DSC module's partial shading induced temperature was significantly smaller in comparison to silicon solar cell.

- *Irregular Temperature Allocation*

In the applications of solar cells temperature is distributed ununiformly due to the influence of internal parameters like produced heat in the system, solar cell's material, as well external influences like incident sunlight and wind parameters. Hot spots appear in the cell due to non-uniform temperatures management where current also mismatches that results decrease in overall efficiency and in the long run it damages the module structural formation [113]. The PV system would be further impacted by the damage to solar cells. The PV system's performance will be impacted by this non-uniform temperature. The system's efficiency drops as a result of output power loss. Thermal fatigue in a PV system is also caused by temperature variation that damages the system permanently and the system's reliability is also lost due to excessive heat generated in the system [114].

Temperature issue and its impact on the output, longevity of the PV system is studied and many research works are conducted by the academics and in many industrial sectors. The influence of environmental temperature and solar cell temperature difference in the back side and front side with its output analysis is studied using 2D finite difference approach in [115]. In this study they considered the usual crystalline-silicon cell for commercial purpose. They considered three types of thermal mechanisms to study the temperature behavior of the panel that deviates from the ideal thermal properties. Considered thermal processes are Peltier and Thomson heat generation effect, heat produced or absorbed during recombination and carrier generation operation and joule heat mechanism. The behavior of temperature increase throughout the process of photoelectric conversion and internal temperature variation is discussed in [116]. Furthermore, it was noted that an uneven distribution of temperature is responsible for panel deterioration that results in performance reduction and loss of ideal working conditions. Optical illumination in PV system is also a cause of non-uniform temperature distribution and efficiency reduction [117].

Temperature Loss Modeling of PV Cell

In the process of photovoltaic energy conversion, temperature is considered as one of the most important factors. PV module's efficiency is negatively impacted by an operating temperature increase of more than 25º C. In the literatures there are several correlations provided that may be used to describe the impact of changes of temperature in the system [118]. Monitoring the temperature is also crucial for calculating the PV materials' thermal stress and, consequently, evaluating the PV modules' deterioration [119]. It is also required for projecting the longevity of the PV module in a system. Since it is impossible to measure temperature losses directly, models that show how the module's efficiency changes with temperature and the value of which must be known beforehand are used to compute the loss [120]. After determining losses of temperature, miscellaneous losses can be obtained by the difference between global losses and obtained temperature losses. It is shown in the equation as:

$$L_{MC} = L_C - L_T \tag{2.22}$$

Here, L_{MC} is miscellaneous capture loss, L_C is capture loss, L_T temperature loss.

- *PV System Energy Balance*

In steady-state conditions, energy balance is considered by the equality of the energy balance occurs between outside area and the system itself. It means that the balance will be calculated using the comparison between the total absorbed energy and the total electrical power output including dissipated thermal energy by the system. The three main heat transport mechanisms that take part in the energy balance of a PV system are namely conduction, convection and radiation [121-122]. The conventional solar energy conversion process using photoelectric effect is not being so efficient and effective because a large portion of the energy from photons is instead transformed into heat and by this reason the module temperature elevates from its operating temperature.

After heat is generated then it is carried out to various layers of PV cell using heat conduction method. It reaches the exterior surfaces located in the back side and front side of the module. With respect to the smaller surfaces and the flow via the mounting frames, the lateral sides effect often gets neglected. Heat is transferred to the environment through radiation and convection on the module's two larger exterior surfaces; the latter can be categorized as forced or free or natural [123]. After analyzing literatures based on PV systems thermal models, it is obtained that it may be used to represent heat transfer by conduction as thermal capacity and thermal resistance [124]. Thermal resistance is counted as heat flow resistance of the material and thermal capacity signifies the absorption and heat storage capacity. Coefficients for conduction heat transfer of a material are the values that consist of thermal capacities and resistances. These values of a material actually depend on the characteristics, sizes and type of PV panel layers [120].

The involvement of long wave radiation is found in the heat exchange by radiation in a PV system. It considers emissivity or radiative conductance value to determine the heat balance contribution in this type of system. It is also necessary to consider emissivity specifically both sides of the surfaces of the PV panel with sky face part and back part. It usually involves an observation of the sky's corresponding temperature and the soil temperature. In that context, the ambient temperature and the soil temperature can be regarded as being the same value [122]. Still, observations of sky temperature are more difficult and often unavailable due to its dependence on the composition of surrounding atmosphere. However, there are a number of expressions that are available in many works [122, 125]. In PV system, heat exchanges via conduction, convection and radiation may be represented using electrical equivalent values based on their heat transfer coefficients properties [125]. The analysis of heat transfer results shows that determination of coefficients of heat transfer for conduction, convection and radiation seems to be complicated and ineffective to be used of these PV systems in commercial purpose. Implementation and analysis of heat transfer mechanisms required modules design parameters and specific thermal properties of the system that are not always provided by the manufacturer. Obtaining PV operating temperature using parameters correlations from mathematical perspective is normally implicit and to calculate the relevant parameters it requires iteration procedure [121, 126].

- *PV Cell Temperature Models*

Ther are many existing models discussed in the literatures. PV power generation in the real system can be demonstrated using the most commonly utilized method [120]

$$P_{Tc} = P_{STC}\left(1-\beta\left(T_c - T_{a,STC}\right)\right) \tag{2.23}$$

where, cell temperature is T_c, nominal power at STC is P_{STC}, β is PV module temperature coefficient for power. This formula is derived from Evans and Florschuetz basic statement for calculating PV module efficiency. Power generation variation due to temperature value changes is also required to be kept into consideration while the panel does not follow the standard conditions, this behavior is determined by parameter β. The value of this coefficient for power temperature is normally characterized by the manufacturer in the data sheets. It is required to know the operating temperature of a PV module in order to calculate the temperature losses in the system.

- First Model

In general, the operating PV cell temperature is obtained by the measured temperature from the back side of a PV panel using a temperature sensor which is the module temperature of the system T_m. In this model, it works based on assumption that the panel temperature is homogeneous, and module temperature is equivalent to cells operating temperature while it ignores cells and modules temperature difference [127-128].

- Second Model

One of the models commonly used in the research to calculate PV cell temperature value is this model [129-130]. The expression for this model is shown by the following equation [121]

$$T_c = T_a + \left(\frac{H_{NTE}}{H}\right)\left(\frac{I_{Irr}}{I_{Irr,NTE}}\right)\left(T_{NOCT} - T_{a,NTE}\right)\left[1 - \frac{\eta}{(\tau\alpha)}\right] \tag{2.24}$$

In this equation, ambient temperature is T_a, NTE stands for nominal terrestrial environmental conditions, total coefficients for heat transfer is *H*, solar irradiance is I_{Irr}, $T_{a,NTE}$ is ambient temperature at *NTE*, panel efficiency is η, both diffuse and beam radiation (τ) and absorption coefficient (α) product is used to obtain module cover's transmittance is $\tau\alpha$. In NTE conditions, considered parameters for NOCT are $T_{a,NTE}$ is 20º C, speed of wind V_{NTE} is 1 m/s for both back and front side of the panel, irradiance value $I_{Irr,NTE}$ is 800 W/m^2. The simplistic form of the equation 2.24 is obtained as [131]

$$T_c = T_a + \left(I_{Irr}/800\right).\left(T_{NOCT} - 20\right). \tag{2.25}$$

In this equation, the solar radiation and environmental temperature value is used directly to calculate the cell temperature, and it does not require accumulation and calculation of the temperature of the module using temperature sensor in the back side of the system. The literature discussed that this simple form of temperature shows better output if it is installed in the roof or any open space where there is natural flow of wind or ventilation, but it malfunctions in the context of overall output gain while it is integrated with roof or walls as there is no space for ventilation [127, 132].

- Third Model

In this model, the temperature of the PV cell is obtained as [120]

$$T_c = T_a + \left(I_{Irr}/800\right).\left(T_{INOCT} - 20\right). \tag{2.27}$$

The expressed equation 2.27 is the solution derived from the previous second model of cell temperature. In the second model, temperature for NOCT was considered but in here it is replaced by adding *INOCT* (Installed Nominal Operating Cell Temperature) [120]. It is considered mainly cell temperature based on nominal operating conditions. It is not provided by the manufacturer but rather it counts the position and location where it is mounted and oriented. The PV panel installation and mounting configuration and NOCT temperature are applied to avail the value of T_{INOCT} [121]. For the installation of an open rack mounting case the expression for T_{INOCT} is found as

$$T_{INOCT} = T_{NOCT} - 3^{o}C. \tag{2.28}$$

There is higher temperature difference between both the temperature T_{INOCT} and T_{NOCT} while PV panels are directly integrated into building roofs or façades where they might have up to 18 ºC of temperature difference [133-134].

- Fourth Model

In this model, it is considered the cell temperature is directly proportional to the irradiance value which is a simplified expression. The value of irradiance proportional factor *k* depends on PV installation assembly and PV modules type. The equation is expressed as

$$T_c = T_a + k \cdot I_{Irr} \tag{2.29}$$

In 1976, R.G. Ross first proposed this linear expression that has no load and wind parameters and later on many authors adopted it [121] [135-136]. Based on the type of assembly of PV system, the authors consider the value of *k,* and it is also known as Ross parameter. In many research studies it is found that it ranges from 0.02 – 0.06 km^2/W [121].

- Fifth Model

The empirical model of thermal analysis established in Sandra National Laboratories is used to describe this model. The equation for thermal analysis of a PV cell is obtained as follows [137]

$$T_c = T_m + \Delta T \cdot \left(I_{Irr} / I_{Irr,STC} \right) \quad , \tag{2.30}$$

where $I_{Irr,STC}$ is the irradiance at standard condition. It is projected that the operating temperature (T_c) of PV cell is greater than the external temperature of the module (T_m) which is generally measured on the back of the panel. This temperature is calculated using the ratios between the normal irradiance and STC irradiance value.

- Sixth Model

In this model, using environmental temperature and irradiance incident on the PV surface the operating temperature is obtained and can be expressed as

$$T_c = 30.006 + 0.0175(I_{Irr} - 300) + 1.14(T_a - 25) \tag{2.31}$$

This equation is mainly targeted and based on the crystalline silicon system, and it is established in Lasnier and Ang [138]. Additionally, this model does not consider wind speed value and any other cooling methods for PV system. Also, there is no need to measure the module temperature in the plant.

PV System Cooling Technologies

Dropping the operating temperature increases electrical power produced by the solar cells [139]. Furthermore, extending the longevity of PV will increase the overall electricity generation as the output.

The efficiency of PV panel varies substantially based on the solar radiation wavelength and material's bandgap. It could be improved using novel material to produce solar cells. The electrical power output of a PV cell significantly decreases while the system temperature has a higher increased tendency. Only about 5-20% of solar radiation that hits the solar panel surface's is converted to electrical power [140]. The remainder of the radiation, however, is either absorbed by the cell as heat or sent backwards. Due to this heat absorption the temperature of the panel rises close to 70ºC. To increase the efficiency of PV panels numerous studies have been conducted on various PV system cooling techniques [141].

The optimal operating temperature of PV is one of the main barriers to its usage expansion in both residential and industrial sectors. There is a deep relation between the performance and temperature of a PV panel which is determined by stability of induced heat due to incident irradiation. Though PV cooling is one of the simplest ways to increase performance but in practical application and development it is very challenging [142]. The impact of high temperature could lead to negative performance on PV cell's current-voltage characteristics. PV system performs best at lower temperatures and declines with the temperature rise. Due to the increases temperature circuit voltage decreases and that is why the output of the system also decreases. PV system's performance and efficiency are also impacted by this power loss [143]. Further research on cooling technology is required to enhance the performance of existing panels. In the purpose of PV module's increased efficiency and cost effectiveness researchers are looking for more effective cooling techniques. The process of general cooling mechanism is provided by the following figure 2.18.

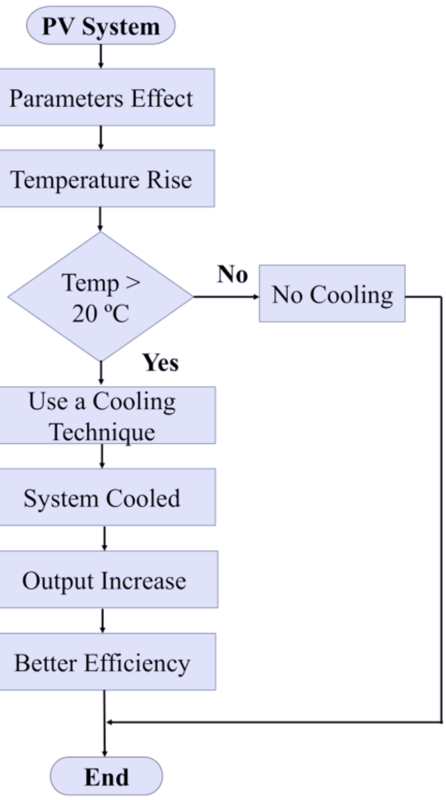

Figure 2.18: Cooling process of a PV module.

Researchers are developing both active and passive cooling technologies to lower the operating temperature of existing solar cells. PV system's proper cooling helps to enhance its reliability and decreases output loss. Both passive and active cooling techniques are utilized to enhance the PV modules' performance. A coolant such as air or water is necessary for active cooling, and a fan or any pump is required in this type of cooling system. On the other hand, passive cooling cools PV cells without the need for additional electricity consumption [144]. Significant research has been done about the use of air, liquid coolant, other types of liquid like glycols and water to maintain the module temperature at an optimum level.

In the paper [141], the authors mentioned three types of passive cooling techniques are water passive cooling, air passive cooling and cooling by conduction. Additional parts of passive cooling, such as a heat pipe, natural cooling exchanger, heat sink may be used also [145]. Actually, the material used in the heat sinks has high thermal conductivity. They are designed to be positioned at the solar panel's back side so that heat can be transferred easily from the module to the surrounding area [146]. One of the main advantages of passive cooling is that it is easy to install and cost-effective in comparison to the active type of cooling. There are other existing complex cooling methods like thermoelectric generators, nano fluids, heat exchangers, microchannels, phase change materials (PCMs), heat sinks and other hybrid system also. Beam splitting technology is also referred to as spectrum filter technology is considered as a novel invention that uses specific wavelengths to convert both electrical and thermal energy using photovoltaic thermal system [141].

Active Cooling Techniques

Active cooling methods use a cooling medium such as water or any other liquids. It requires external energy to run fans, pumps that move the cooling medium. These methods are more efficient in the context of processing heat transfer from the panel, and it needs extra devices and energy supply.

- Active Air Cooling

It is one of the most common methods to be used in a variety of devices to reduce temperature and management of thermal energy. Air cooling is not so effective as liquid cooling, but it has benefits like cost effective material and low operating cost. For this type of cooling, a mechanical component, for example a pump is used for air circulation to lower temperature. An active air-cooling system for performance improvement in a PV system is provided in [147]. It is compared the PV system without cooling in normal conditions and PV panel employing active air cooling which results in power ratio increase of 6 % and electric efficiency increase of 7.2%.

In addition, the PV system's performance may be impacted by the air-cooling system's geometrical characteristics. In [148], a total of four electric fans were employed for cool air circulation inside the

PV panel through a specific designed channel inside it. They also verified the impact of channels characteristics and size on efficiency. The results showed that channel depth decreased, increased thermal efficiency, and it has no considerable impact on electrical efficiency. Also, the total number of fans for cooling the system is a significant element to be considered that takes part in the efficiency and performance of the PV system. The number of fans and increased efficiency relation is discussed in [149].

- Cooling using Liquids

PV modules can also be effectively cooled by forced convection generated by inside channels liquid flow while it is placed at the backside of the panel [150]. A comparative analysis of different cooling methods employing reflectors in the Egyptian regions is provided in [151]. It is studied mainly three distinct cooling methods in their work are air cooling, water cooling and combination of both air and water. According to the experimental analysis it is found that in the Egypt's environment condition water cooling was the most efficient among all the three methods. By comparing PV panel without using any cooling mechanism and with employing water cooling, it is obtained in [152] that module temperature was reduced to 20% and therefore overall efficiency was increased around 9%.

At the back side of the PV module, the use of heat pipes can be integrated simultaneously while cooling of PV panel using water circulation. The heat extracted by the working fluid can also be used for any other uses and thus how extra energy will be added to the overall output. In this process of heat transfer mechanism using pipe has impact on the systems overall efficiency [141]. There is also another method that discusses the possibility of using water for cooling purpose is known as liquid immersion. It results in temperature reduction of a larger amount and exhibits lesser impact in the environment.

The main advantage of cooling PV panel using forced water flow is that it is very efficient, and the water can be reused in this system. The temperature is reduced by approximately around 20-30 ºC by integrating this method. The main drawback of this method is that it requires high investment, and it assists the degradation of the system. The principal advantage of liquid immersion cooling method is that it is highly efficient and eco-friendly. It can reduce the panel temperature by around 40 ºC. The issue is that in cloudy weather situation it performs very low, and it has water impact due to ionized situation [141].

- Water Spraying Cooling

The performance and electricity generation of a PV system can eventually be improved by cleaning PV panels' surface [153]. Liquid spraying can be used to lower modules temperature and clean its surface at the same time. This system uses a pump and associated pipes to spray water through sprinklers over the front side of the PV panel. In adverse weather conditions the efficiency may rise by 15% due to the use of water spraying which is obtained from previous research. This technology can be a good affordable option for floating PV plants as it consumes and wastes a lot of water when it is mounted on the overland PV plant. It is investigated both the front and back side liquid spraying effect and efficiency is analyzed in [154]. According to the findings, cooling in the front side of the panel provided better outcomes than cooling in the back side of the panel. About 14.6% improvement in electrical power because of using water spraying was obtained by this analysis.

For cooling PV panels, a water spray method was developed in [155]. The components used in this cooling system are a pump, water tank, recycle module, nozzles spray and the PV panel. The temperature of the PV panel was reduced to around 35 ºC by using this water spray cooling system. In the investigations it is mentioned that the advantage of water spraying cooling is that it is a very efficient and simple process and temperature can be reduced up to maximum temperature. The main drawback of these types of cooling is that it is just cool only partial section of the panel and there is a lot of water wastage issue [141].

- Evaporative Cooling

Evaporative Cooling is one of the best options to cool the PV panel by the use of water evaporation and it works on the same behavior how the human body gets cooled down after sweating in summer. It uses surrounding air for evaporating water and reaches in an equilibrium stage. The most efficient, practical and promising way to control PV panels temperature through evaporative cooling. Not so much research works have been investigated based on evaporative cooling though it has high advantages in cooling system panels. The main benefits of evaporative cooling are implementation simplicity, and it is less costly in comparison to other methods. But this type of methods works better and shows effectiveness mostly in dry and hot climatic conditions [141].

- Cooling based on nano-fluid

For the PV panel cooling purpose and system performance improvement, different nanoparticles and water combination are used to create nano-fluids. To improve heat transfer, different percentages of nanoparticles are used [156]. The commonly used nanoparticles are copper oxide, magnetite, boehmite and titanium oxide.

- Microchannel Heat Exchanger

The method of cooling using heat exchanger is one of the several popular cooling techniques. In this kind of method, heat is transferred from one fluid to another fluid and from a single medium to another type of medium. It may obtain maximize efficiency at high temperatures. In order to gain maximize efficiency CFD analysis is studied with an optimum flow rate for a cooling medium. To fulfill that purpose and cool PV panel the use of microchannel could be a better solution. Additionally, it is also feasible to use hybrid PVT systems. The main challenge of employing this method is to efficiently manufacturing and experimental setup of microchannels [141].

- Thermoelectric Cooling Method

This type of cooling method is also defined as Peltier cooling. Another efficient approach to lower PV panel temperature is thermoelectric cooling. Excess induced heat from PV module is captured and converted to electrical power by employing thermoelectric module. The Peltier effect is the basis of the technology which uses electrical energy for PV panels cooling. The Peltier effect and the Seebeck effect are the basic fundamentals of this type of cooling. In here, heat flows inside of an electric junction in a certain direction using Peltier effect. In one part of the junction, it experiences heating while the other part experiences cooling impact. For both heating and cooling method, flow rate is solely dependent on temperature differences and its voltage and current characteristics [141]. Cooling of a PV panel using Peltier effect is described in [157]. It has been demonstrated that this thermoelectric cooling can be successfully included into high concentration PV cells.

The following figure 2.19 provides the summarize type of methods of active cooling methods for PV system.

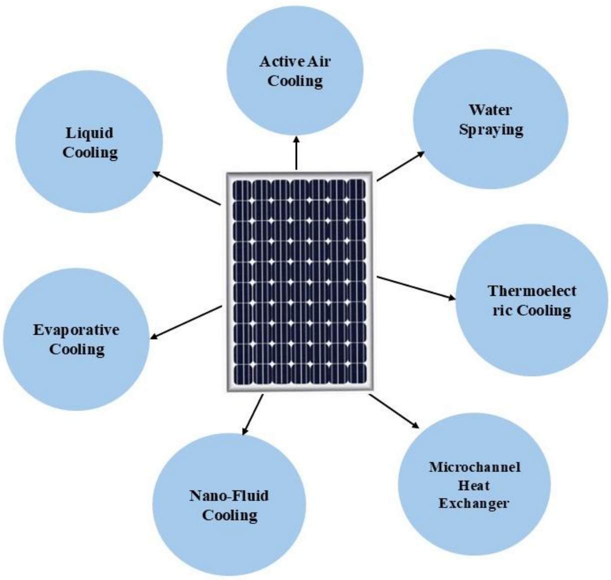

Figure 2.19: Active cooling techniques.

Passive Cooling Techniques

Passive Cooling techniques are also as important and effective as active cooling techniques. The main difference between active and passive cooling mechanisms is that the passive cooling technique does not use any other extra mechanical devices for functioning. To be more specific, the passive cooling system does not use external power system to run its operation. That is why passive cooling techniques require less cost for maintenance, and it has a simpler structure than the active cooling.

- Phase Change Material (PCM)

This type of cooling is a passive distinct cooling by conduction. The capability of PCM is to retain thermal energy facilitates and maintain the stabilization of temperature. The absorption and release of latent heat while melting phase and freezing cycle is the key principle of PCM cooling. There exist several types of PCM, for example eutectics, inorganic salt hydrates and organic oil. The operation of PCM and cooling system is dependent on the melting point and latent heat of the elements. Although this isn't a straightway passive cooling technique, it does not require additional work. Heat conduction occurs here, and it has the ability to maintain and persevere the actual temperature. Most importantly the PCM integration in a PV system is an alternative better option due to its heat absorption capacity during hot weather conditions during day and quicker releasing tendency during low temperature time and thus how it balances thermal energy. The significant properties of PCM are that it maintains unchanged temperature level during its phase change moment, latent heat is generally higher, high potential for absorption before it reaches to melting point or start solidification process [141].

PV cooling system based on PCM material, and its related characteristics is discussed in [158]. They considered a setup based on paraffin wax positioned at the back of the panel and its normal melting point range is 38 ºC to 43 ºC. The results demonstrated that the cooling system increased around 5.9% electrical energy production yearly in the hot regions. An economic analysis is also completed to demonstrate the benefit of using this PCM based cooling technology.

- Heat Pipes cooling

Heat pipe cooling uses condensation and evaporation of fluid to cool and source to sink thermal energy transformation in the PV system. Among the traditional heat pipes, the most common type of pipes are aluminum and copper that has thermal conductivity in higher range also and it is kept sealed during cooling activities. The use of heat pipe helps to lower panel temperature and increase its efficiency through the conversion of heat to water or air from the panel. In some cases, performance of heat transfer gets lower due to the thermal resistance in between the used heat pipe and the PV panel. Using a solid PV panel and new micro heat pipe of flat design is developed for a heat pipe cooling system in [159]. An experimental investigation of PV panel cooling of heat pipe using water and air as transfer fluid is described in [160]. The result shows that the use of air in the cooling system resulted in 4.7 ºC of temperature reduction and an increase in output of 8.4%. Besides, in water cooling case the temperature was reduced to 8 ºC and systems efficiency was increased by around 14%.

- Wick Structure Cooling

Lower cell temperature in a PV system is possibly obtained by the use of fluid flow like water and other liquids. A capillary structure can be used to continuously provide this fluid for cooling panels. For cooling a system cotton wick is used in the PV panel back side that delivers capillary fluids to the fluids which is represented in [161]. They utilized three main types of cooling fluids are CuO/water, water and Al_2O_3/water. In the obtained results it is described that using water in this structure reduces 30% temperature, use of CuO/water reduces 11% of temperature and use of Al_2O_3/water reduces 17% temperature in comparison to the panel while there no cooling technique was used.

- Radiative Sky Cooling

It is also another type of passive cooling mechanism. This type of cooling provides another innovative cooling mechanism by combining visible wavelengths of 8-13 μm and outer space's ability to act as a heat sink. The temperature difference between earth items along with outer space are used to apply the radiative cooling. Cooling of an earth object when it is sun facing accomplish by using radiative function. An experimental investigation of radiative cooling techniques using solar absorbers is examined in [162]. This experimental result shows that the temperature was reduced to 13 ºC due to the use of radiative cooling [162].

Though cooling PV panel is very efficient and it increases efficiency but still it is a challenge to provide cost effective cooling systems. Among the various cooling systems, water based, and air-based cooling systems are found very acceptable, and it has wider acceptance. The other type of cooling like heat pipes cooling, refrigerant based cooling is also developed but due to cost and other technical issues it is not still used in the larger scale. Heat sinks offer great potential as cooling devices for PV systems and their development should be given more attention. Summarized existing passive cooling techniques are provided in the following figure 2.20.

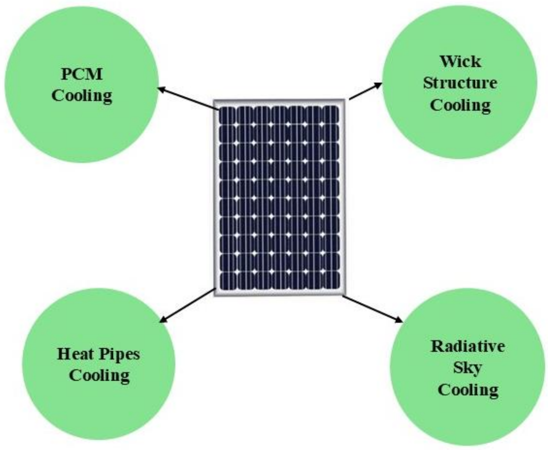

Figure 2.20: Passive cooling techniques.

Evaporative cooling is also interesting but research and development work on this cooling system is not so extensive. Thermoelectric generators also can contribute extensively to PV cooling in future, but proper development is required to be used commercially. According to the economic and technical point of view, a fin-equipped passive air cooling might be a better solution. The use of PCM is a bit costly and it can be feasible to use and commercialize if the cost can be reduced [141]. Other type of cooling mechanisms can also be used but the constraints and economical aspects should be analyzed.

Cooling in a PV system enhances the energy output and performance in all aspects. The cooling system described either requires extra force or it can be passive. Though the study reveals that active cooling is more efficient than passive cooling techniques. The question that arises here is that the cooling techniques are capable of just cooling the PV panel and improving performance, but it requires in general extra energy to run it and to establish an effective cooling mechanism is energy consuming as well. By considering all of these facts, the idea of photovoltaic thermal (PVT) system is proposed as a solution that also provides useful energy using thermal extraction mechanism. It simultaneously improves performance, and it is also energy efficient in comparison to cooling systems.

2.2 Photovoltaic Thermal System (PVT) Study

One of the most significant technological issues arising regarding integration of PV plants with the existing electrical grid is ensuring the supplied power stability either directly or indirectly. The issues arise from variations in solar radiation intensity and temperature over time, which compromise the reliability of the electrical network. In certain situations, environmental and seasonal factors could lead to disruptions in its productivity. The unpredictability of PV energy generation systems is increased by the significant weather variability. Therefore, energy storage devices are essential for PV in order to reduce irregularities in electricity generation [163-164].

A brief description of the advancement in photovoltaic technology over the past two decades are addressed in [165]. The installation and prices of PV module ended up more affordable and that is why PV technology is widely accepted and being used in many locations. All entities related to PV technology and the manufacturing process are in competition and focus on more cost reduction. There are a lot of manufacturing entities producing a variety of products related to PV technology to enhance the ability of accessing and developing PV system in order to produce electricity from renewable energy. That is why the selection of materials for PV components construction is absolutely essential as the manufacturers have to keep in consideration the lower cost and higher efficiency. A quick overview of a variety of PV components based on silicon and other non-silicon materials are discussed in [166]. Crystalline silicon manufacturing and processing technology is comparatively cheaper, and it provides higher performance. For that reason, this technology is very popular and widely accepted [53].

Solar radiation strength and intensity depends on various geographical location and additionally other related parameters like dust, wind velocity, moisture content, air particles also. Each of these factors are responsible for PV system’s performance variation and low production as the variation also impact on its total output [59, 167].

Several research studies analyze and assess the climatic conditions' impact on the output and PV system's performance. PV has been shown to be significantly impacted by the continuous high temperatures and higher level of incident sunlight. Additionally, it was found that wind had no noticeable effect during test period on the temperature of the PV panel [60].

Many research studies have indicated that the development of solar technology is limited due to higher costs for installation and maintenance and inadequate performance when compared to existing energy production using fossil fuels. The main reasons for these limitations are that the elevated temperature of the PV cells during operation is mainly impacted by the ambient temperature, the incident irradiances intensity and other optical properties such as reflection, refraction of sunlight properties. Eventually, these negative impacts can be significantly reduced by conducting enhanced research and laboratorial experiment. This perception of increasing efficiency has led us to the development of several techniques of cooling panels that help to increase overall output and efficiency of a Photovoltaic/Thermal (PV/T) system [53].

Thermal collectors of PVT systems are integrated in the PV panels rear portion in order to facilitate the processes of heating for thermal energy and cooling for electrical efficiency. In order to maintain an adequate temperature at the users end this process should be able to absorb excess heat from the system. Thermal energy is collected by the used fluid which is also called base fluid that is used inside the proposed system and then extracted thermal portion are transferred to a reservoir. Along with the heat extraction fluid/material and reservoir for thermal storage, it also consists of a heat exchanger that exchanges heat from the fluid inside an insulated system. The thermal energy or specifically hot water or the heat is exchanged and separated using this heat exchanger and later on stored on the reservoirs.

Efforts to enhance the performance of the PV/T system and actively implement the system started in the beginning of 1970s when it was in the early development stage. PV systems efficiency increases with the temperature reduction from this system which is demonstrated in many works. By maintaining a single structure both electrical and thermal energy is produced at the same time in the PVT systems that serves the idea of hybrid of PVT system. Though there are potential complexity and challenges in PVT system development, it could possibly be considered as a direct process by incorporating thermal collectors and PV panels. The emerging idea of the development of PVT system was introduced to improve PV systems efficiency and performance improvement to meet the energy demand [168].

Research and investigation on PVT system are still going on in many places by focusing on its operation and design analysis to optimize the performance. Such expanding and motivated research studies demonstrate people's growing interest regarding the beneficial use of renewable energy sources. Consequently, there is increased focus on discussing and studying this system's electrical and thermal efficiency and that should be the primary concern in the development of PVT system. As far as it is already mentioned that all portion of the solar spectrum do not convert to electrical power rather than converted to heat. This produced heat is either needed to be removed by cooling or thermal extraction to maintain the optimum temperature of the panel. Silicon solar cell response with regard to spectrum of sunlight is provided in the figure 2.21 below.

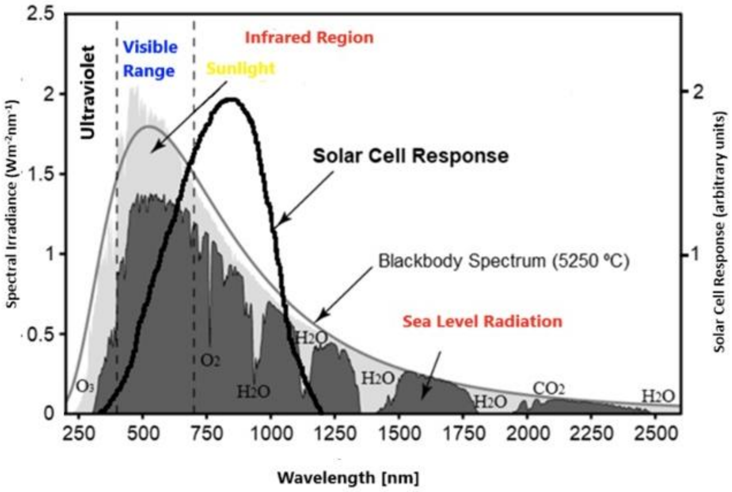

Figure 2.21: Silicon cell response with solar irradiance [53].

This figure provides solar cell response with different wavelengths of irradiance in different portion. It has almost negligible response in the ultraviolet region where it has greater response in visible and infrared region. In a PV system, visible regions' wavelength ranges from 400-700 nm and near-infrared regions wavelengths are converted to electricity and the rest of them are almost converted to heat. In the purpose of revering that excess heat and making it to useful energy hybrid PVT system is introduced and developed.

Hybrid PVT System

Utilizing solar PV and thermal panels, solar radiation can be utilized in renewable energy systems to generate thermal and electrical energy [169-170]. Solar photovoltaic technology typically captures solar radiation and creates it into electrical power [171-172]. At the same time, the purpose of employing solar collector is to absorb solar radiation and convert it to thermal energy to fulfil the other purposes of thermal energy demand including in the residential and industrial sector. After several phases of research and investigations, the PVT system was introduced and discovered in the mid of 1970s [173]. A yearly performance and output analysis of a hybrid PVT solar collector based on liquid type for an individual residential family is investigated and studied in 1976 [174]. For thermal modeling of a flat plate collector the "Hottel Whillier model" and its main parameters are considered in [175], and a study of thermal and electrical performance of hybrid PVT system including the "Hottel Whillier model" parameters modifications are described in [176]. The concept of PVT solar collectors has existed for over 40 years, although adequate commercialization of this system is not completely established. With the objective of PVT collector's performance improvement and cost reduction research studies considering several aspects of this system are conducting recently [177-179]. PVT systems currently emerged to be a better solution because these are environmentally friendly and minimize dependency on conventional energy resources.

A PVT collector, which is developed and paired with PV panel and a thermal collector that is designed to produce electric and thermal energy at the same time. It helps and compensates for energy loss in traditional PV systems and is also referred to as hybrid PVT module [17, 180]. The energy captured from sunlight is converted into heat by the thermal collector and electrical energy by PV module. A PVT system is also possible to develop within the same given area even smaller than separate PV module and PVT collector that can use the maximum solar energy to produce efficient and effective electrical and thermal energy. The figure 2.22 below provides an illustration that allows one to understand about the development of PVT system.

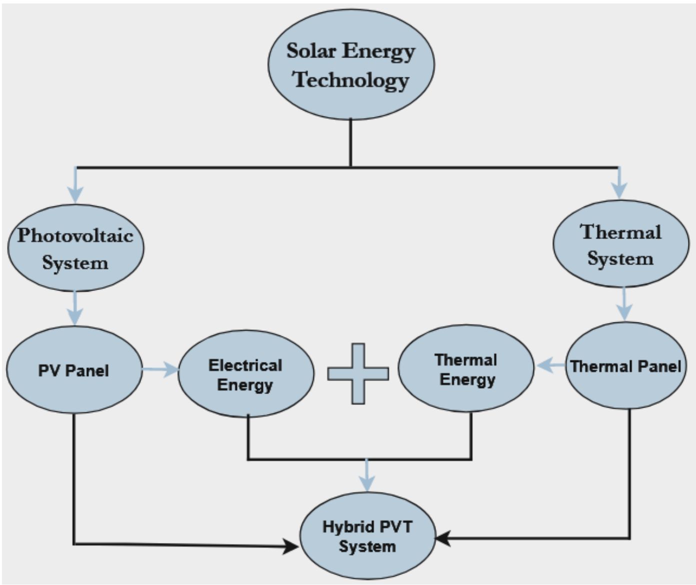

Figure 2.22: Concept of Hybrid PVT system [53].

Maximizing solar thermal and electrical energy and building an efficient system are the primary goals of utilizing hybrid PVT technology. The comparison analysis shows that PVT system requires less space than conventional PV or thermal collector technology. Furthermore, PVT has the ability to generate more electric and thermal energy occupying the same area than a typical thermal collector and PV module produces separately. It provides a clear and straight solution and that PVT technology performs efficiently than using two systems PV and thermal separately. Additionally, it works perfectly even with a limited installation area [53]. Furthermore, both existing technologies for electricity and thermal energy production technologies are integrated into one system is the PVT that reduces not only installation costs but also has a quicker payback period [17].

There are various types of system architecture in the PV modules namely hybrid, standalone, grid-tied, tracking systems and so on. The traditional components of the PV system consist of PV panel for generation, battery for storage, MPPT tracker, inverter and charge controller. The PV system is already very popular in both urban and rural areas, and it is also integrated into various types of applications. Not every energy plant based on PV system is very energy efficient and cost effective and still it is expected to become a dependable and widespread source of energy in the coming years. It has resulted in many research studies that high temperatures have a direct impact on the open circuit voltage and reduces its value hence electrical efficiency is also decreased finally [181-182]. One of the solutions to this problem is to reduce temperature by cooling techniques and thus it increases the overall performance of the systems also. Besides, the systems lost energy can be recovered using this strategy in the PVT system. For PVT systems cooling and heat extraction purpose the water and air both or air combinedly and water or air separately employed in the system [53].

The low-cost properties of a PV system are possible to identify by analyzing the main system's parameters and its related costs. The efficiency value of a PVT system is utilized to calculate and estimate the total electricity produced in terms of the incident irradiance. The overall efficiency of a hybrid PVT system is far higher than the overall efficiency of a single PV system because of its capacity of transforming waste heat into useful energy [183]. The introduction of PVT systems started in many years, but it is still in the early phase of development and did not expand as it was expected. As the systems have experienced in many cases higher output and greater efficiency with low-cost devices, it is expected to be a popular and possible substitute for a single PV system. Innovative research based on new developments and integration of PVT into buildings is also studying as there are available spaces in the rooftops of the buildings. The objectives of the research are to establish a system for producing thermal power in a less costly manner. It shows the probability of achieving a low-cost PVT system for future energy technology. An optimal system is required to reach this goal, and this system should be constructed with an optimum energy efficient design with cost effective materials. In addition, considering the space and effective design, it should occupy less space and should be designed according to the building shape while it is planning to be set up in a building [184].

There are significant advantages to using and implementation of PVT system. Typically, a higher part of the incidence radiation is collected and used by the collector to produce thermal and electrical energy in this type of system. Usually, PV cells absorb the wavelength of visible light and thermal collectors section receive the infrared wavelength from the spectrum. If tandem solar cells are taken into consideration and combine both PV and collector technology in the same device then it will be able to absorb most of the spectrum and will be more efficient. In cost perspective, PVT system is economical as it is less costly than the installation of separate PV and thermal system is a significant advantage of PVT system that motivates to invest in it. Besides, PVT system does not occupy bigger space in comparison to PV and thermal system together. An additional advantage of PVT system is that in summer season it helps to reduce temperature in the residential buildings, surface shading is also improved using this technology. The integration of PVT systems in residential buildings will enhance the beauty and structure of these buildings rather than installing PV and thermal system separately. Besides these advantages, PVT systems are also efficient as they produce and have potential to produce higher range of electrical energy and help to compensate for the thermal losses occurred in the existing typical thermal technologies.

The total efficiency of a PVT system determines the overall performance and improvement of energy production in it. Total efficiency is determined by [53, 185]

$$\eta_{Total} = \eta_{Thermal} + \eta_{Electrical}, \tag{2.31}$$

where thermal efficiency is $\eta_{Thermal}$ and electrical efficiency is $\eta_{Electrical}$. Considering PVT panel as a thermal collector thermal efficiency is obtained by [53]

$$\eta_{Thermal} = \frac{Q_{Useful-Heat}}{I_{Irr} \times A_{Panel}}, \tag{2.32}$$

where area of the panel is A_{Panel}. The useful heat of the system is evaluated as [53]

$$Q_{Useful-Heat} = \dot{m} C_p \Delta T, \tag{2.33}$$

where mass flow rate of the given fluid is $\dot{m}$, specific heat of the fluid is C_p, temperature difference between inlet and outlet fluid is ΔT. Electrical output of the thermal flat plate collector by conventional way is obtained as [53]

$$\eta_{Electrical} = \frac{I \times V}{I_{Irr} \times A_{Collector}}. \tag{2.34}$$

Produced thermal energy by using this system is possible to transform into usable energy. Panel temperature dependent on the varying electrical efficiency of a PV system is provided as [53]

$$\eta_{Electrical} = \eta_{ref} \left(1 - \beta \left(T_{PV} - T_{ref}\right)\right), \tag{2.35}$$

where system's reference efficiency is η_{ref}, panel temperature is T_{PV}, reference temperature of the system is T_{ref}, temperature coefficient is β.

Using these equations, electrical efficiency, including thermal efficiency of the system can be obtained. Inclusion of other related parameters and consideration of the mathematical model with numerical modeling of this system provides more advanced and complex model in the sense of parametric analysis.

Classification Analysis of PVT

Classification of PVT system provides insights into the types, kinds and different types of working methodologies used. For PVT classifications various methods exist in literature. In this study, works on several research publications are analyzed in the range of 2010-2023 years. An overview of the selected articles for this study and its related year of publication is shown in the figure 2.23 below.

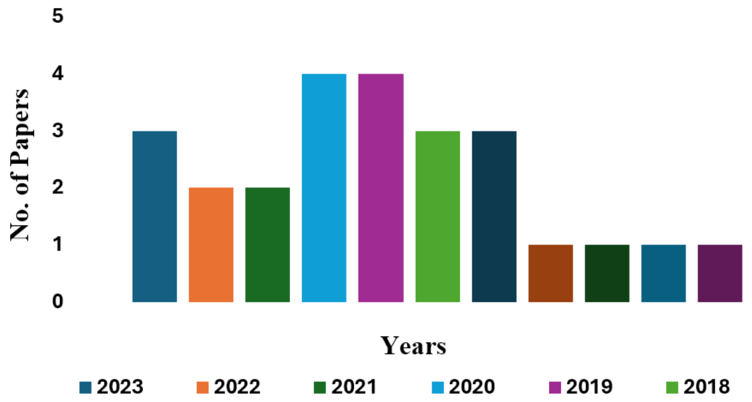

Figure 2.23: Total selected papers by years [53].

Figure 2.23 describes the papers studied by years for this work and it also shows that maximum papers were selected from the year 2019 and 2020. In this study, the maximum seven papers are considered from the very recent time such as from 2021, 2022 and 2023. The main reasons for selecting these papers are to gather information regarding recent updates, modification of the PVT system and its classifications. Some paper shows innovative classifications of the improvement of PVT systems. Others selected papers are also from recent years like 2018, 2019 and 2020.

The following table 2.4 is structured and established based on the extensive literature review from the selected publications of recent years about hybrid PVT system.

Table 2.4: Classification analysis of hybrid PVT system [53].

Reference	Year	Classification	Types
[186]	2023	PVT Systems	• Water-based • Air-based • Bi fluid based. • PCM based. • Heat-pipe based
			• Heat-pipe collectors

[187]	2023	PVT Collectors	• Concentrated collectors • Air-based collectors • Building-integrated collectors • Dual air-water collectors • Liquid-based collectors
[188]	2023	PVT System	• Absorber Configuration • Absorber material
[189]	2022	PVT Collector	• Type of glazing • PV cell • Working fluid • Solar thermal collectors
[190]	2022	PVT Collector	• Glazing • PV Cell Type • Absorber • Collector • Heat Extraction Medium
[191]	2021	PVT Collector	• Liquid-based PVT • Air-based PVT • Concentrated PVT • PCM-based PVT • Air & Liquid based PVT
[192]	2021	PVT Systems	• Novel PVT system • Flat-plate PVT system • Concentrator type PVT system
[17]	2020	PVT Collectors	• Working Fluid • PV Cell • Glazing • Thermal Absorber • Solar Thermal Collector
[193]	2020	BIPVT	• Hybrid BIPVT • Water Based BIPVT • Air based BIPVT
[194]	2020	PVT System	• Concentrated PVT • Nanofluid based PVT • Air and Water based PVT • Water based PVT • Air based PVT
[195]	2020	PVT System	• Conventional Systems i. Water ii. Concentrator iii. Air iv. Bi-fluid • Novel-based Systems i. PCM ii. Nanofluid iii. Refrigerant • Heat Pump
[196]	2019	PVT System	• Material type • Coolant type • Collector type
[197]	2019	PVT System	• PV material type • Module type • Coolant type
[198]	2019	PVT Collector	• Novel PVT • Concentrator type PVT • Flat-plate PVT

[199]	2019	PVT System	• PCM/PVT • Air PVT • Refrigerant PVT • Water PVT • Heat pipe PVT • Air and Water PVT • Nanofluid PVT
[200]	2018	PVT Systems	• Type of heat extraction • Type of solar input • Medium of heat extraction • Systems configuration
[201]	2018	PVT System	• Type of PV • Working Fluid Type • Collector design type • Panel covered type • Fluid flow type
[18]	2018	PVT System	• Flat plate air • Concentrator • Flat plate liquid • Vacuum tube
[202]	2017	PVT Collectors	• Coolant type • PV material type • Collector type
[203]	2017	PVT System	• Novel PVT Systems • Conventional PVT systems
[204]	2017	PVT Collector	• Air Collector • Combination of water and air • PVT Water Collector
[205]	2016	PVT System	• Water based PVT • Thermoelectric based – PVT • Air based PVT • Refrigerant based PVT • Air & Water based PVT • Concentrated PVT PCM based PVT • Heat pipe Based PVT
[206]	2012	PVT Collectors	• PVT concentrator • Air PVT collector • Liquid PVT collector
[207]	2011	PVT Collector	• Air Collectors i. Unglazed ii. Double pass iii. Glazed iv. Channel flow v. Single pass • Water Collectors i. Unglazed ii. tube absorber iii. Sheet and tube iv. Glazed v. Round tube absorber vi. Square/rectangular • Channel flow
[208]	2010	PVT Products	• PVT concentrator • Liquid PVT collector • Ventilated PV with heat recovery • Air PVT collector

The provided table above shows the analysis of hybrid PVT system's classification. It demonstrates various types of classification mentioned and discussed in a number of research papers. Discussed classification is analyzed based on several parametric evaluations of PVT systems and collectors. Such as heat extraction medium based classification is provided in [186-188, 193-195, 199, 18, 205-207, 209], design of PVT system is considered for classification in [192, 196, 198, 208], overall system's configuration-based classification is provided in [17, 189, 190, 197, 200, 201, 202, 203]. A summary of the various classification criteria and related configuration is discussed in the following figure 2.24.

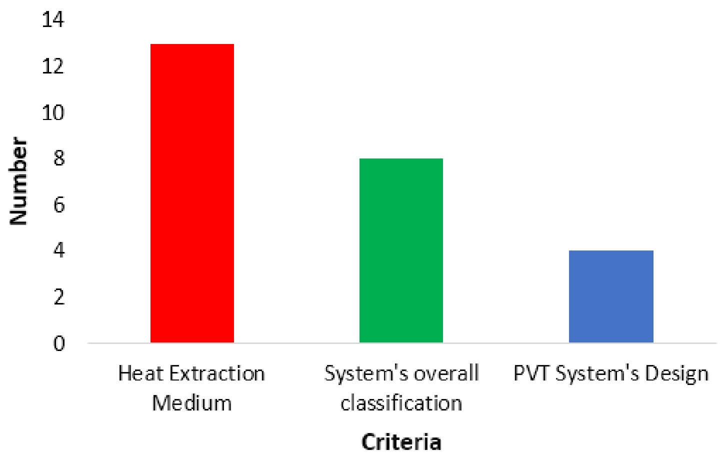

Figure 2.24: Considered selection criteria for PVT classification [53].

The considered and employed classification criteria of this work are displayed in the given figure 2.24. Three major criteria are obtained after studying and analyzing the research summary, and research works of the existing literature are PVT System's Design, Heat Extraction Medium and System's Overall Classification. After analyzing it is found that heat extraction medium based classification is used in thirteen papers from the total twenty-five papers, PVT system's design-based classification was considered in four papers. Additionally, classification considering system's overall parameters are demonstrated in the total eight research works. After analyzing and assessing the literatures it is found that no comprehensive classification of PVT system is provided in any of the paper. Additionally, there is no such classification that is completed with detailed analysis that may provide clear and comprehensive idea about the PVT system. A proposed classification of hybrid PVT system based on the studied research works and published literature on PVT system is provided in figure 2.25.

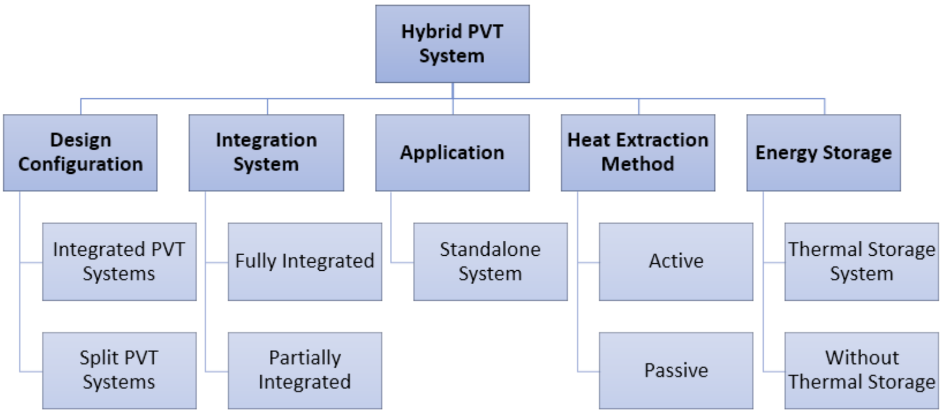

Figure 2.25: Hybrid PVT classification [53].

The parameters considered for this classification are based on its application, heat extraction method, design configuration, energy storage and integration system. In design configuration, it has two subparts that are integrated PVT systems and split PVT systems. The integration system consists of either a fully integrated or partially integrated system. Due to simplicity and use in the remote area the application section is divided into only standalone part. In the extraction method, two types of prioritized system are active and cooling method. In consideration of storage, this system can be developed with thermal storage or without thermal storage, and electrical energy storage exists by default setup. Mainly, by using this classification method it is possible to gain knowledge on complete overview of the existing and improved PVT system.

To use most of the incident radiation of a PVT system, it is necessary to develop an improved heat extraction method to extract the maximum thermal energy. The following figure 2.26 provides a classification of heat extraction method of PVT system after analyzing existing methods in recent literature. In this classification, two types of possible heat extraction are studied namely active heat extraction and passive heat extraction. Active heat extraction requires extra energy to run the process but in passive heat extraction it does not require an extra source of energy to function. The main types in the active heat extraction methods are active air heating, heat exchangers method, active PCM, selective active coatings, direct fluid flow control, heat pump, desiccant-based extraction, thermal energy storage-based extraction, nanostructured materials based extraction, thermoelectric generator extraction and combined heat and power system.

Passive heat extraction methods can be employed in the PVT system also. The methods that can be considered for heat extraction that also provide significant impact on the output thermal are natural ventilation, radiative cooling based heat extraction, natural convection, thermal find and heat sinks, PCM based heat extraction, thermal mass and natural evaporative cooling based heat extraction.

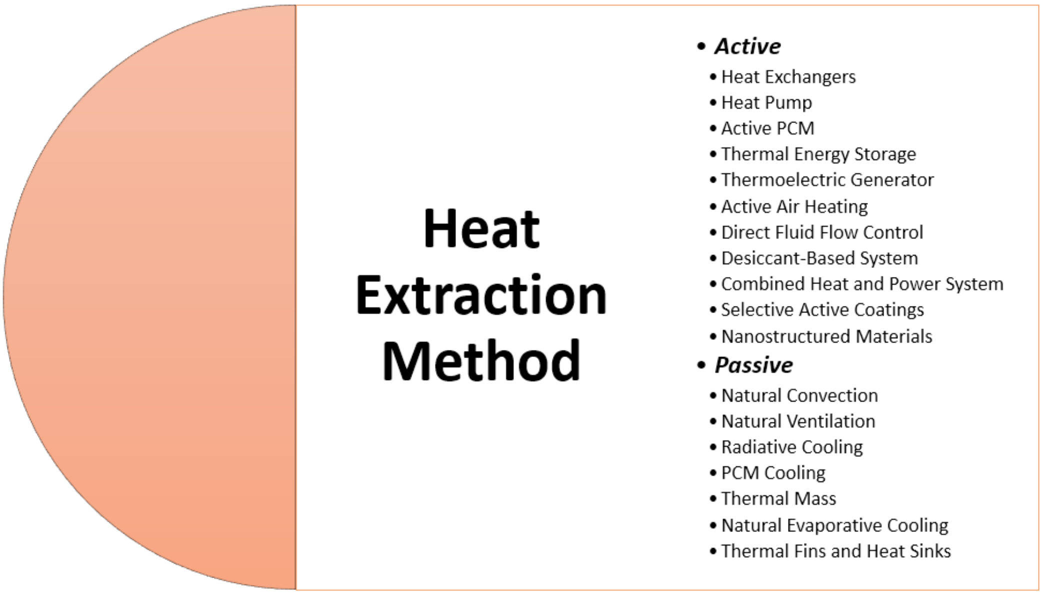

Figure 2.26: Heat Extraction Methods of PVT system [53].

Parametric Optimization of PVT System

Performance evaluation and efficiency analysis of hybrid PVT systems inevitably involves its parameter study and optimization. For performance evaluation and increase of its properties, researchers focused on mainly discussion and finding optimization of different related parameters of hybrid PVT system. A comprehensive understanding of the several parameters associated with hybrid PVT performance can be established through a parametric analysis [206]. The paper [207] established research and parametric analysis based on channel air flow and ambient flow. For this analysis, the parameters studied are mass flow rate, channel shape and heat exchanger resistance. Performance of a PVT system significantly related to different flow regimes that is discussed in [208]. In this work a number of research work from reputed publishers is considered and studied for performance analysis purpose. The following figure 2.27 provides an overview of the papers analyzed for this work [53].

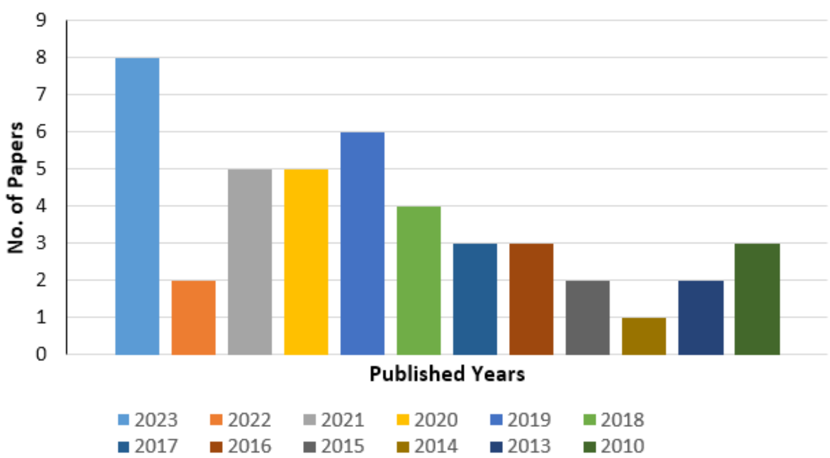

Figure 2.27: Articles publication years.

Figure 2.27 provides an overview of the publication years of the selected articles for parametric analysis purpose. It also describes that the year 2023 has the most selected publication year for this analysis has total of eight papers, and from the year 2019 few papers also included in this study. The summary of the review papers and articles that are obtained by using an extensive and comprehensive study is provided by the table 2.5.

Table 2.5: Hybrid PVT system parametric properties analysis [53].

Reference	Year	Analysis Topic	Parameters
[206]	2023	Parametric	• Air velocity • Mass flow • Wind speed • Channel thickness
[186]	2023	Optimization	• Operating conditions • Geometric parameters
[207]	2023	Parametric	• Wind speed • Solar insolation • Mass flow rate • Air temperature • Glazing cover • Micro-channel heat pipes • Packing factor
[208]	2023	Parametric	• Different flow regimes • Design parameters
[209]	2023	Parametric	• Temperature evolution • Meteorological parameters
[210]	2023	Parametric	• Thermal conductivity • Fluid and air velocities • Receiver side length • Fluid channel diameter
[211]	2023	Parametric	• Different fins shapes • Temperature
[212]	2023	Parametric	• Geometric parameters • Climatic parameters
[213]	2022	Parametric	• Ambient temperature • Solar irradiance • Dust • Humidity • Wind speed • Nanofluid type • Volume concentration • Flow rate
[214]	2022	Optimization	• Geometric parameter
[215]	2021	Optimization	• Irradiance • Ambient temperature • Position • Dust • Humidity
[193]	2021	Optimization	• Environmental conditions • System design
[216]	2021	Parametric	• Boundary conditions • Design parameters
[193]	2021	Parametric	• Weather conditions

			• Design parameters
[119]	2021	Parametric	• Electrical losses • Solar irradiation • Cell temperature • Incidence angle
[218]	2020	Parametric	• Air temperature • System voltage/current • Different parameters
[219]	2020	Parametric	• Cooling type and efficiencies • Thermal collector • PV cells
[61]	2020	Optimization	• Wind velocity • Coolant temperature • Packing factor • Glazing
[141]	2020	Parametric	• Irradiance • Ambient and module temperature • Wind speed • Humidity • Shading, dust • Design parameters
[220]	2020	Parametric	• System parameters
[221]	2020	Parametric	• Electrical parameters • Thermal parameters • Design parameters
[197]	2019	Optimization	• Design parameters
[198]	2019	Optimization	• Design parameters
[196]	2019	Optimization	• Design parameters
[222]	2019	Parametric	• Thermal parameters • Meteorological parameters • Geometric parameters
[223]	2019	Optimization	• Incident parameters • Meteorological parameters • Design parameters
[224]	2019	Parametric	• Electrical parameters • Design parameters
[198]	2018	Optimization	• Design parameters
[180]	2018	Optimization	• Design parameters
[225]	2018	Optimization	• Electrical parameters • Meteorological data
[226]	2018	Parametric	• Thermal capacity • Heat transfer
[201]	2017	Optimization	• Design parameters • Meteorological parameters
[200]	2017	Optimization	• Design parameters • Natural parameters
[227]	2017	Optimization	• Thermal parameters • Weather parameters • System configuration • Technological parameters • Location
[228]	2016	Parametric	• Irradiance • Heat capacity • Density • Velocity • Thermal conductivity
[229]	2016	Parametric	• Thermal parameters • Electrical parameters

[230]	2016	Parametric	• Phase change material • Solar irradiance • Ambient temperature
[231]	2015	Optimization	• Heat transfer coefficient • Temperature • Solar radiation • Meteorological parameters
[178]	2015	Parametric	• Wind speed • Global radiation • Temperature
[232]	2014	Parametric	• Mass flow rate • Design parameters
[233]	2013	Parametric	• Mass flow rate • Packing factor • PVT Materials • Efficiency
[132]	2013	Parametric	• Design parameters • Operating temperature
[205]	2010	Parametric	• Mas flow rate • PV/T dimensions • Air channel geometry
[234]	2010	Optimization	• Design parameters
[235]	2010	Parametric	• Design parameters

Different parameters and optimization properties analysis from various recent research papers are discussed in this given table 2.5. After comprehensive analysis of this review study is summarized and classified in the following figure 2.28.

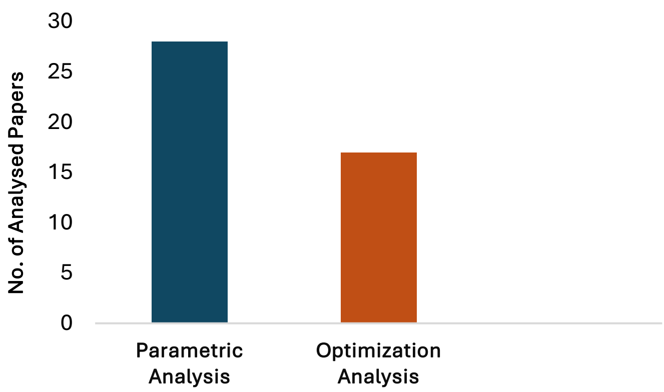

Figure 2.28: Classification based on analysis [53].

A classification based on summary of the research study is provided in the figure 2.28. After analyzing the figure, the information obtained from there is that many of the authors described and choose parametric evaluation for PVT systems efficiency study. Besides, some of the authors show optimization method depending parametric analysis for efficiency study. The way of parametric evaluation for performance analysis varies from work to work and authors to authors. For instance, climatic parameters where the main concern in various research works, design parameters [208] are considered in some works, meteorological properties [209] are also considered in many works, geometric and climatic properties are studied in few of the works. It is studied and discussed flow of fluid including velocity of air and design with shape analysis in [210]. Systems various fin shapes and temperature evolution are discussed by [211].

To analyze the system's performance evaluation related parameters are focused on [213]. The properties of geometric parameters and their optimization are discussed in [214]. Performance analysis of a PVT system is obtained considering geographical position and climatic parameters in [215]. Weather situation including design parameters based parametric study is provided in [193]. Climatic parameters, loss of electrical portion and incidence angle value are analyzed in [217]. One of the significant parameters to obtain better efficiency and performance improvement is temperature of the outside air is studied in [218]. It is proposed the use of passive and active cooling for efficiency increase and to cool the panel by several authors [33]. For evaluating the performance of the system, optimization of design parameters is given preference in [195-197].

It is expected that PVT system delivers both thermal and electrical energy where heat transfer technologies are required to extract thermal energy. In the purpose of parametric evaluation of PVT system its capacity related to thermal and electrical output is established in [226]. The simple parameters of electrical and thermal that has impact on the PVT output is described in [224]. The implication of PCM and its use for thermal energy extraction process is provided in [230]. Heat extraction fluid is one of the most crucial factors in PVT system, the properties of this fluid such as mass flow rate, packing factor that has important contribution in the efficiency of PVT is derived in [231]. There is a relationship between Hybrid PVT systems and their design parameters [151, 234, 235] which is considered for its performance analysis.

Efficiency of a PVT system depends how the system is performing based on its given and ambient parameters. Parameters and optimization based on these parameters are studied, analyzed and briefly discussed in many literatures study to improve the performance, output and effectiveness of the PVT system. Several authors focused on ambient parameters, many of them focused on characteristics-based parameters, others focused on design parameters, some of them also considered heat extraction parameters. After analyzing these literatures, it is found that a complete, clear, energy effective parametric model or parametric classification is significant to provide and establish an energy efficient model. For that purpose, a classification model for parametric and optimization analysis is proposed in this work is provided in the figure 2.29.

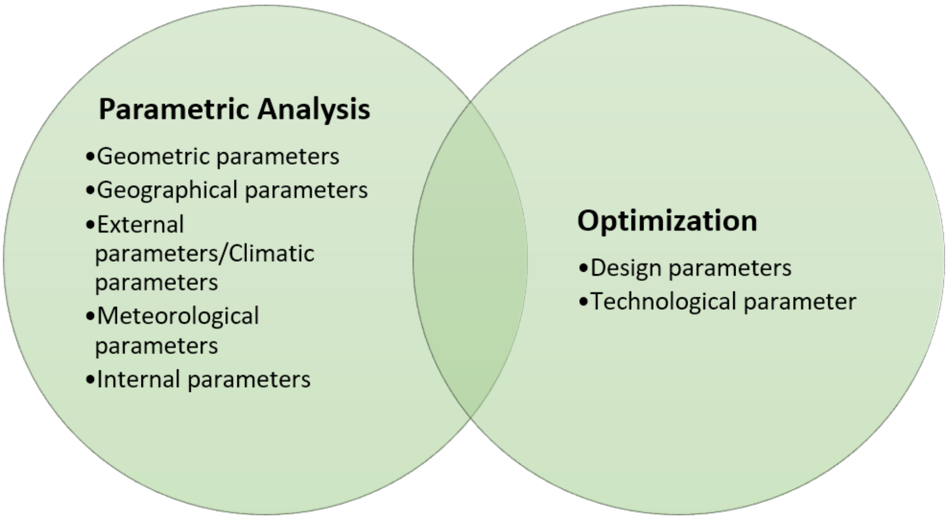

Figure 2.29: Classification for parametric analysis and optimization [53].

The considered parametric classification is mainly divided into two main parts: parametric analysis and optimization analysis. The parametric analysis of this model is based on all related internal and external parameters of the system that have direct or indirect impact on the output and efficiency. The considered parameters in parametric analysis are internal parameters, external parameters or climatic parameters, geometric parameters, meteorological parameters, geographical parameters. The optimization parameters are technological parameter and design parameters.

For PVT system construction, geometric parameters are the basics parts and significant properties which take part in the output and performance improvement. The related parameters for geometric analysis are provided in the following figure 2.30.

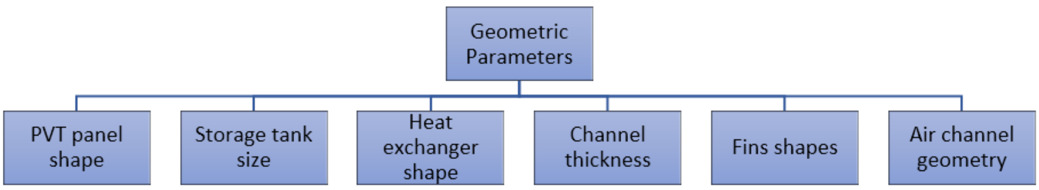

Figure 2.30: Factors of geometric parameters [53].

The parameters related to geometric classification are air channel geometry, PVT panel shape, heat exchanger shape, fins shapes, storage tank size and channel thickness. These parameters are selected based on consumer demand, available space and required output from the system.

In many locations like deserts, forests, highlands the installation and the position of the system has a great impact on the output and performance. The main properties of geographical parameters are considered and discussed here. In the classification of geographical parameters location, incidence angle and latitude and longitude are provided in the figure 2.31.

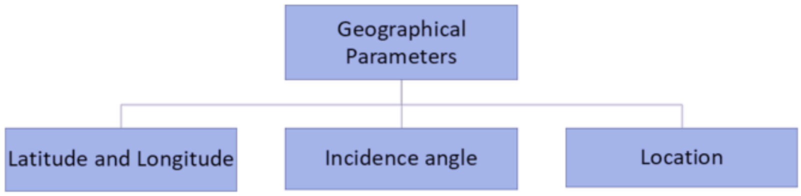

Figure 2.31: Factors of geographical parameters [53].

The most significant parameters of hybrid PVT system that have direct impact on the performance and efficiency are climatic parameters also identified by external variables.

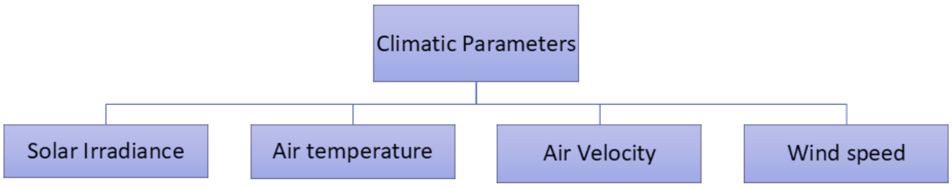

Figure 2.32: Factors of climatic parameters [53].

An illustration of this classification of climatic parameters is provided in figure 2.32. Solar irradiance is the type of parameter that has a direct impact on output and efficiency as it is the main source of energy in the PVT system.

Depending on the location, the impact of meteorological parameters also varies and in accordance with this parameter the performance of the system also changes. A summary of these parameters related to meteorological factors are provided in the figure 2.33 below.

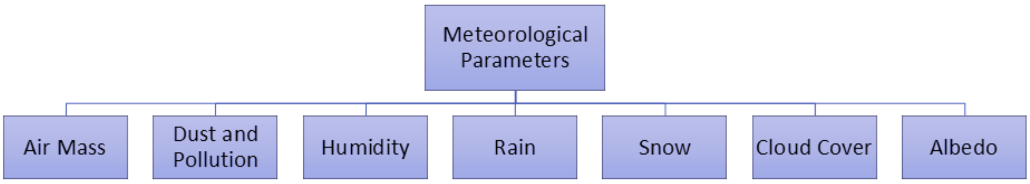

Figure 2.33: Factors of meteorological parameters [53].

The impact and characteristics of these parameters of hybrid PVT systems are analyzed in many research works. It also provides information from these literatures about how significantly it changes or increases the performance of the system due to these parameters variation.

The above-mentioned classification and consideration of PVT systems parameters are mostly external or outside parameters. Along with outside parameters, the inside or internal parameters have significant contribution to the output and performance improvement analysis. The classification of internal parameters factors is provided in the figure 2.34 below.

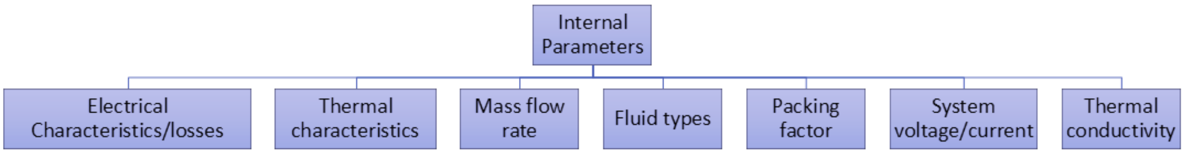

Figure 2.34 Internal parameters elements [53].

In the internal parameters the most dependent and reliable source of parameters are electrical characteristics that are related to gain or losses. Thermal characteristics of PVT systems are solely responsible for the thermal output and efficiency. Besides, there are other parameters that also influence and related to PVT systems are thermal conductivity, packing factor, voltage and current of the system, mas flow rate and types of used fluid.

This discussion is related to the classification of the parameters of PVT based on parametric analysis obtained from several research studies. It reveals a complete form of understanding and realizing the important parameter of the system. It classifies the parameters based on its classes and subclasses. It is already mentioned that for parametric analysis the study is divided into two main parts are parametric study or classification based on internal and external parameters and another part is optimization based parametric analysis classification.

The classification of optimization parameters and its related other factors are discussed in the following figure 2.35. In the figure it is provided that the classification based on optimization parameters are divided into design parameters and technological parameters.

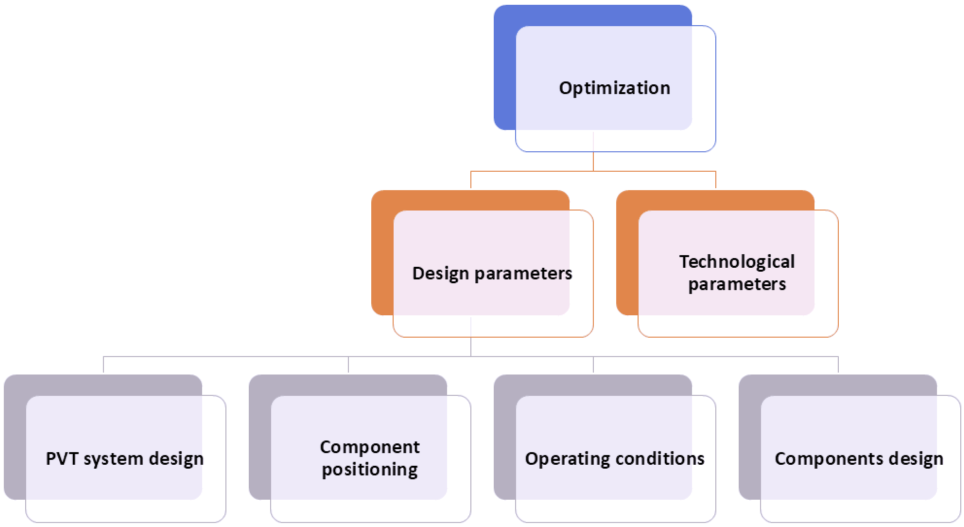

Figure 2.35: Elements of optimization parameters [53].

Based on optimization, a section is divided named design parameters that are regarded as one of the primary concerns in the construction of PVT systems. There are four factors or elements considered for this part namely component positioning, components design, PVT system design and operating conditions.

Important optimization parameters that affect the PVT system's performance are covered in this section. It mainly demonstrates the dependency of PVT parameters for optimization and analysis purpose. The latest literature review explains that optimization study and parametric analysis are required for PVT performance improvement. The researchers and its community will have an excellent overview of PVT parametric optimization and performance study by gathering the knowledge and information proposed and discussed in this work. Besides, the appropriate parameters selection and design construction idea can be chosen from this analysis that will help to establish an appropriate PVT system [53].

A parameter model and related classification is proposed in this work after an enhance review from the literature. This study also includes the described analysis of several variables, including meteorological, geometric, external/climatic, geographical and other internal variables. By this study, it reveals an improved understanding and road map to develop an efficient parameter based PVT system. Additionally, it will show a pathway for establishing PVT systems in practical case that are capable of running efficiently with improved performance even in adverse environmental conditions [53].

Design parameters including technological factors are considered for performance optimization of PVT is discussed in optimization section analysis of this work. Recent published works emphasized addressing and focusing on parameters optimization classifications that contribute to the performance analysis of the system and that serves the motivation of investigating parametric analysis and consideration of optimization parameters. The proposed analysis will also help to choose the appropriate technical and design parameters that will enhance the performance of PVT system [53].

This section is mainly composed of analysis, proposal and study of hybrid PVT system review that summarizes performance and efficiency dependent parameters and classifications of these parameters. It also studies and shows existing research profiles related to parametric and optimization analysis. Classifications are provided based on existing methodologies and concepts explained in other related works. In order to overcome the gap found in previous research works based on parametric and optimization analysis the provided classification is introduced in here. Additionally, it will help to enhance the capability of classification-based analysis that will contribute to the performance development of the system. The other subsection described and studied various parameters from both internal and external context including optimization parameters that proposes a parametric model for effective and energy efficient PVT system [53].

This chapter discusses the introduction of solar energy, photovoltaic and photovoltaic thermal technology. The earth, atmosphere and sun relation with the existing ecology and its importance in solar energy technology is also discussed. It also provides insights about solar system, PV technology, PV cell working process and other significant process in solar energy technology. In the photovoltaic part it describes design configuration of PV system, solar cell classification the type of photovoltaic system like on grid and stand alone. Classification of PV system is also discussed and provide a glance about the existing PV technology.

Modeling of PV system is necessary to understand the behavior and characteristics of the existing techniques. The conversion to electrical equivalent circuit from the ordinary solar cell and its mathematical model provides the insight of the parameters. Parameters evaluation of this model based on internal and external case is also shown. Significant parameters mathematical model and its development are also provided here. Modeling and information regarding I-V and P-V curve with maximum power point shows the real characteristics of the system. Parameters of different types like environmental, design based, implementation based, and management related are also described here.

Temperature related issues are the main concern of a PV system among all other parameters. Temperature evolution in a PV module is discussed. The effect of temperature in micro level and macro level is analyzed. Several PV cell temperature models from the literatures are discussed and related mathematical model are also established here. It is found that every model is dependent on specific parameters related to the PV system. Cooling technologies are the solution that can easily and constantly cool the PV system. Various cooling technologies mentioned in the literature are described and provided here. The type of cooling systems and its properties and materials are also summarized in this chapter just to provide a short idea regarding temperature issue and its cooling effect.

Photovoltaic thermal system, that is the main theme of this work is introduced here. The concept and a summary of working methodology are also discussed. Efficiency of a PVT system is mainly evaluated based on its thermal and electrical output. The summary model related to efficiency and performance improvement is also studied. To develop an efficient PVT system, it is necessary to analyze the existing types, kinds and methods employing the performance of this system. A brief literature review based on this concept is done and existing classifications of several types are discussed. Most of the papers are considered from the very recent updates and inclusions in the field of hybrid PVT systems. After this analysis, a classification of hybrid PVT system is also developed and provided here in this chapter. The summary of existing heat extraction method and an analyzed model is provided based on the observations.

Parameters of the PVT system that are the key concern of the development and efficiency analysis are also summarized here. The developed and discussed work in this chapter is going to provide an insight into solar energy development and existing methods and parameters. This chapter is developed based on an enhanced literature study and discussion. The main purpose of developing this chapter is to introduce and discuss the possible elements related to increasing efficiency and necessity of excess heat recovery in the PVT system. In here, the classifications of PVT and different approaches based on various research works are briefly reviewed. An innovative classification is suggested following an analysis of these studies. Three main criteria are developed in this research work where the summary of the classifications discussed in many of the literature is also included. It is expected from the outcome that it may help to provide an overview of the classification methods used in the several literatures related to PVT. The study of parameters is divided and classified into two main categories are parametric based analysis and optimization analysis. These classifications reveal all the parameters that are involved in the PVT systems efficiency and performance study.

There are both minor and major issues and challenges related to PVT's are found in the literature. The major challenge is to keep a balance of thermal output and electrical output of PVT system in the context of efficiency and optimization of performance. Another challenge is to determine and maintain optimal parameters during operation for better performance without any effect on efficiency. It is possible to handle this issue using and following the proposed parametric classification and analysis. The design structures of existing systems integration into developed systems are also difficult and a major challenge. By the analysis discussed in this chapter, the integration and compatibility challenge are also possible to improve.

The developed work in this chapter provides an overview of the solar PV system, PVT system and its parameters and other related factors. This study considers the starting of developing an efficient hybrid PVT system. Despite this, it is significant to develop and characterize a PVT system based on mathematical modeling, design study and parameters sensitivity analysis that has certainly impact on the output and efficiency of this system.

Chapter 3: Modeling and Development of Hybrid PVT System

3.1 Introduction to PVT System

One of the main concerns of the 21st century is the energy generation using sustainable, renewable, dependable and environment friendly technology that helps to protect our environment and climate by maintaining appropriate ecosystem [236]. This purpose can be served using renewable technologies like solar energy system, wind energy, hydro power, biomass and other existing green energy technologies. Solar energy engineering is developed to provide energy in the residential, industrial, and commercial sectors advancing with on-grid or off grid systems. The thermal energy demand is also increasing day by day rapidly due to expansion of industries and premises that require processed thermal heat energy for their daily needs. This scarcity and existing problems due to both thermal and electrical energy demand can be mitigated by employing and introducing renewable energy, most specifically hybrid photovoltaic thermal (PVT) technology [237].

Thermal energy and electricity production in an efficient and affordable manner is possible by using PVT system. Only a small portion of irradiance incident from the sun which is approximately 5-25% is used to produce electricity in the PV panel and the rest of it is transformed into thermal energy due to the reflection, refraction or conversion process. Because of this absorption in the PV panel, there is an impact on the total output due to the temperature increase in the system. Because, with the increasing temperature value there is decreasing output power of the system. The solution to this unwanted behavior and significant temperature rise impact is reduced by introducing cooling system which is implemented in many systems.

The better and most efficient way of fulfilling this purpose can be by using a PVT panel that will boost cooling and increase output. Due to these benefits, a number of residential houses and industries are experiencing use of this technology. Though there are challenges due to economics, technology, law, policy, but the research on PVT system is still developing worldwide [238]. Another challenge of inconsistency in demand and supply for thermal and electrical energy is also discouraging the development of this technology [239]. The industrial entities should come forward to advance this technology by overcoming the existing challenges. The use of PVT technology will provide significant impact to these sectors of both residential and industrial where it requires heats from low to high level of temperature [240].

The manufacturing sectors in the industry are responsible for consuming over half of the total thermal energy needed in the world [241]. The needs of this thermal energy demand are mostly accomplished by fossil fuels, and a very little amount is covered by biomass and other existing renewable technologies. There are many possible locations, whether they are in urban or rural area, the use of solar thermal energy is prominent but due to the limitations of the PVT technology it is difficult to explore

[242]. The existing decarbonize methods like biomass and hydrogen use, heat production using electrification in the industries and carbon capture with sequestration (CCS) are initiated to cover thermal demands, but the challenge is the economic feasibility of these existing technologies [243].

Many research works are developed based on thermal demands of small-scale system for example the use of hot water for residential purposes, space heating though PVT system which is capable of supplying thermal energy for the large industrial processes [219]. The impact of climate change and increasing energy costs can be reduced by addressing the use of different solar energy sources like solar PV and solar thermal that may replace conventional sources in future.

The implementation of hybrid PVT systems that integrate both thermal and electrical energy in the same device can mitigate this interdependent drawback in the existing electrical and thermal system. In the hot regions, with the increase of cell temperatures there is significant impact on the overall output of PV system [80] and systems size is restricted by the roof area [244]. There are also other parameters that take part in the total output of the PVT system are location, wind, dust and shading.

PVT system consists of two types of system such as PV modules and thermal absorbers in the same design and structure. During operation the panel cools down as heat flows and at the end surplus heat is supplied to the end users. Production of thermal and electrical energy process and related elements overview is provided in the following figure 3.1 below.

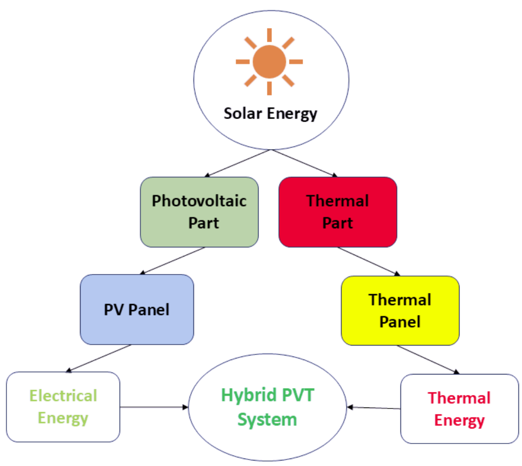

Figure 3.1: Formulation overview of Hybrid PVT System [245].

From figure 3.1 it is realized that typically PV panel produces electrical energy, and thermal panel produces thermal energy, but PVT panel produces both of that energy which is efficient than separate operations.

The main advantage of using PVT systems is its efficient operation methodology and effective impact on the PV systems physical properties. It is already mentioned that PV panel and thermal collectors have different operation methods, and it also absorbs different level from the solar spectrum. It is discussed and established in many research studies that PV panel absorbs the visible part of the spectrum while thermal modules absorb the infrared part. So, the benefit of employing PVT system is that it can absorb both visible and infrared portion at the same time and transform it into useful energy.

In today's competitive world the cost of manufacturing, installation and maintenance is a great deal that sometimes hinders the development of new technologies. There are separate costs associated with PV installations and maintenance where the thermal collector has the same type of costs associated. In the context of cost effectiveness, the PVT system is also providing scope to the manufacturers that reduces cost, time and required materials to produce separate systems.

With the increasing population and by this race the energy demand is also increasing which strikes also the space issues in this limited part of the earth where most of the spaces are occupied with water. In this sense, it provides an opportunity to save space as PVT systems do not occupy the amount of space occupied by the PV and thermal systems separately. PVT system also helps to reduce thermal load during summer season by surface shading and thermal insulation. Besides, in the view of design, structure used in PVT system is more compact and design friendly than using both PV and thermal energy extraction system independently. So, the architecture of a residential building will have a better orientation.

The parameters responsible for sensitivity and variation analysis are also significant for renewable energy technology. Because many of the renewable technologies are directly or indirectly dependent on ambient or external parameters. The issues arise here regarding the handling of these technologies such as solar, wind system, hydro power in adverse climatic conditions. Additionally, the output of these technologies is mostly dependent on the weather situation like if there is not available sunlight there will be very little output which is almost negligible. In this situation, parameters optimization is the main concern. For PVT, it is less complex than optimizing parameters separately in PV system and thermal collectors.

These are the main advantages that attract and motivate us to devote ourselves to the development and enhancement of PVT technology. For broader knowledge on PVT, a comparison of simple operation methodologies between photovoltaic, thermal system and PVT system is provided in figure 3.2.

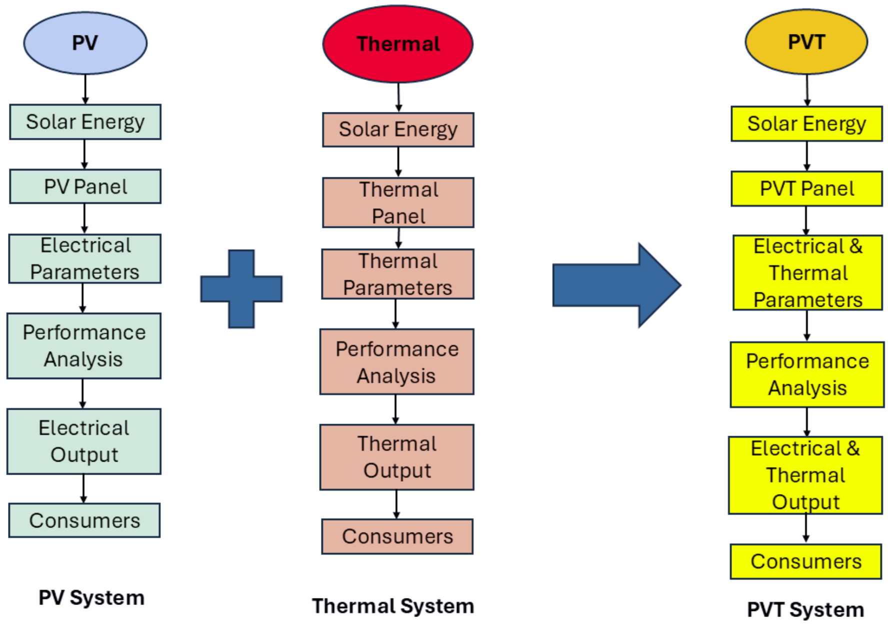

Figure 3.2: Relationship between PV, thermal and PVT system.

From the given figure 3.2 it is provided that for photovoltaic system it just considers electrical parameters of PV panel, and then analyze performance based on electrical parameters of the system. Finally, electrical output is only taken for consideration and provided to the end users or consumers. By the same way, in the thermal system thermal panel is used and thermal parameters are given priority. After obtaining thermal output energy it is provided to the users like for residential and industrial processes. It is also quite interesting while it comes to the operation of PVT system. A simple PV panel with heat exchanger module with or without heat transfer fluid produces electrical and thermal energy. So, in general situation we can describe and accept that PVT system is efficient and convenient than PV and thermal system.

For PVT panels cooling, the fluids are typically used in the existing systems are water, air or any type of refrigerant [246]. In many of the work cooling system is added using nanofluids and different types of phase change materials [158, 247]. The process temperature in a system is classified as low, medium and high and based on that requirement heat transfer fluid is chosen. The usual thermal characteristics of water are very significant for using it as HTF like it has boiling point with higher value, specific heat capacity is also high and better melting point. For these thermal properties water can be used in most of the systems [248]. The main reason for using water is because hot water demand during winter season is very high. Both theoretical and practical work is already done on a water-based hybrid PVT system. The main focus was to reduce the system costs and improve efficiency by analyzing and studying this system from various aspects. It is obtained electrical efficiency around 8.7% and thermal efficiency around 79% where it makes total efficiency around 87% by improving optical parameters of a PVT collector that is provided by an experiment in [249]. The integration of thermal system in a PV module also increases its electrical efficiency and improves performance in this system which is investigated in [250]. Also, it was compared the thermal output of PVT hybrid system with the thermal output of traditional PV system where the hybrid output was higher. The combine operation of thermoelectric generator (TEG) and PV panel is utilized to fix the issue of non-uniform temperature distribution including special thermal materials which are studied in [251]. After analyzing it is obtained that in all of these experiments using heat transfer fluid in PVT system improved both electrical and thermal efficiency thus increasing overall efficiency. PVT system consists of several layers in its structure. Different kinds of PV module such as monocrystalline, polycrystalline and amorphous silicon module can be used. In the back of PV panel, a heat exchanger pipe is attached to it and the pipes can be any type like aluminum, stainless steel, copper and many other existing metal pipes in the market. The selection of this pipe depends on the supply and demand associated with its design framework. The fluid flow occurs in the pipe and there is an inlet and outlet point at each end where fluid enters and exits consecutively. To reduce heat losses by convection and conduction an insulation layer is also necessary and provided in the back of the panel. Maximizing efficiency, output and greater performance also varies based on this insulation layer. On the top of the panel the glass cover is also responsible for optical properties and reflection and refraction of irradiance. The protection layer or the back cover is used and placed to overcome any challenges due to external obstacles. A typical PVT system structure and illustration is provided in figure 3.3.

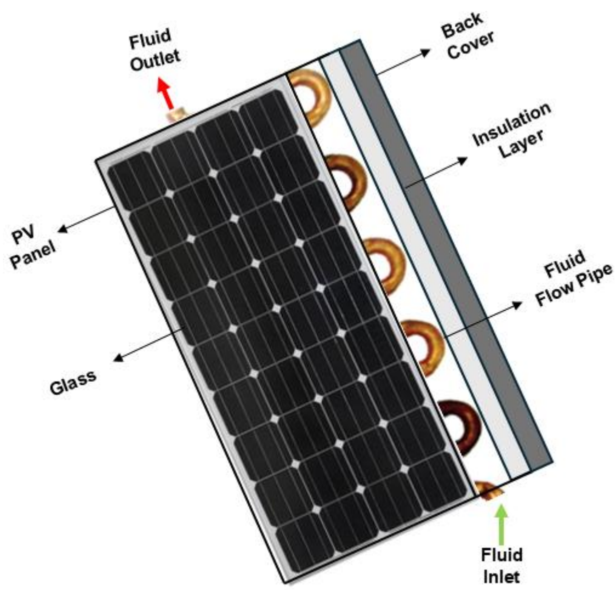

Figure 3.3: Structural overview of a PVT system.

The design configuration of PVT systems can be based on active or passive method where it can function either indirect which is also called as closed loop or direct system. There are some restrictions where it is required to implement and use separate heat exchangers in order to keep the water clean. For example, during the use of special type of fluid like nano-fluids or any type of ethylene glycol is required an extra heat exchanger in the storage so that it does not mix with the usable water.

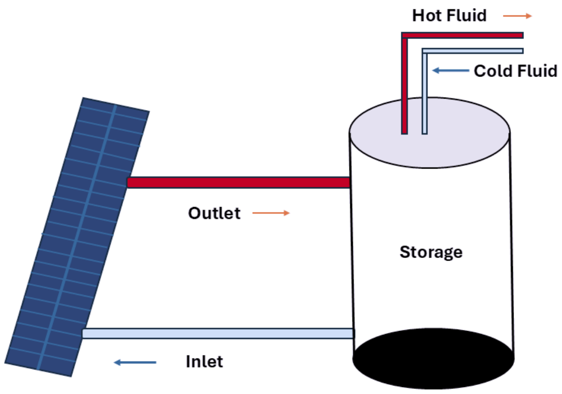

Figure 3.4: PVT system direct passive flow.

A direct passive flow technic of PVT system is provided in the figure 3.4 where water circulation is provided by natural convection and no additional force or energy is required to run this system. On the other hand, in a direct or indirect system the help of any pump and other electrical components is required in order to flow the fluid is known as active systems. The water circulation by a pump in an active system of a PVT module is provided in the figure 3.5.

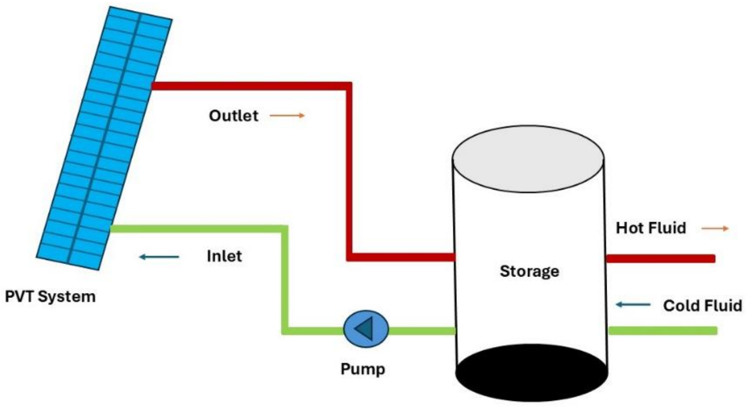

Figure 3.5: PVT system direct active flow.

In an indirect system a heat exchanger inside the storage is used that transfer heats to the liquid. It is mainly used in the very cold region where the heat transfer fluid has chance to be frozen in the pipe. An overview of indirect active flow is given in figure 3.6.

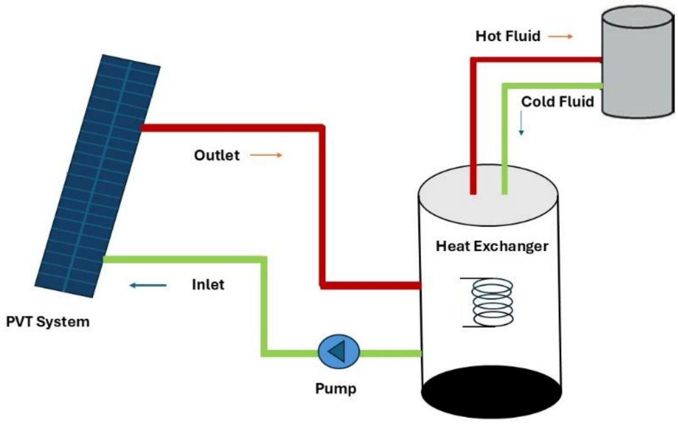

Figure 3.6: PVT system indirect active flow.

3.2 PVT System Classification

There are many kinds of PVT system existing such as PVT to supply hot water, PVT for facades ventilation and it also can be used for cooling or refrigeration purpose. Nowadays, use of both PV systems and thermal module has increased and thus the market has also expanded. The effort on technological development and performance improvement keeping pace with demand is also continuing to support both domestic and industrial sectors. The possibility of integrating PVT is not only limited to residential purpose but also open to being used for larger scale like commercial premises. Designing and choosing an appropriate PVT system according to requirement is a big challenge. Depending on design structure, fluid type, absorber characteristics, there are various kinds of PVT systems available. It is classified as four main types by some authors: air based PVT, liquid based PVT, concentrator based PVT and heat recovery PVT using ventilation. Typically, the top surface of the PVT system is covered by a glass to protect thermal losses by optical properties. In many of the works they mentioned using cover system in the glass called glazed and if not then it is mentioned as unglazed [205].

Use of glazing in a PVT system reduces thermal energy losses and thus increases thermal energy absorption in the system by increasing HTF temperature. It provides better yearly output while integrated into medium range to higher range temperature applications. In addition to advantage the use of glazing has disadvantages like it may be the reason for decaying of the panel due to hotspot sensitivity. Also, the overheating issue in the bypass diode may arise and electrical performance will be compromised due to reflection losses. As a result, the temperature increase in the modules internal circuit will reduce electrical efficiency.

In short, the summary of this discussion is that it is important to make balance between electrical and thermal output in such a way so that the overall efficiency increases. Additionally, it is necessary to be careful that the PVT panel should be also in good condition and not to be degraded very quickly so that the optimized output can be obtained. The performance improvement and higher efficiency of a PVT system depends on the type of PVT used for that purpose. It is significantly important to have appropriate contact with PV panel and thermal absorber to obtain optimized thermal and electrical efficiency [196].

Air based PVT Systems

The temperature regulation is obtained using an air based PVT system that uses mainly air as heat transfer fluid as a working fluid. The additional laminated layer is used on the top or bottom side of the panel in the air channels used for ventilation. The positioning of this type of system is designed in a way that it can be placed in the building roof or facade where air passes through the PV panel back part. The general use of this system is for space heating in residential buildings, increase of electricity generation, ventilation purpose and drying of agriculture products. There are existing designs of air based PVT system where air can pass from the top or bottom side even in all side of the absorber [252].

Air based PVT are mainly divided into two types are flat plate and concentrator type. The most common, simple, well known and available design is the flat plate type. Air based PVT systems are mainly used and appropriate in the buildings applications of high and medium altitude and it is less costly in comparison to liquid or fluid type PVT system. The efficiency of this type of system depends on ambient weather conditions. For example, in the lower altitude area the environment temperature is very high during summer and in this situation, the shorter period of air based PVT application provides better electrical efficiency than applying it for a longer period [187].

Heat extraction from a PV panel is performed using ambient air from the surroundings and it is the main mechanism of this type of system. The cold air is injected through the channel and hot air is gained and supplied to the consumers. In this method, the mass flow is a significant operation that works to decrease the temperature of the panel thus increasing efficiency of the module. It can be classified and summarized in many classes depending on the flow of air inside it. In the conventional system, air passes through the back of the panel using a single air duct. Another traditional system is double pass PVT where on the top of the panel there situated a pipe and on the back side another pipe is attached. The flow of inlet air is collected at the top of the pipe and the hot air is supplied back to the channel added below the system. By this way, fluid circulation is provided for a longer period of time [190].

The design and structure of PVT air based system depends on the position and the location or place where it will be used. The calculation of overall efficiency is obtained by summing the thermal efficiency and electrical efficiency of the system [61]. The total efficiency of an air based PVT system $\left(\eta_{T,Air}\right)$ is obtained as [61]

$$\eta_{T,Air} = \eta_{E,Air} + \eta_{Th,Air}, \tag{3.1}$$

where $\eta_{E,Air}$ is the electrical efficiency of an air based PVT system, $\eta_{Th,Air}$ is thermal efficiency of an air based PVT system. Thermal efficiency of the PVT air based collector $(\eta_{Th,Air})$ is obtained as

$$\eta_{Th,Air} = \frac{Q_{u,Air}}{I_{Irr} A_{Panel,Air}}, \tag{3.2}$$

where $A_{Panel,Air}$ is the panel area. And useful heat of air based PVT $(Q_{u,Air})$ is calculated by

$$Q_{u,Air} = m_{Air} C_{p,Air} (T_{out} - T_{in}), \tag{3.3}$$

where $C_{p,Air}$ is the specific heat of air, T_{out} is outlet air temperature and T_{in} is inlet air temperature. Additionally electrical efficiency is calculated by

$$\eta_{E,Air} = \frac{V_m I_m}{I_{Irr} A_{Panel,Air}}, \tag{3.4}$$

The system performance is also significantly dependent on exergy efficiency analysis. For a single-glazed PVT systems exergy efficiency is obtained as [253]

$$\eta_E = \frac{Ex_{Out}}{Ex_{In}} \times 100, \tag{3.5}$$

Exergy balance expression for PVT system of a single channel is calculated as [254]

$$\sum Ex_{Out} = \sum Ex_{Th} + \sum Ex_E, \tag{3.6}$$

Thermal exergy efficiency for this same PVT system of single channel is obtained as

$$\sum Ex_{Th} = Q_u - mC_p T_0 \cdot \ln\left({T_{Out}}/{T_{In}} \right), \tag{3.7}$$

And electrical exergy efficiency is obtained as

$$\sum Ex_E = \left[\frac{\eta A_c I_{Irr}}{1000} \right] \tag{3.8}$$

From the source obtained input energy is calculated as [255]

$$\sum Ex_{In} = A_c N_c \times I_{Irr} \left[1 - \left(\frac{4}{3} \right) \left[\frac{T_0}{T_{Sun}} \right] + \left(\frac{1}{3f} \right) \right] \left[\frac{T_0^4}{T_{Sun}^4} \right], \tag{3.9}$$

The hemisphere part protected by radiation reservoir is considered by the geometric factor *f*.

PVT air based systems are classified, and design is established based on several factors. First of all, the air circulation pattern in the system is used and its behavior is considered. Force circulation requires energy, and natural circulation does not cost additional energy though forced circulation is more efficient. But the required energy in the forced circulation system reduces the net electrical output due to use of electrical devices which require electrical energy to run. In the liquid based system there is restriction of liquid flow in a limited space but in the air based system it has almost all space to air to pass. Separate glazing part is required in this system so that air can pass on the top of the panel which increases thermal performance but in the perspective of electrical performance it has fewer impact. The cell operating temperature is increased due to air flow and reflection losses of the irradiance occurs also. Air based PVT systems design and cross sectional view are provided in the figure 3.7 below.

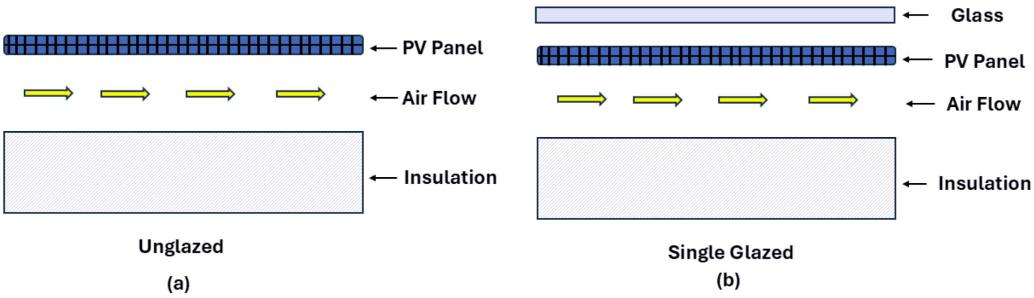

Figure 3.7: (a) Unglazed and (b) single glazed air PVT system.

In the unglazed system, air flow happens at the bottom side and in single glazed air PVT system air flow happens also in the bottom side but there is an additional layer used to improve performance. The modified glazed air module and double glazed module are shown in figure 3.8.

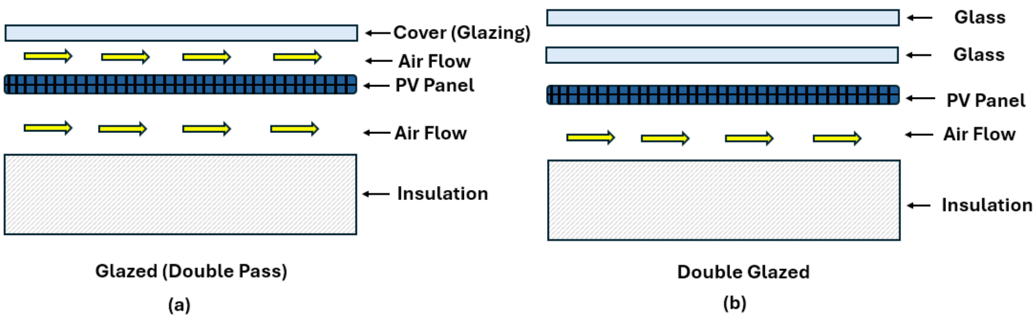

Figure 3.8: (a) Glazed with double pass and (b) double glazed air PVT system.

In the glazed double pass system air passes from both top and bottom of the panel and there should be a glazing cover on the top side of the panel. Besides, on the double glazed panel, air flows only in the lower part of the panel and there are two glasses on the top of the panel.

Water based PVT Systems

Water based PVT systems are appropriate for high temperature systems due to their better thermal properties and on the other hand air based system is less effective than water based system as it does not have higher thermal properties. Both passive and active cooling system can be used in the water based system where liquid tubes are attached to the back side of the PV module. The heated water is received from this system as it extracts heat from the panel and thus the system gets cooled too. The hot water received from this system can be utilized for many purposes like residential and industrial sectors. A water based PVT system generally consists of a PV panel, heat extraction pipe, a storage tank and pump to circulate water in an active system. The water supplies from the back of the storage tank and passes through the panel utilizing pipe and then received hot water is sent to tank from its bottom section. As a result, high density cold water converts to lower density hot water due to stratification process and the performance is improved by both electrical and thermal efficiency context [186].

Water based PVT is considered one of the most efficient technologies among other PVT system where preheating water is needed all the year round and the location has sufficient sunlight and ambient temperature value is higher [234, 256-257]. Significant research is already done in the configurations of water based PVT system and its geometrics and material properties due to an increase interest and performance analysis [186, 258].

The main characteristics of these types of system are that it provides both electricity and thermal energy simultaneously. It is found that PVT water based system and air based system have similar designs and configurations except the channel/pipe where water based system uses pipes for water flow. The output of this system depends on its design configurations. The design configurations of sheet & tube and channel PVT system based on [259], is provided in the figure 3.9.

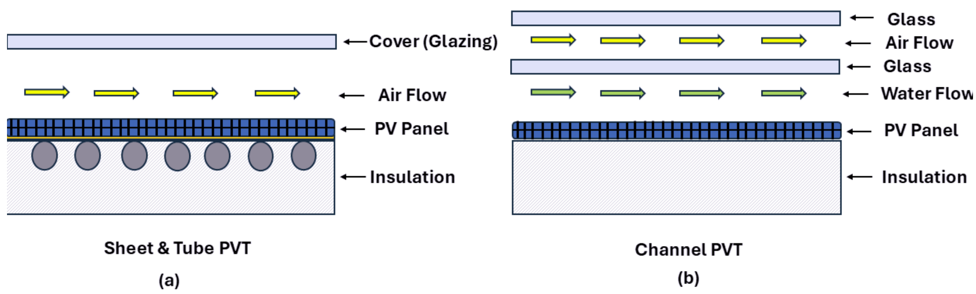

Figure 3.9: (a) Sheet & tube and (b) channel type water PVT system.

In the sheet & tube PVT system there is only single cover and air flows on the top of PV panel. An additional tube is attached to the panel for heat extraction purpose. And, channel PVT has two glasses covers and on the top of panel water flows where below the topmost glass air flows.

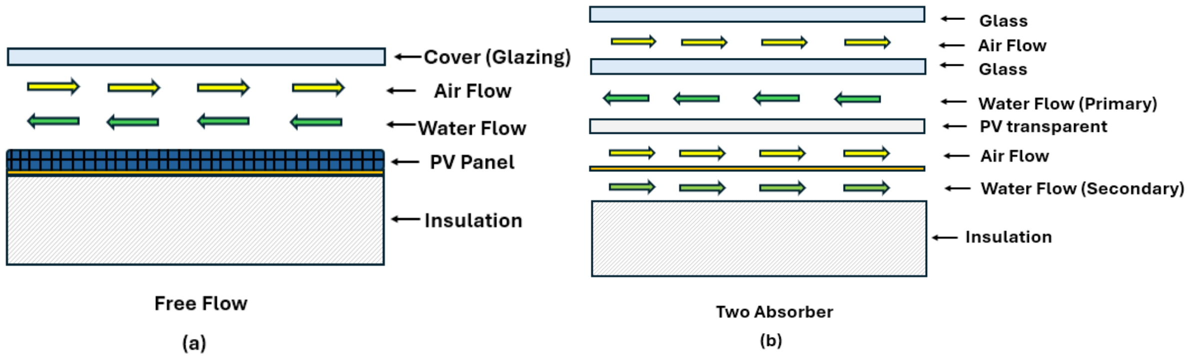

Figure 3.10: (a) Free flow PVT and (b) Two absorber water PVT system.

The figure 3.10 given above describes free flow PVT and two absorber PVT system. In free flow PVT, water and air flows on the top of the PV panel and in the two absorber model, there exists a transparent panel where air and water flow below and above the panel.

Copper has a very significant thermal conductivity and that is why it is widely used as a thermal conductor in the PVT system. Sheet and tube absorber is the most commonly used model that uses liquid to flow in the back part of the module including with series or parallel pipes [187, 258, 260]. The pipe used in the system can be of several designs like parallel pipes or direct flow, web flow which is used in [164, 168]. For web flow design the results provide very low output with 41-48% of efficiencies depending on flow rate of the fluid while the outlet temperature is 50 ºC – 65ºC and a bit greater output is obtained in the direct flow system which is 46-54%. Among these designs, 56-68% of thermal efficiency and electrical efficiency of 13-14% was obtained using spiral flow design, beside the temperature of the module also reduced to a significant level [168]. There are also several other types and designs available in literature which have various efficiencies depending on the mass flow rate. The designs and shapes of the pipes are provided in the figures 3.11 and 3.12 for better illustration.

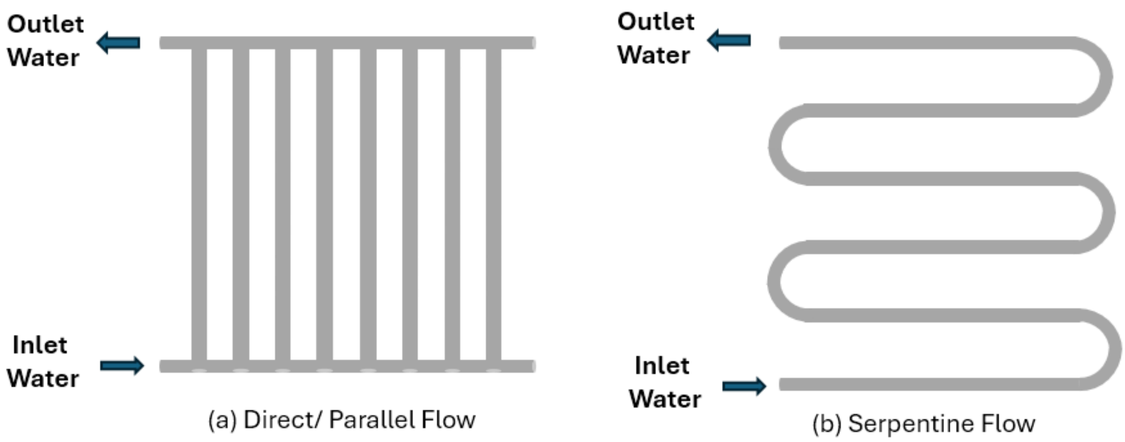

Figure 3.11: Direct/ parallel tube and serpentine tube for PVT [187].

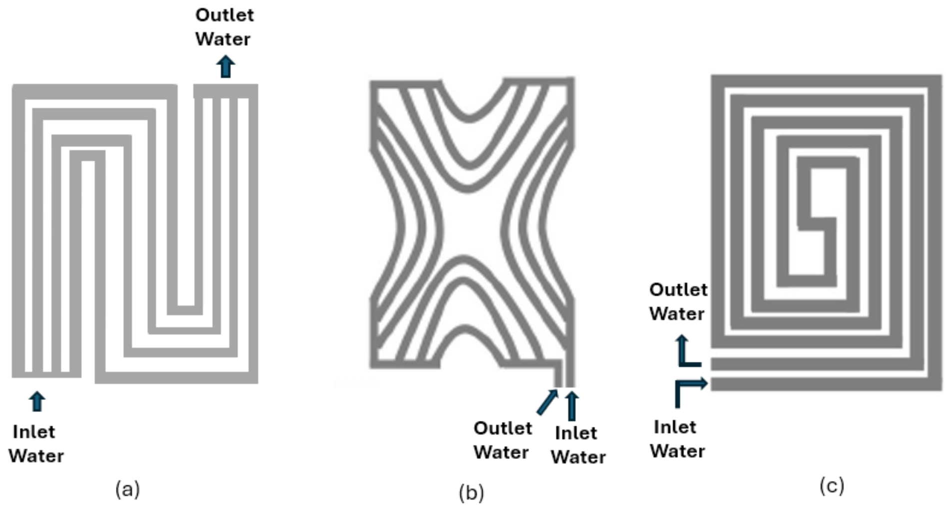

Figure 3.12: (a) Parallel serpentine, (b) Web flow type (c) Spiral tube for PVT [187].

Heat Pipe PVT Systems

A heat transfer technique that uses heat conduction capacity and phase transformation is known as heat pipes based PVT systems and it is considered as better efficiency based mechanism. It is also identified as probable optimized solution for extra heat reduction and thermal energy transmission in PVT which has three typical separate parts are condensed division, evaporated and adiabatic divisions [252]. These types of techniques are also used in many kinds of devices like spacecraft and cooling of electronics which provides elevated heat transfer efficiency. In comparison to other techniques, it is more beneficial in the context of lifetime and longevity, rates of thermal energy transfer and no additional active elements with consumption of extra energy are required. In [261-262], the heat pipe is divided into two main parts namely condenser and evaporator sections.

In this system, the heat is absorbed in the evaporator and later on evaporator sections evaporate the fluid. In the condensed section, the working fluid is condensed and thus how heat is transformed to another form and then heat is released. Extremely highly effective heat transfer is obtained due to the use of heat pipes in PVT and its available phase transition properties. The main motive of using heat pipes in PVT system is to remove waste heat from the PV module and use this extracted heat for another purposes. Additionally, it is also considered to be helpful to overcome the limitations of using PVT systems based on refrigeration method [252]. Heat pipe based PVT systems schematic [187] is provided in the figure 3.13.

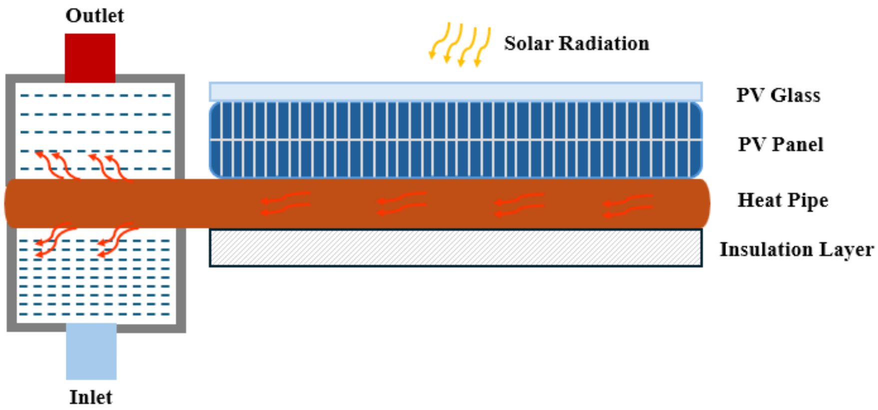

Figure 3.13: Heat pipe based PVT system.

The extra heat generated in the panel is absorbed by the heat pipe which is added to the back side of the module. The generated heat in the module and extracted/absorbed by the pipe passes to the condensation section and heat transfer fluid is used there, later on this heat is collected by the fluid for further use. In this case, the medium of heat transfer is a heat pipe at the first level which has very high thermal conductivity and at the second level water or any other fluid is used for heat transportation [263].

The use of this type of mechanisms has various sections like preheating of water, thermal and electrical energy supply performance improvement, load balance by reducing consumption for residential temperature regulation and control [264]. Among several existing heat pipe variations, the application of flat type microchannel heat is discussed in [265]. The efficiency of the system due to the use and integration of microchannel type increases around 40% during summer season. Another kind of heat pipe based PVT system is copper made cylindrical type [266]. Pipe is attached at the bottom side of the panel and after heat absorption operation is completed by the pipe then it is transferred using fluid specifically water. With the increasing numbers of heat pipe, the heat extraction reaches to efficiency increases. Daily thermal efficiency is increased by 10% while the number of pipes is increased by 10 [267]. In conclusion, it is obtained that due to its anti-freezing characteristics which depends on appropriate fluid selection can provide better performance than traditional water based PVT systems [268].

PCM based PVT Systems

It is important to the use of thermal energy storage during nighttime to fulfil the demand of electricity and thermal power [269]. In the conventional renewable energy generation system, electrical energy is stored and used batteries for covering the demand during off peak periods. Phase change materials (PCM) are considered to be the suitable solution in the context of thermal energy storing and supplying using the abundant amount of solar energy earth receives [270]. PCM is able to perform at a higher level, and it has improved charging and quicker discharging capability. Besides, these types of materials are environmentally friendly as they do not release any toxic elements to the environment, comparatively less costly and it is very convenient to use, and it is available almost everywhere.

Like PVT systems based on water, PCM based systems are still in early development and optimization phase. The main difference in these two systems is that water is used as heat transfer fluid in the water based system and in PCM based systems a PCM block with PCM materials is integrated in the bottom side of the panel. Higher range of thermal conductivity, chemical balance and stability with higher density of energy storage are the main characteristics of the PCM. It is very useful for thermal applications both in residential and commercial industries. It is significant to choose appropriate materials because PCM that has lower thermal conductivity will not be effective to use in this system. There are two types of PCM: organic PCM and inorganic PCM. The main sources of organic PCM are plants, petroleum items, and animals, but they do not possess a higher level of thermal conductivity. Inorganic PCM has higher level of thermal conductivity [190]. A schematic of PCM based PVT system is provided in the figure 3.14.

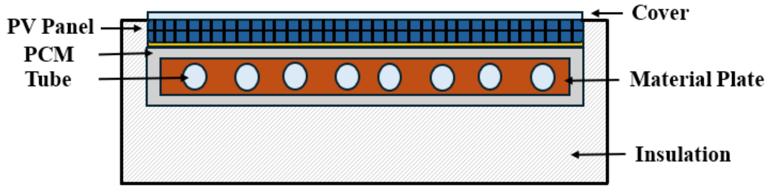

Figure 3.14: Schematic of PCM based PVT system.

In PCM based system, PV panel with glass cover is situated on the top section and on the bottom is insulation section. Inside the PCM box, a material plate and liquid flow tube are attached.

The use of PCM in building integrated (BI) PVT system is also recently being introduced in many works [271]. An investigation of two PCMs used in BI shows the improvement of electrical efficiency as the ambient temperature level is maintained by this [272].

Refrigerant based PVT Systems

Refrigerant based PVT system integrating with heat pump is studied and being focused on the recent times. In the solar heat pump PVT system, the upper layer part functions as evaporator of the heat pump [273]. The coils are attached below the PV module which evaporates the fluid while it flows at very low temperature ranges around 0 ºC to 20 ºC and by this way the module is cooled and generates thermal energy [252, 274]. It results in improved efficiency as the flow of refrigerant activities remove the dissipated heat from the system. Typically, copper made serpentine based coils are used in this type of system but there is also other system that exists like parallel tubes made of copper. The main advantage of refrigerant based PVT system is that it can operate at very low temperature and that is why it is more beneficial to use in compared to water and air based PVT system. But the main challenges are that in this system it may face leakage risk of the refrigerant, the refrigerant distribution may be nonuniform, degradation due to UV and proper sealing if it is not purely airtight [187].

3.3 PVT System Applications

There are several existing applications of PVT system among these most significant are water heating for domestic purposes, heat storing, district heating, desalination, drying for a small/large scale, air conditioning, greenhouse of solar. The use of PVT system and its application is classified based on temperature range is provided and discussed in [275]. The figure 3.15 provides an overview of the summary of PVT applications based on temperature level. The applications based on temperature range are classified into three main categories are low temperature level (LTL) ranges from 25-50 ºC, medium temperature level (MTL) ranges from 51-80 ºC and high temperature level (HTL) are the level greater than 80ºC. The use of LTL is mainly mentioned for heating of swimming pools or spas that require temperature around 27-35 ºC, and for heating of residential or commercial spaces which requires temperature up to 50 ºC. The use of LTL in PVT system can also be used for heat pump that does not require high amount of temperature which should be below 50 ºC. MTL is useful for residential hot water distribution with temperature value up to 60 ºC so that Legionellosis problem does not come into effect. But the use of hot water and its temperature level depends on the consumers' needs and that is why it may vary conventionally from 45 ºC to 60 ºC. It may also be used for heat pump that require temperature level higher than LTL.

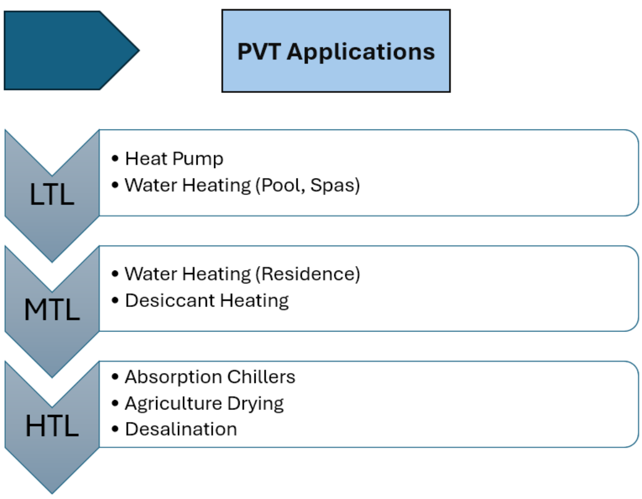

Figure 3.15: Applications of PVT system based on Temperature.

And HTL is applicable for absorption chillers that are used in large industry. It is also used to dry agriculture products and process, desalination purpose. PVT has a variety of applications like PVT based heating systems, combined heating cooling and industrial processing systems.

PVT Heating Systems

The simultaneous electrical and thermal energy is generated in the PVT system. Using the air based PVT system, the residential or commercial buildings space is heated by the output thermal energy in the form of heated air. Using water based PVT system it is possible to heat the water to a certain level like for household uses like dish washing that does not require very high temperature, water heating of pools, spaces. PVT also can generate process heat to be used in industrial purposes like pasteurization and mechanical devices washing. For obtaining higher temperature for use in large scale industries applications concentrator type PVT system can be used. In domestic water heating systems, it uses PV module, water storage, heat exchanger and extra storage tank. It can be active or passive heating where in an active heating system an auxiliary pump is required to water flow to the destination. The most popular use of PVT system is in the domestic water heating in residential buildings.

PVT Space Heating Systems

Air based PVT module is considered in many works for space heating system [276-277]. PVT double pass model of semi-transparent device is used in [278] for space heating that increases room temperature around 5-6 ºC from environment temperature. The integration of air based PVT system with heat pump also provides a better solution for buildings space heating [258]. The limitation of air based system is established due to lower air capacity of heat and less density. In remote areas like in the desert where water sources are not available, this type of PVT system is always adopted as an efficient solution. Space heating is also obtained by using a water based PVT system. The supplied hot water is stored in a storage tank and later on supplied to the consumers. In many models, an additional thermal storage tank is used where a heat exchanger exchanges the produced heat and supply to the consumers. This thermal energy is also used to space or floor heating using water flow below the floor. For space heating heat pump integrated PVT liquid systems are also used in several works.

Drying

Various types of PVT based drying systems are available among these air type drying is most commonly used. For food and agriculture products preservation purpose it is used and considered as the most conventional method of drying in the developing countries. A performance evaluation of PVT greenhouse drying using mixed-mode type is analyzed in [279] which shows theoretical value of energy as 1.92 kWh where experimental value is 2.03 kWh. The performance of a greenhouse drying system is improved if an absorber coated with black color and a chimney is integrated into the system. The efficiency in greenhouse drying using sunlight provides better drying facility and performance than normal sun drying method.

For biogas heating, PVT system integrated with greenhouse is used that includes glazed PVT modules and in inclination of 30º with the greenhouse. The biogas production is improved by this way, crop drying and electricity is also generated by using this system. It is also obtained that proper dust removal from the system provides better output including improved thermal performance [280]. The study also provides that biogas production using PVT greenhouse is continued in both sunny and cloudy weather conditions.

Desalination

The process of solar desalination uses sunlight/irradiance that helps to remove mineral contents from salty water. This produced water is used for drinking and in the irrigation process where normal water is not available. The significance of PVT based solar desalination is that it produces potable water and generates electricity simultaneously. In remote areas where there is scarcity of drinking water solar desalination is very effective and lifesaving. To run this desalination process it requires high temperature which can be gained using concentration based PVT systems. There are two main categories for water desalination like active and passive solar still. An active solar still PVT system which is self-sustainable is designed and developed by [281]. This system is more efficient than a passive system and for pump operation 43% power is saved here. The desalination process using PVT system is also helpful to provide electricity, drinking and irrigation water for islands and deserts.

Air Conditioning

Traditionally in winter season PVT system is used for space heating and water-based heating in small residential uses. And, in summer this generated thermal energy cannot be used and that is why cooling/air conditioning using PVT system is introduced to use wasted heat. But the main challenge is to perform cooling of space by PVT system that requires high temperature. High temperature in the PVT system is obtained by using several methods such as absorption and adsorption cycle, desiccant, and use of solar mechanical devices. The main components of PVT cooling system are PV panel, control section, cooling section or chiller, storage tank. The main components of cooling process are chillers that remove heat from PV panel using a fluid flowing process. The cooling process is performed using the generated heat by the fluid. There are normally two types of adsorption processes that are single effect and double effect chillers. The operation of single effect performs at 70-100 ºC temperature range and double effect requires very high temperature and it uses steam to cool [190].

3.4 PVT Systems Modeling

Typically, photovoltaic system comprises with a PV panel, charge controller, inverter and a storage system. During the operation several internal and other external parameters take part in the output variation. Among external parameters, irradiance and temperature are established as the most significant in performance analysis that influences overall output. Excessive temperature generation reduces power output and longevity of the PV system [79]. PV systems operations and functional analysis method provides clear indication of the whole system is analyzed in the flowchart depicted in figure 3.16.

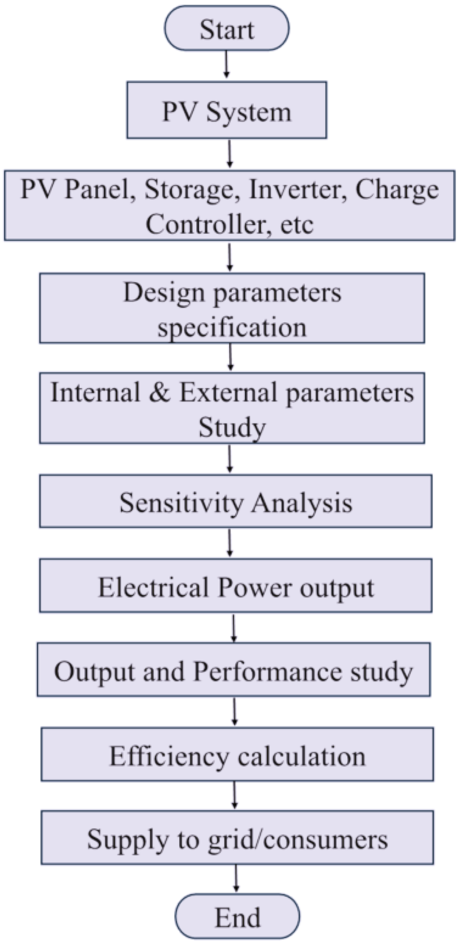

Figure 3.16: Operation and performance analysis of PV system.

PV system is dependent on the components used in it for example for on grid system there are specific assembly of components and for standalone it varies, and additional modification is required. Design parameters like tilt angle, location and position of the system are also significant for obtaining improved output. Performance study is related to internal and external parameters analysis that influences the overall performance. Sensitivity analysis provides an idea regarding the sensitivity of panels' output related to parameters. By this way obtained electrical power and the system performance and efficiency are calculated.

PVT system is developed using PV panel, electrical storage, and other electrical components for electrical power management. Besides it consists of heat transfer fluid, heat exchange pipe, thermal energy storage, heat exchanger, if necessary, additional storage and for active system pump is used for fluid flow. It is similar to PV system, but additional equipment is used for thermal extraction. Operations and performance analysis of a PVT system are provided in a linear flow depicted in figure 3.17.

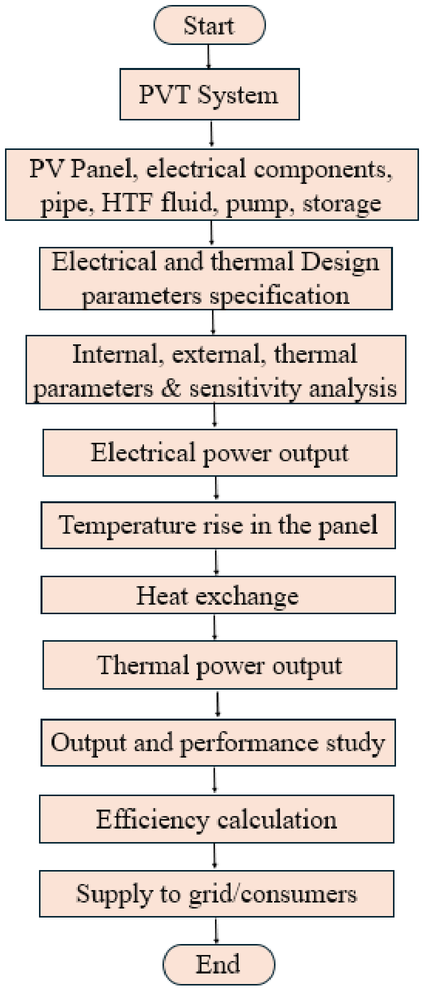

Figure 3.17: Operation and performance analysis of PVT system.

PVT system has two main sections are electrical and thermal module. Electrical power is generated using photovoltaic effect in the upper part including lower part is designed for generating thermal energy that uses heat extraction method. As a result of thermal extraction in the PVT system the panel gets cooled and electrical energy generation improves that enhance overall efficiency of the system. In figure 3.18 an illustration of a simple PVT system that produces hot water as thermal energy is provided.

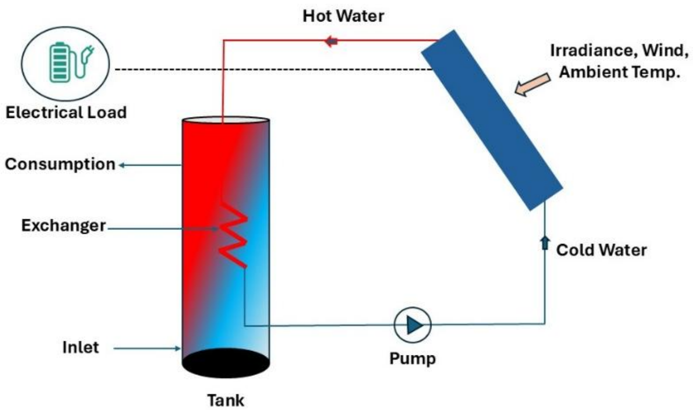

Figure 3.18: Simple PVT illustration.

It is composed of a PV panel, a pipe for heat exchange that is attached in the back of the panel, a water tank, a heat exchanger coil, a pump that facilitates fluid flow, inlet is used for water entry into the pipe, outlet is used for consumption. Additionally, this system has electrical load that use electrical power from it. A more detailed and complete PVT system is provided in figure 3.19.

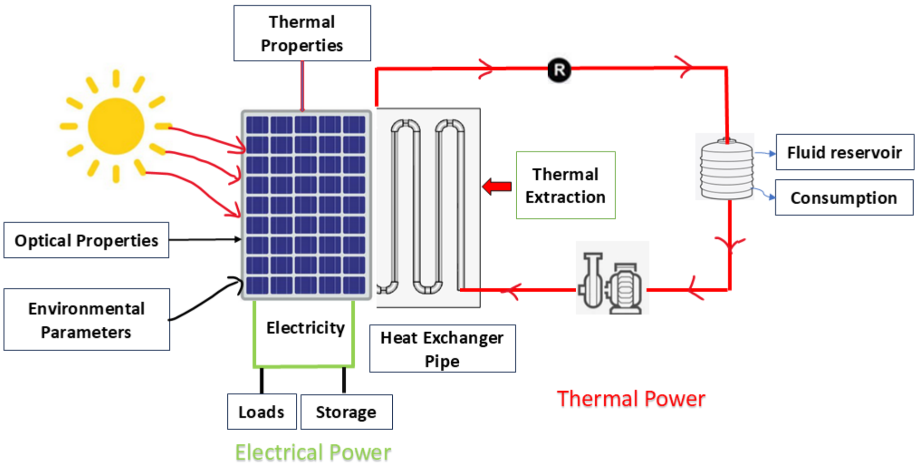

Figure 3.19: Layout of the used PVT system [245].

The figure 3.19 shows the PVT systems layout which consists of a PV panel, a heat exchanger pipe that extracts the heat lost due to conduction, convection and radiation water. In general, it just uses water flow in the pipe and the output hot water is used for residential consumers. Additionally, for improved thermal extraction a separate heat exchanger can be used also. The extracted heat is an additional output in this system while electrical power is generated using PV panel. There are significant parameters that have influence in the output, for example: environmental parameters; optical parameters; thermal parameters and design parameters.

Performance Analysis

PV Systems Performance

The efficiency of a PV cell is calculated based on the electrical energy obtained from the incident irradiance. In other way, it is simply obtained using the ratio of the sun's input and output energy [152]. PV cell efficiency is related to parameters such as wavelength of sunlight; recombination; temperature of cell and other optical properties. Efficiency decreases with the increase of cell both inside and outside temperature. PV cell energy conversion efficiency is obtained by [282]

$$\eta_{Cell} = \frac{V_{oc} I_{sc} FF}{A_{Cell} I_{Irr}}, \tag{3.10}$$

where A_{Cell} is the cell area. In equilibrium reference environment condition, the maximum obtained work is considered as the exergy. Exergy efficiency of a PV cell depends on operating, design and weather conditions [282]. The exergy efficiency of a PV cell $\eta_{EX,Cell}$ is obtained by [283]

$$\eta_{EX,Cell} = \frac{V_{MP} I_{Mp} - \left(1 - \frac{T_a}{T_{Cell}}\right)\left(\tilde{U} A_{Panel}\left(T_{Cell} - T_a\right)\right)}{Ex_{Solar}}, \tag{3.11}$$

where, T_{Cell} is the cell temperature, heat loss coefficient is $\tilde{U}$, Ex_{Solar} is the solar irradiance exergy calculated as [282]

$$Ex_{Solar} = \left(1 - \frac{4}{3}\frac{T_a}{T_{Sun}} + \frac{1}{3}\left(\frac{T_a}{T_{Sun}}\right)^4\right) A_{Panel} I_{Irr}, \tag{3.12}$$

where the sun temperature is T_{Sun}. Capacity factor (CaF) of a PV system is obtained as [282]

$$CaF = \frac{Effective\,Output}{Rated\,Output} \times 100\%. \tag{3.13}$$

Final yield (FiY) is calculated by using the total alternating current (TAC) and total PV rate power (TPVRP) is shown as [282]

$$FiY = \frac{TAC}{TPVRP}. \tag{3.14}$$

The performance ratio (PeR) of a PV system is calculated as [282]

$$PeR = \frac{FiY}{\mathrm{Re}Y}, \tag{3.15}$$

where $\mathrm{Re}Y$ is the reference yield is obtained by using total effective solar energy (TESE) and standard conditioned reference solar energy (RSEn) [282]

$$\mathrm{Re}Y = \frac{TESE}{\mathrm{R}\,SEn}. \tag{3.16}$$

Levelized cost of energy (LCOE) is considered by the minimum selling price of energy that may achieve total investment over a period of time. It is a cost metric applied to evaluate efficacy by several methods of electricity production. The cost of energy production for the lifetime of the project and related components costs are also associated with it. The related expenses associated with it are system installation, design, cash capitals, taxes and legal fees, operation and maintenance and other issues. LCOE is obtained as follows [284]

$$LCOE = \frac{Lifetime\,Costs}{Lifetime\,Energy\,Output}. \tag{3.17}$$

The accurate calculation of LCOE is provided by [285] is given as

$$LCOE = \frac{\sum_{t=0}^{n} \frac{\left(CaC_t + OpC_t + FeC_t + MaC_t\right)}{\left(1+r\right)^t}}{\sum_{t=0}^{n} \frac{EnY_t}{\left(1+r\right)^t}}, \tag{3.18}$$

where PV plant lifetime is n, t is years, percentage of discount rate is r, CaC_t is capital cost, OpC_t is operation cost, FeC_t is extra fee costs, MaC_t is maintenance cost and yield of energy is EnY_t.

PVT Systems Performance

The assessment of PVT system is significant to calculate its efficiency and overall output analysis. The performance of a PVT system is divided into two parts, namely electrical and thermal analysis. The performance analysis of electrical part is simple and easier as the consumption can be immediate, and in general it is not mandatory to use electrical power storage. Thermal performance is analyzed based on the obtained results of heat extraction and hot water supply in the domestic water heating based PVT system [234]. Based on equation 2.31, electrical efficiency is obtained as

$$\eta_{Electrical} = \eta_{Total} - \eta_{Thermal}. \tag{3.19}$$

Electrical efficiency of a PVT system is also provided by [234] as

$$\eta_{Electrical} = \frac{V_{MP} I_{MP}}{A_{Panel} I_{Irr}}. \tag{3.20}$$

But the conventional way of obtaining electrical efficiency is [17]

$$\eta_{Electrical} = \frac{I \times V}{A_{Panel} I_{Irr}}. \quad (3.21)$$

The relationship between cell efficiency (η_{Cell}) and electrical efficiency is provided as [184]

$$\eta_{Electrical} = \frac{\eta_{Cell} A_{Cell}}{A_{Panel}}, \quad (3.22)$$

where cell area is A_{Cell}. Electrical efficiency considering the induced temperature inside the panel is [227]

$$\eta_{Electrical} = \eta_{ref}\left(1 - \beta\left(T_{Panel} - T_{ref}\right)\right), \quad (3.23)$$

where panel reference efficiency is η_{ref}, temperature of the panel is T_{Panel}, reference temperature of the panel is T_{ref} and temperature coefficient is β.

The conventional way of expressing thermal efficiency is obtained using reduced temperature is expressed as

$$T_r = \frac{T_{In} - T_a}{I_{Irr}}, \quad (3.24)$$

where input temperature is T_{In}. Elaborately, thermal efficiency of the PVT system is obtained as

$$\eta_{Thermal} = \frac{\dot{m}C\left(T_{out} - T_{In}\right)}{I_{Irr} A_{Panel}}. \quad (3.25)$$

Thermal efficiency by modified Hottel-Whillier-Bliss equation is found by [234]

$$\eta_{Thermal} = F_{R,\text{mod}}\left[\left(\tau\alpha\right)_e\left(1 - \eta_a\right) - \left(\frac{T_{In} - T_a}{I_{Irr}}\right)U_{L,heat}\right], \quad (3.26)$$

where heat removal factor (modified) is $F_{R,\text{mod}}$, effective transmittance is $\left(\tau\alpha\right)_e$, η_a is the efficiency of electrical power at ambient temperature, $U_{L,heat}$ is the coefficient based on total heat loss. Alternatively considering average fluid temperature (T_{avg}) and efficiency factor (F') thermal efficiency is [234]

$$\eta_{Thermal} = F'\left[\left(\tau\alpha\right)_e\left(1 - \eta_a\right) - \left(\frac{T_{avg} - T_a}{I_{Irr}}\right)U_{L,heat}\right]. \quad (3.27)$$

So, the total efficiency of a PVT system is obtained as [234]

$$\eta_{Total} = \eta_{Electrical} + \eta_{Thermal}. \quad (3.28)$$

Electrical Modeling

Electrical modeling of a photovoltaic system requires the analysis of equivalent circuit. A single diode equivalent circuit of a PV system is provided in the figure 2.8 which is redesigned and shown in the figure 3.20.

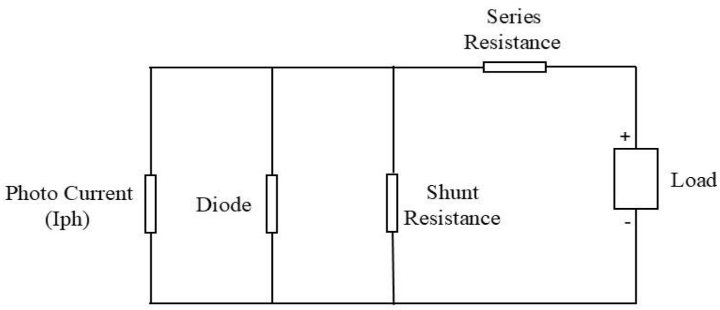

Figure 3.20: Single diode model equivalent circuit.

From the single diode equivalent model applying KCL we obtain [68],

$$I_{ph} = I + I_D + I_{sh} . \tag{3.29}$$

Shockley diode equation provides the current across the diode is [68]

$$I_D = I_s \left(\exp\left(\frac{qV + qR_s I}{NKT} \right) - 1 \right). \tag{3.30}$$

Using equation 3.30 in equation 3.29 it provides photo current as [68]

$$I_{ph} = I + I_D = I_s \left(\exp\left(\frac{qV + qR_s I}{NKT} \right) - 1 \right) + I_{sh} . \tag{3.31}$$

The current of the shunt resistor is obtained as

$$I_{sh} = \left(\frac{V + R_s I}{R_{sh}} \right). \tag{3.32}$$

Finally, substituting all equation 3.30, 3.31 and 3.32 in the equation 3.29 we obtain the load current as [68]

$$I = I_{ph} - I_s \left(\exp\left(\frac{qV + qR_s I}{NKT} \right) - 1 \right) - \left(\frac{V + R_s I}{R_{sh}} \right). \tag{3.33}$$

In this discussion an analytical solution to this load current from the electrical equivalent circuit is discussed. Equation 3.31 can be rewritten as follows [68]

$$I = I_{ph} - I_s \left(\exp\left(\frac{qV + qR_s I}{NKT} \right) - 1 \right) - \frac{V}{R_{sh}} - \frac{IR_s}{R_{sh}} , \tag{3.34}$$

and,

$$I+\frac{IR_s}{R_{sh}}+I_s\left(\exp\left(\frac{qV+qR_sI}{NKT}\right)-1\right)=I_s-\frac{V}{R_{sh}}+I_{ph}\,. \tag{3.35}$$

Dividing I_S in both side of the equation 3.35

$$\left(\frac{R_s+R_{sh}}{R_{sh}I_s}\right)I+\left(\exp\left(\frac{qV+qR_sI}{NKT}\right)\right)=1-\frac{V}{R_sI_s}+\frac{I_{ph}}{I_s}, \tag{3.36}$$

and,

$$\left(\frac{R_s+R_{sh}}{R_{sh}I_s}\right)I+\left(\exp\left(\frac{qV}{NKT}\right)\times\exp\left(\frac{R_sI}{NKT}\right)\right)=1-\frac{V}{R_{sh}I_s}+\frac{I_{ph}}{I_s}\,. \tag{3.37}$$

The equation 3.37 refers to that analytical solution is not possible in general as load current (*I*) appears in both terms $\left(\frac{R_s+R_{sh}}{R_{sh}I_s}\right)$ and $\left(\exp\left(\frac{qV}{NKT}\right)\times\exp\left(\frac{R_sI}{NKT}\right)\right)$. The extraction of load current using an analytical solution is very complicated here. A possible solution is obtained ignoring some important elements like series resistance. If it considers $R_s=0$ then the equation 3.37 is rewritten as

$$\left(\frac{0+R_{sh}}{R_{sh}I_s}\right)I+\left(\exp\left(\frac{qV}{NKT}\right)\times\exp(0)\right)=1-\frac{V}{R_{sh}I_s}+\frac{I_{ph}}{I_s}, \tag{3.38}$$

and,

$$\left(\frac{R_{sh}}{R_{sh}I_s}\right)I+\left(\exp\left(\frac{qV}{NKT}\right)\right)=1-\frac{V}{R_{sh}I_s}+\frac{I_{ph}}{I_s}, \tag{3.39}$$

and,

$$\left(\frac{R_{sh}}{R_{sh}I_s}\right)I=1-\frac{V}{R_{sh}I_s}+\frac{I_{ph}}{I_s}-\left(\exp\left(\frac{qV}{NKT}\right)\right), \tag{3.40}$$

and finally, we obtain the load current as [27]

$$I=I_s-\frac{V}{R_{sh}}-I_s\left(\exp\left(\frac{qV}{NKT}\right)\right)+I_{ph}, \tag{3.41}$$

In the given condition of $(R_s=0)$ equation 3.41 provides the analytical solution of the load current equation of an equivalent electrical circuit. Due to the complexity of analytical solution, a numerical solution like bisection, Newton Raphson method is used to solve the load current equation.

Characterization of a PV cell requires parameters extraction. Primary parameters such as panel characteristics related to current, voltage, and rated power are provided in the datasheet by the manufacturer. Following parameters relation are obtained from the equation 3.33 [68] where n_s is no. of series connected cell.

$$I_{sc} = I_{ph} - I_s\left(\exp\left(\frac{I_{sc}R_s}{n_sV_t}\right)\right) - \frac{I_{sc}R_s}{R_{sh}}. \tag{3.42}$$

Current at maximum power is obtained as

$$I_{mp} = I_{ph} - I_s\left(\exp\left(\frac{V_{MP}+I_{MP}R_s}{V_t}\right)\right) - \frac{V_{MP}+I_{MP}R_s}{R_{sh}}. \tag{3.43}$$

Open circuit current considering open circuit voltage is extracted as

$$I_{oc} = I_{ph} - I_s\left(\exp\left(\frac{V_{oc}}{n_sV_t}\right)\right) - \frac{V_{oc}}{R_{sh}}. \tag{3.44}$$

Generally, these parameters are provided by the datasheets from the manufacturer. It is also obtained that power derivative with respect to voltage is 0.

$$\left.\frac{dP}{dV}\right|_{\substack{V=V_{MP}\\ I=I_{MP}}} = 0. \tag{3.45}$$

The fifth parameter is obtained using the derivative of current with respect to voltage at short-circuit position.

$$\left.\frac{dI}{dV}\right|_{I=I_{sc}} = -\frac{1}{R_{sh}}. \tag{3.46}$$

Thermal Loss Modeling

In a PV system most of the incident solar energy is transformed into heat that not only reduces efficiency but also decreases longevity of the panel. Cooling or heat extraction method can reduce these problems and improve performance of the panel. PVT system is introduced and implemented based on heat extraction and cooling strategies. An equivalent electrical circuit model of a PV system that considers losses transformed as heat is described. Alternatively, it is an equivalent circuit for a PVT system.

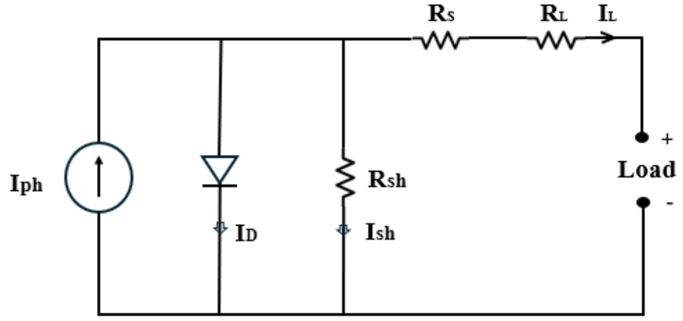

Figure 3.21: Thermal loss model equivalent circuit.

Loss current (I_L) of the equivalent circuit is obtained as:

$$I_L = I_{ph} - I_s\left(\exp\left(\frac{qV + qI_L\left(R_s + R_L\right)}{NKT}\right) - 1\right) - I_{sh}, \tag{3.47}$$

where R_L is the equivalent loss from incident irradiance to thermal energy. Diode current from this model is obtained as

$$I_D = I_s\left(\exp\left(\frac{qV + q\left(R_s + R_L\right)I_L}{NKT}\right) - 1\right). \tag{3.48}$$

Current generated in the shunt resistor is obtained as

$$I_{sh} = \left(\frac{V + \left(R_s + R_L\right)I_L}{R_{sh}}\right). \tag{3.49}$$

Substituting equation 3.49 to the equation 3.47 we obtain loss current equation as

$$I_L = I_{ph} - I_s\left(\exp\left(\frac{qV + qI_L\left(R_s + R_L\right)}{NKT}\right) - 1\right) - \left(\frac{V + \left(R_s + R_L\right)I_L}{R_{sh}}\right). \tag{3.50}$$

Using equation 3.50, the loss current is obtained from this system. Short-circuit current is

$$I_{sc} = I_{ph} - I_s\left(\exp\left(\frac{I_{sc}\left(R_s + R_L\right)}{n_s V_t}\right)\right) - \frac{I_{sc}\left(R_s + R_L\right)}{R_{sh}}. \tag{3.51}$$

At Maximum power, current value is

$$I_{MP} = I_{ph} - I_s\left(\exp\left(\frac{V_{MP} + I_{MP}\left(R_s + R_L\right)}{V_t}\right)\right) - \frac{V_{MP} + I_{MP}\left(R_s + R_L\right)}{R_{sh}}. \tag{3.52}$$

Mathematical formulation to calculate open circuit voltage is

$$I_{oc} = I_{ph} - I_s\left(\exp\left(\frac{V_{oc}}{n_s V_t}\right)\right) - \frac{V_{oc}}{R_{sh}}. \tag{3.53}$$

PV panel parameters value determination flowchart based on [286] is provided in the figure 3.22.

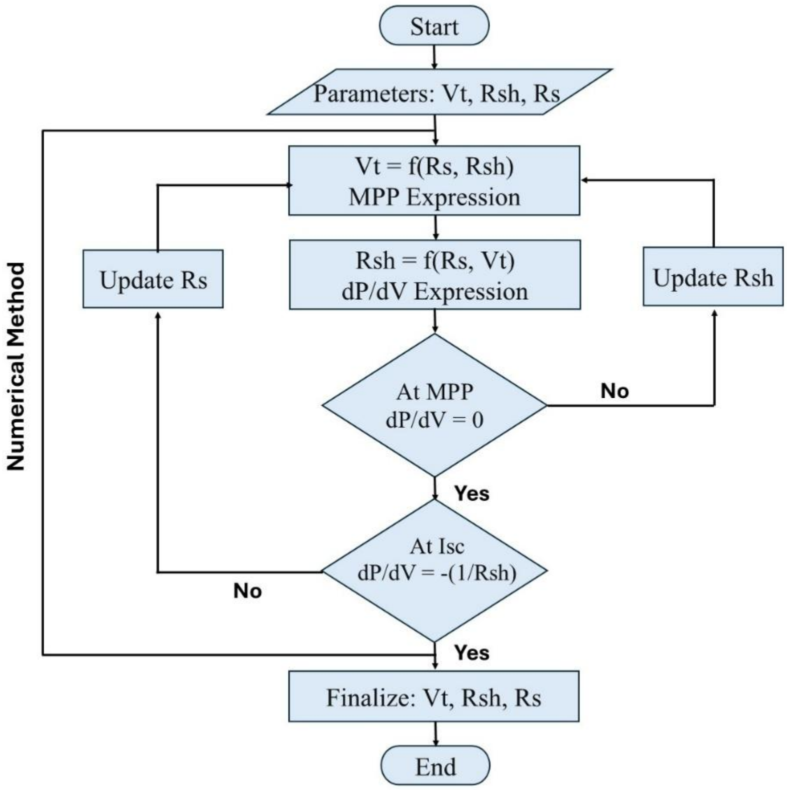

Figure 3.22: PV module parameters determination flowchart.

Thermal Modeling

PV module temperature is affected by the environmental and structural properties including other heat extraction mechanisms of the system. Thermal energy distribution and transfer to other portion make the system more complex to measure its junction temperature. The temperature of the PV system is dependent on the other parameters that influence its value besides it is implicit, dynamic and shows nonlinear behavior. Modeling approaches can be based on accurate prediction, temperature profiling and complex models. Temperature shows dynamic behavior before it reaches a static position, and it is ignored by many researchers as they do not consider thermal capacity effect of the material and temperature variation lag. Based on this analysis temperature modeling is divided into two main types: dynamic model and steady state or static model. Static model does not consider dynamic changes of temperature, whereas dynamic model provides precise output that considers changes due to other parameters [287].

There are several existing models that analyses and discusses thermal model. Mathematical equations and structural parameters are used to obtain thermal model that are based on direct equations. Experimental measurements and other parametric observations are used to develop thermal model based on empirical expressions. It is simple, does not require many inputs thus provides lower accuracy for outputs. In dimensional analysis model, temperature dynamics and thermal loss mechanisms are considered as a system that requires relatively higher cost. Balancing and evaluating heat equation for different layers of the module also used to develop a model for thermal analysis [287]. There are various heat loss mechanisms in the PV system which are included in a single form to simplify the thermal analysis.

Electronic junction temperature measurement using conventional methods is not capable of measuring whole internal and external temperature of a PVT module. The exact calculation and approximation require thermal modeling which is discussed in this section. Heat balance equation (HBE) is one of the most popular approaches that can be used to determine the overall thermal energy balance is determined by the following equation [287]

$$H_{Abs} = H_{Conv} + H_{Lost}, \tag{3.54}$$

where absorbed heat is denoted by H_{Abs}, converted heat is H_{Conv} and lost heat is H_{Lost}. The absorbed energy represents the total energy of the system collected from the incident irradiance on the module. Converted energy is the output energy of electrical and thermal system. Equation 3.54 describes heat losses to the surroundings of the module. Firstly, heat is lost due to temperature difference of the surroundings and module temperature. Secondly, there is heat lost due to other effects like losses in diode, accumulation of dirt, joule heat effect in the wire.

The total energy received by the module from short wave irradiance/spectrum is the total energy absorbed by the system. Absorbed energy is affected by several parameters such as direct and diffuse irradiances intensity, optical properties that include reflection, absorption and transmission, physical structure and design of the module. Absorbed energy from short wave irradiance is determined as [287]

$$q_{Abs} = I_{Irr} \cdot \alpha_{abs} \cdot A_{Panel} \quad , \tag{3.55}$$

where front surface absorptivity is α_{abs}. Converted energy is determined by

$$q_{Converted} = q_{Thermal} + q_{Electrical} \quad , \tag{3.56}$$

where electrical energy is $q_{Electrical}$ and thermal energy is $q_{Thermal}$.

It is necessary to use current and voltage of maximum power point to determine total electrical energy

$$q_{Electrical} = P_M = I_{sc} V_{oc} (FF) = q_{Abs} \cdot \eta \cdot \tau , \tag{3.57}$$

where the front layer transmittance is τ. Various heat transfer methods are included in the PVT system such as conduction, convection and radiation. Conduction heat transfer occurred in the structural frame of the module. There is a very low temperature difference between holding structure and the module and that is why conduction between these two structures is neglected. Thermal resistivity and capacity are normally considered for measuring conductive heat transfer of each layer of the system.

Newton's cooling law is applied in the PV module and its nearby air to calculate heat transfer mechanism by convection [288]. Heat convection in a module is calculated as follows

$$q_{Conv} = -A_{Panel} \cdot h_c \left(T_{Panel} - T_{Amb}\right), \tag{3.58}$$

where heat transfer coefficient is h_c, T_{Panel} is panel temperature, T_{Amb} is ambient temperature. Radiation heat transfer in the module occurs from the irradiance long wave portion. Using Stefan-Boltzmann law, heat transfer by radiative energy exchange is determined

$$q_{Rad} = \in \cdot F \cdot \sigma \cdot \left(T_{Object}^4 - T_{Surface}^4\right), \tag{3.59}$$

where Stefan-Boltzmann constant is σ, F is view factor, surface emissivity is $\in$, panel surface temperature is $T_{Surface}$ and object radiation temperature is T_{Object}.

Thermal and electrical performance of the PVT system can be obtained using one-dimensional steady state model. Hottel-Willer's modified equation is used to model this system. Generated thermal energy due to incident irradiance is obtained as

$$E_{Irr} = I_{Irr}\alpha\tau\left[1 - \frac{\eta_e r_c}{\alpha}\right], \tag{3.60}$$

where solar absorptance is α, glass transmissivity is τ, packing factor is r_c, electrical efficiency is η_e. PVT systems overall thermal loss is provided by the following equation [245, 289]

$$U_{Th,Loss} = \tilde{U} - I_{Irr} \cdot \tau \cdot \eta_{ref} \cdot r_c \, \beta_{ref}, \tag{3.61}$$

where panel absorber-ambient heat loss coefficient is $\tilde{U}$, reference temperature electrical efficiency is η_{ref}, PV cell temperature coefficient is β_{ref}. Heat removal factor (HRF) of the panel is determined as [245], [290]

$$\tilde{F}_R = \frac{m_h C_{pw}}{A_{Panel}\tilde{U}}\left[1 - \exp\left[\frac{\tilde{U}A_{Panel}}{m_h C_{pw}}\right]\right], \tag{3.62}$$

where water mass flow rate is m_h, specific heat of water is C_{pw}. Efficiency factor of the PVT system is obtained as [245], [289]

$$F = \frac{1/U_{Th,Loss}}{W\left[\frac{1}{U_{Th,Loss}[2a + (W - 2a)\eta_{fin}]} + \frac{1}{C_b} + \frac{1}{\pi D_i h_i}\right]}, \tag{3.63}$$

where distance of the tube is W, average of the bond width is a, efficiency of fin is η_{fin}, thermal conductance of bond is C_b, force convection heat transfer coefficient is h_i, inner part diameter of the tube is D_i. The useful heat gain of the flat plate PVT system is calculated as [245], [289]

$$Q_u = A_{Panel}\tilde{F}_R\left[I_{Irr} - U_{Th,Loss}(T_{In} - T_a)\right]. \tag{3.64}$$

Total loss coefficient is calculated as [290]

$$\tilde{U} = U_{bottom} + U_{edge} + U_{top}, \tag{3.65}$$

where U_{bottom} is the bottom loss coefficient, U_{edge} is the edge loss coefficient, U_{top} is the top loss coefficient.

As, $U_{bottom} = \frac{K_{bottom}}{L_{bottom}}$ and $U_{edge} = \frac{A_{edge}}{A_{Panel}}$, equation 3.65 is rewritten as

$$\tilde{U} = \frac{K_{bottom}}{L_{bottom}} + \frac{A_{edge}}{A_{Panel}} + U_{top}, \tag{3.66}$$

where back insulation thickness is L_{bottom}, back thermal is K_{bottom}, edge area is A_{edge}. Overall input energy is obtained as [245]

$$E_{in} = A_{Panel} \times I_{Irr}, \tag{3.67}$$

Also, thermal efficiency of the PVT system is provided as [245]

$$\eta_t = \frac{Q_u}{E_{in}}, \tag{3.68}$$

where for total input energy is E_{in} and useful energy is Q_u.

In a domestic water heating PVT system, the temperature of the inlet (cold) and outlet (hot) water can be used to evaluate the performance of a counterflow heat exchanger. Heat transfer unit (NTU-ε) effectiveness is analyzed by [245]

$$\varepsilon = \begin{cases} \dfrac{1 - e^{\left[-NTU(1-C_r)\right]}}{1 - C_r e^{\left[-NTU(1-C_r)\right]}} & C_r \neq 1 \\ \dfrac{NTU}{NTU+1} & C_r = 1 \end{cases}, \tag{3.69}$$

where capacity ratio is $C_r = C_{min}/C_{max}$, C_{min} is minimum hot fluid capacity, C_{max} is maximum hot fluid capacity, heat transfer unit number is $NTU = UA_{Ex}/C_{min}$ where exchanger area is A_{Ex} and U is overall heat transfer coefficient. In this consequence, the total solar energy received by the storage tank is [245]

$$Q_{ST} = \varepsilon C_{min}\left(T_{hi} - T_{ci}\right), \tag{3.70}$$

where T_{hi} is the hot water temperature that enters to heat exchanger, T_{ci} is the cold water temperature that exit the exchanger. Heat exchanger outlet temperature is calculated as [245]

$$T_{co} = T_{ci} - \frac{Q_{ST}}{C_c}, \tag{3.71}$$

where heat exchanger's cold water capacity rate is C_c. Long term performance of a hot water based PVT system is evaluated by integrating energy balance over the course of time. Loss in the ambient air of the hot water storage is determined by

$$Q_L = A_S U_S \left(T_s - T_a\right), \tag{3.72}$$

where storage tank aera is A_S, heat loss coefficient of the water heater is U_S, storage tank starting temperature is T_s. The supplied energy to the household heater is calculated as [245]

$$Q_{LS} = m_S C_{pw} \left(T_s - T_m\right), \tag{3.73}$$

where extracted heat from storage tank to load is Q_{LS}, T_m is water composition temperature, specific heat of water is C_{pw}. As a result, storage tanks energy balance for a well-mixed water tank at the given time is

$$\left(C_{pw}\rho_w V_{Tank}\right)\frac{dT_s}{dt} = Q_{ST} - Q_{LS} - Q_L, \tag{3.74}$$

where ρ_w is density of water, V_{Tank} is the tank volume.

The analysis of mathematical modeling, simulation techniques and efficiency study provide the performance improvement acceleration of the PVT system.

Optical Modeling

Establishment of an effective and optimal PVT model requires and considers loss/gain due to its optical properties. For precise evaluation and analysis panel glass cover's optical properties are modeled. Reflection, absorption and transmission coefficients based equations are established depending on Fresnel equations and other fundamental properties of the system. The behavior of two media is glass to air and air to glass is described by using the Fresnel equations. For first boundary which is from air to glass, reflection coefficient of parallel p-polarization is [245]

$$r_{1p} = \left(\frac{n_{rel}^2 \cos\left(\theta_i\right) - \sqrt{n_{rel}^2 - \sin\left(\theta_i\right)^2}}{n_{rel}^2 \cos\left(\theta_i\right) + \sqrt{n_{rel}^2 - \sin\left(\theta_i\right)^2}}\right)^2, \tag{3.75}$$

where incidence angle is θ_i, refractive index is n_{rel}. S-polarization (perpendicular polarization) reflection coefficient is [245]

$$r_{1s} = \left(\frac{\cos\left(\theta_i\right) - \sqrt{n_{rel}^2 - \sin\left(\theta_i\right)^2}}{\cos\left(\theta_i\right) + \sqrt{n_{rel}^2 - \sin\left(\theta_i\right)^2}}\right)^2. \tag{3.76}$$

First boundary effective reflection is governed by

$$r_1 = 0.5\left(r_{1p} + r_{1s}\right). \tag{3.77}$$

Second boundary effective reflection is governed by

$$r_2 = 0.5\left(r_{2p} + r_{2s}\right). \tag{3.78}$$

Equations (3.75) to (3.78) are derived from the reflection coefficients that are involved in the performance analysis of the PVT system. Additionally, it is also significant to determine transmission coefficients of the two boundaries.

At the first boundary transmission is calculated as

$$t_1 = 1 - r_1. \tag{3.79}$$

At the second boundary transmission is calculated as

$$t_2 = 1 - r_2. \tag{3.80}$$

Light attenuation due to absorption within the glass is obtained by the following model

$$\tau_g = e^{-\alpha_g \frac{d_g}{\cos\theta_2}}, \tag{3.81}$$

where, reflection angle of the inner part of the glass is θ_2, thickness of the glass is d_g and absorption coefficient of the glass is α_g.

Recursive transmissions and reflections are used to calculate effective coefficients. For Transmission

$$T_g = \frac{t_1 \tau_g t_2}{1 - r_1 r_2 \tau_g^{\,2}}. \tag{3.82}$$

And, for reflection

$$R_g = r_1 + \frac{t_1^{\,2} \tau_g^{\,2} r_2}{1 - r_1 r_2 \tau_g^{\,2}}. \tag{3.83}$$

Absorbing model is obtained using energy conversion theory is

$$R_g = r_1 + \frac{t_1^{\,2} \tau_g^{\,2} r_2}{1 - r_1 r_2 \tau_g^{\,2}}. \tag{3.83}$$

These equations are governed based on the interaction between the solar panel's glass cover and incident light.

3.5 Parameters and Sensitivity Analysis

Design and development of a PVT system is dependent on various internal and external parameters. These parameters such as climatic, design, and electrical variation impact result in either an increase or decrease in the overall output that also changes the efficiency of the system. In short, the performance of a PVT system is mostly dependent on its various parameters. Additionally, PVT system behavior is dependent on the study of parameters and sensitivity analysis.

External/Climatic Parameters

Irradiance

The source of irradiation is the Sun, and it has variation of almost 7% in a year due to the Sun and Earth distance. During the journey from the Sun to the atmosphere of the Earth there are partial losses of solar irradiance due to dispersion and absorption. Direct radiation reaches the atmosphere without any friction or degradation while diffuse radiation is the dispersed and scattered portion of the incoming radiation. There is a portion of direct radiation that collides with the Earth's surface and reflects is known as albedo.

The variation of solar radiation varies from seasons to seasons even day to day depending on the location and position [291]. Irradiance is one of the most significant climatic parameters that participates in the photovoltaic effect. With the increasing irradiance value, the PV cell electrons get excited as there is increasing energy. This results in increased I-V curve of the system which leads to the increasing output [68]. Average daily global irradiance data of August 2023 from University of Evora weather station is depicted in figure 3.23.

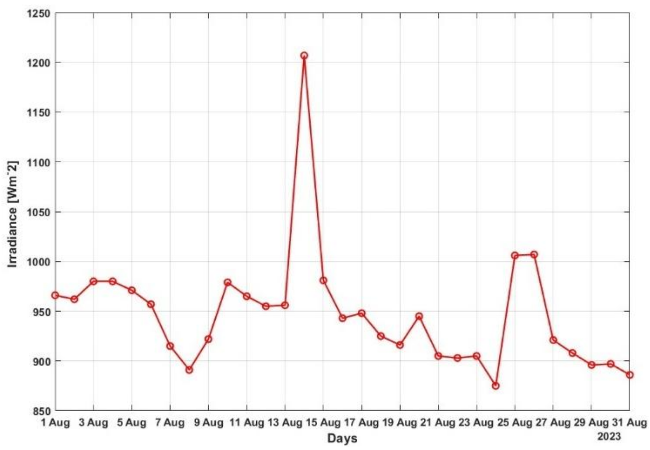

Figure 3.23: Daily average of global irradiance.

Figure 3.23 provides average daily irradiance data which describes irradiance behavior is higher in the middle of the month.

Temperature

The performance of a PVT system is completely influenced by the temperature. The induced voltage in the module is dependent on both cell and ambient temperature that results in efficiency variation. Temperature dependent diode reverse saturation current is determined as [68]

$$I_s(T)=I_s\left({T_{amb}}/{T_{nom}}\right)^3 \exp\left[\left(\left({T_{amb}}/{T_{nom}}\right)-1\right)\left({E_g}/{N.V_t}\right)\right], \tag{3.84}$$

where, T_{nom} is the nominal cell temperature.

PV performance dependency on ambient and cell temperature leads to the introduction of a PVT system. Ambient temperature, cell temperature and wind speed relation are determined as [73]

$$T_{cell}\,\alpha\,\frac{T_{amb}}{v_{wind}}, \tag{3.85}$$

where, wind speed is v_{wind} .

The equation 3.85 shows dependency of cell temperature on wind speed and ambient temperature. Additionally, cell temperature can be calculated using the formula stated in [73]

$$T_{cell}=T_{amb}+0.035\times I_{Irr}. \tag{3.86}$$

Additionally, cell temperature is also calculated as [73]

$$T_{cell}=T_{amb}+\left(\frac{0.32}{8.91+\left(2\times v_{wind}\right)}\right)\times I_{Irr}. \tag{3.87}$$

The equation 3.87 indicates that cell temperature increases with the irradiance and ambient temperature increase. Daily average dew point air temperature data for August 2023 from the University of Evora weather station is provided in the figure 3.24.

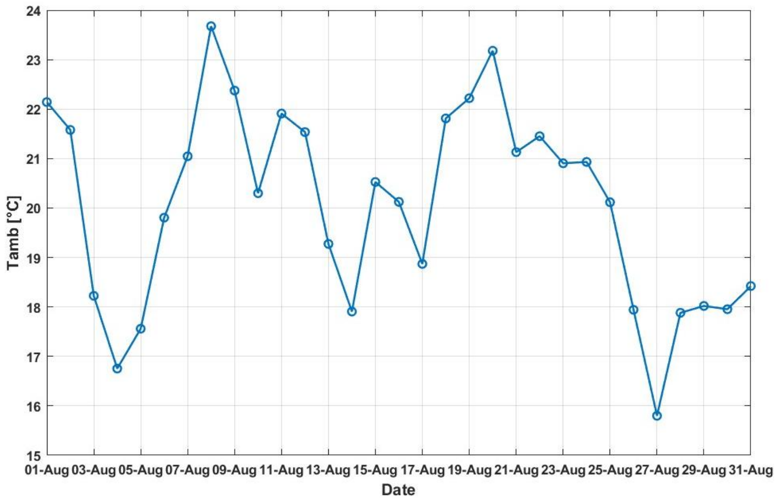

Figure 3.24: Daily average air temperature (dew point) data.

The figure 3.24 shows the variation of average air temperature for a month which clearly shows fluctuation in the value. Additionally, daily average ambient temperature data for the month of August 2023 is provided in the figure 3.25.

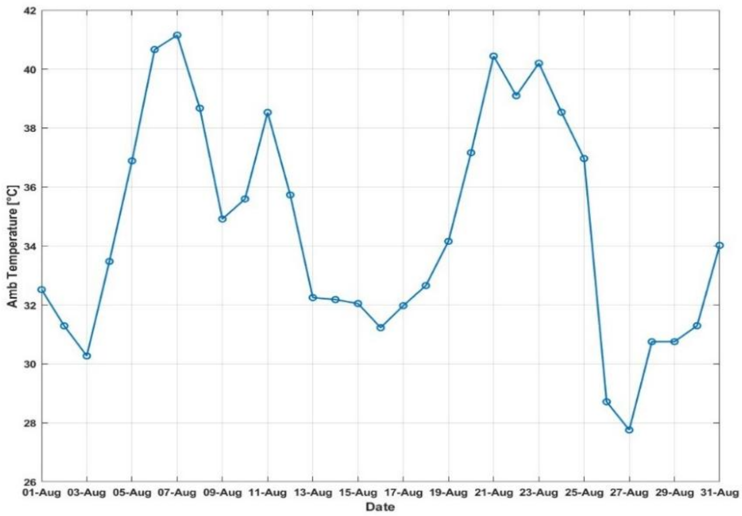

Figure 3.25: Daily average ambient temperature data.

The figure 3.25 shows that the ambient temperature in the given month reaches close to 42 ºC. Additionally, most of the days from this month shows higher ambient temperature value.

Wind

The performance of a PV module is directly influenced by the wind. Solar panels are installed normally outside and it is directly exposed to the wind. There are various impacts on PV cell due to wind speed.

It helps to reduce the temperature of the panel as wind works like a natural cooling mechanism and improves productivity and performance of the panel. Additionally, it also cleans and removes the dusts and accumulated particles from the top and bottom surface of the panel that reduces degradation of the module. As the effect of wind speed normally has a positive impact on the electrical output so it increases electrical efficiency. But the impact of wind speed in thermal efficiency is provided in [292]. The result shows that with the increasing wind speed thermal efficiency decreases. A monthly average data of the value of wind speed collected from the University of Evora weather station is provided in the figure 3.26.

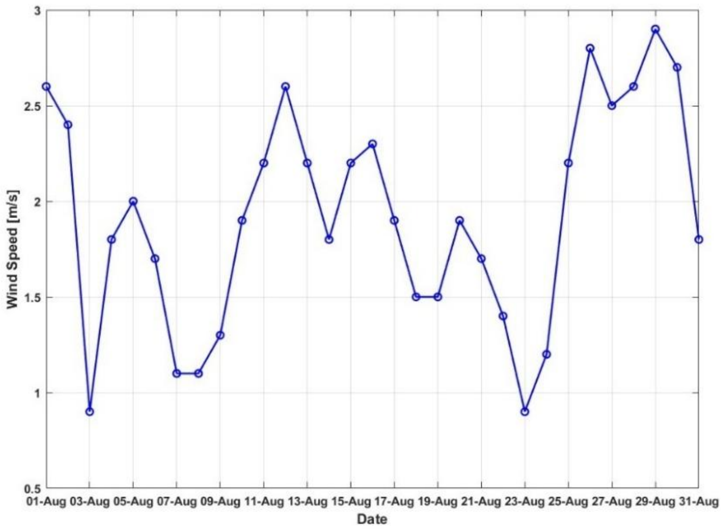

Figure 3.26: Daily average wind speed data.

Dust Accumulation

Dust refers to all solid particles from air that have a diameter smaller than 500 microns. Dust has various sources like pollen, fungus, clothing, motor vehicle pollution and other sources. Dust deposition is also dependent on various climatic and environmental factors. Accumulation of sands and dusts leads to degradation of PV panel and reduces its electrical efficiency. The accumulated dust restricts solar radiation to reach the cell and scattering phenomena also reduces electrical energy production [292].

Humidity

Accumulation of water on the PV cells degrades its polymeric constituents leading to efficiency decrease. The corrosion process in the PV structure, glass, and joints is accelerated by water accumulation also. Air moisture can easily pass through the available spaces, cracks and ventilation of the module. The relation and impact of humidity level over irradiation is discussed in [293]. The intensity of solar radiation cannot properly function in an effective manner due to the relative humidity. It is found that as the humidity increases so the electrical output of PVT system decreases [291]. Average humidity percentage data for a month of 2023 is collected from the University of Evora weather station and its illustration is shown in figure 3.27.

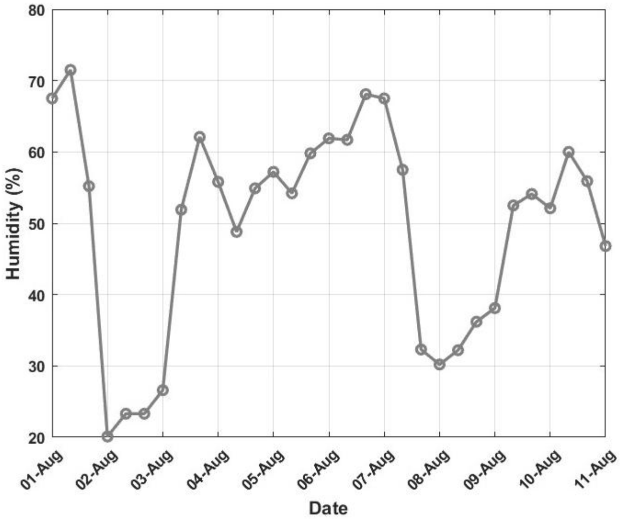

Figure 3.27: Daily average humidity data.

Internal Parameters

Photocurrent

Photocurrent is the current induced while irradiance strikes into the PV panel. It is generated in the negative terminal of the cell. Photocurrent is sensitive to the output of the PVT system, the more it induces photocurrent the more energy receives by the panel. Photocurrent is obtained as [73]

$$I_{ph} = \left(\frac{I_{Irr}}{I_{Irr,STC}} \right) \left[I_{sc} + k_l \left(T_{cell} - T_{cell,STC} \right) \right], \tag{3.88}$$

where, irradiance considered at standard test condition is $I_{Irr,STC}$, cell temperature considered at standard test condition is $T_{cell,STC}$, temperature current coefficient is k_l.

Series Resistance

Series resistance is one of the significant parameters in the electrical equivalent circuit model. The system performance and efficiency are strongly influenced by the selected value of the series resistance. Series resistance can be determined by various methods, for example a well-known one is the townsend method. It is not completely dependent on temperature and irradiance. The higher the value of the series resistance in the system the lower the output obtained in the system [68].

Shunt Resistance

It is another significant parameter to the electrical equivalent circuit model. It uses the process of turning aside or alternative movement and that is why it is called shunt resistance. Measuring high currents is the primary purpose of employing shunt resistance in the equivalent circuit. It provides better result while the value of shunt resistance is good or high enough. Shunt resistance is obtained as [68]

$$R_{sh} = \frac{\left(V + R_s I\right)}{\left(I_{ph} - I_s\left(\exp\left(\frac{qV + qR_s I}{NKT}\right) - 1\right) - I\right)}, \tag{3.89}$$

Saturation Current

Cell behavior and output of the system is influenced by the diode reverse saturation current. Alternative name of this type of current is dark saturation current. It is a parameter that provides the measurement of the recombination. A diode with higher recombination maintains higher value of saturation current.

Diode Ideality Factor

Diode ideality factor mainly refers to as the closeness with any of the ideal diode. Ideality factor has an influence on the performance and overall output of electrical energy. It is obtained in [68] that ideality factor increases in a PV cell increases overall output of the system. There is no change in the value of short circuit current due to the change of ideality factor of the diode.

3.6 MPPT Modeling Analysis

MPP of the PV system is that position in where power output is maximum though it varies continuously according to the input irradiance, system temperature and other environmental parameters. There are two main issues regarding power generation in PV systems that are based on lower irradiance and efficiency. Power conversion efficiency of PV systems is not very high which is around 17%. PV panel's efficient use is determined by the use of maximum power point tracking (MPPT). This is a control technique that always controls and captures the maximum power of the electrical energy output [42].

The operating principle of the MPPT system is based on tracking the highest point from the power-voltage (P-V) curve. It tracks and captures the top points from the P-V curve which is alternatively named as the knee point of the curve. It always functions in real time to capture the highest point as the temperature and irradiance changes very frequently.

The desired output is also achieved using DC-DC controller signal. By measuring various important parameters such as temperature, current and voltage, optimal duty cycle of the MPPT algorithms is calculated which helps to increase converter power. Rapid and accurate duty cycle updating is necessary to adapt with the changing environmental parameters. The illustration of a MPP in the P-V curve is provided in the figure 3.28.

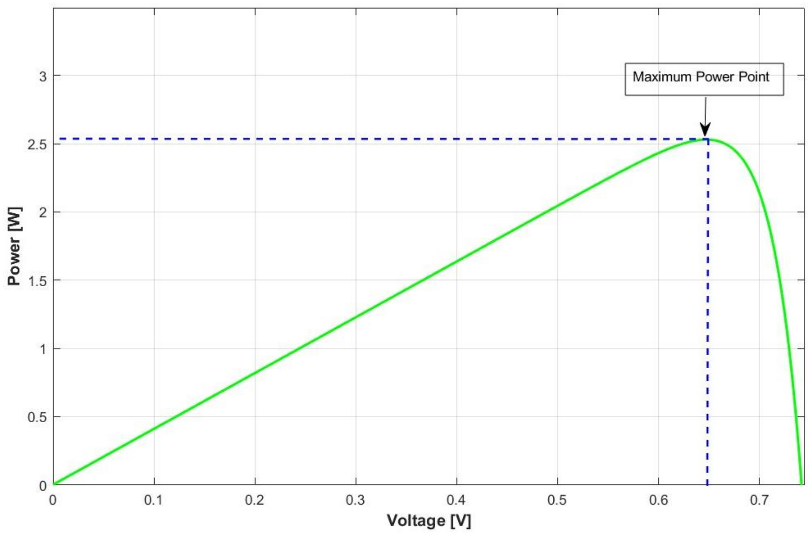

Figure 3.28: MPP curve of a PV module.

In the current research works there are many existing MPPT algorithms discussed. Determining MPPT algorithm based on the system requirements is complex due to the existing available methods. Algorithms are mainly divided and different from one another depending on their required instruments, level of complexity, convergence speed and cost effectiveness. Various types of classifications approaches are provided in different research works. The four main categories of the MPPT methods are given as follows [294]:

- Measurement based MPPT

It focuses mainly on cell parameters such as voltage, current measurement to obtain MPP. The operation principle of this type of method is based on either comparison with the previous calculated results or comparison with the previously specified MPP parameter values. Classification of measurement based MPPT is discussed in [295]. The popular measurement based MPPT methods are Perturb & Observe (P&O), Hill Climbing (HC), Short Circuit Current (SCC), Open Circuit Voltage (OCV) and Constant Voltage (CV).

- Calculation based MPPT

MPP is determined by calculating the equations related to algorithms. Calculation based MPPT examples are linear reoriented coordinates method, incremental conductance (IC), ripple correlation control method, dP/dV feedback control, state-space MPPT method and sliding mode control method.

- Intelligent based MPPT

It uses optimization algorithm based on intelligent systems. Popular methods in intelligent based MPPT systems are particle swarm optimization (PSO), artificial bee colony (ABC), cuckoo search (CS), fuzzy logic controller (FLC) and many other existing methods.

- Combination based MPPT

Combination of existing MPPT techniques is used in this type of MPPT methodology. It is also known as hybrid MPPT techniques. Some of the hybrid MPPT techniques are particle swarm optimization-perturb and observe (PSO-P&O), fuzzy particle swarm optimization (FPSO), adaptive neuro fuzzy inference system (ANFIS), hill climbing adaptive-neuro fuzzy inference system (HC-ANFIS).

Perturb & Observe MPPT

The most commonly used MPPT technique is the P&O method which is also very popular in the commercial sectors. It monitors power value changes (dP) of the system using this method. Alternatively, it can be said that it uses trial and error technique to find MPP or the nearest point of MPP. It gains popularity for its wider use to any system, and it gains appropriate accuracy with minimum cost. It counts on generated PV power based on measured current and voltage of the panel. For updating and correction, duty cycle (D) is adjusted by verifying PV module voltage (dV) sign during execution phase. Power changes output indicates what do in the next phase. Operating voltage of the system keeps continuing to be increased or decreased in the same direction while power increase is detected. The voltage is adjusted in the reverse direction with the power decrease in the PV system. An overview of the P&O is provided in the figure 3.29 [295].

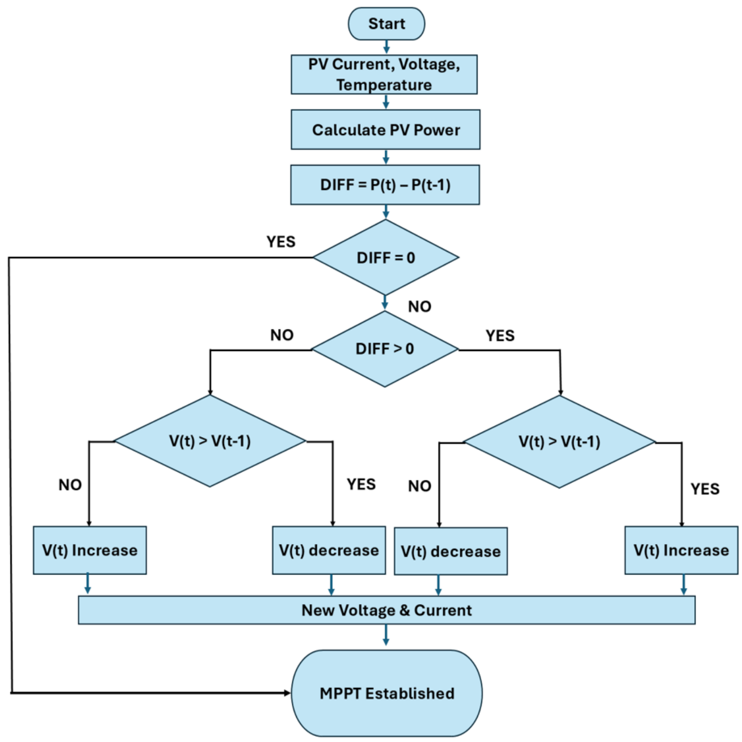

Figure 3.29: P&O algorithm flowchart.

MPP is not captured completely using this method, but a close range MPP value is obtained through nearby oscillation. The main disadvantage of this method is that it may not determine correct MPP value in full or partial shading with other atmospheric conditions rapid change situation.

Incremental Conductance (IC) Method

Fluctuation near MPP value and slow adaptation of various weather conditions are the drawbacks of using perturb and observe method. The motivation to overcome these challenges lead to the introduction of incremental conductance method. MPP tracking in this type of method is related to the PV panels' conductivity. It performs in such a way that it can track varying atmospheric conditions. Conductivity and power of a PV panel is computed by using its output current and voltage. Duty cycle is also determined by this way which is necessary to track MPP. Operation flowchart of IC method is provided in the figure 3.30.

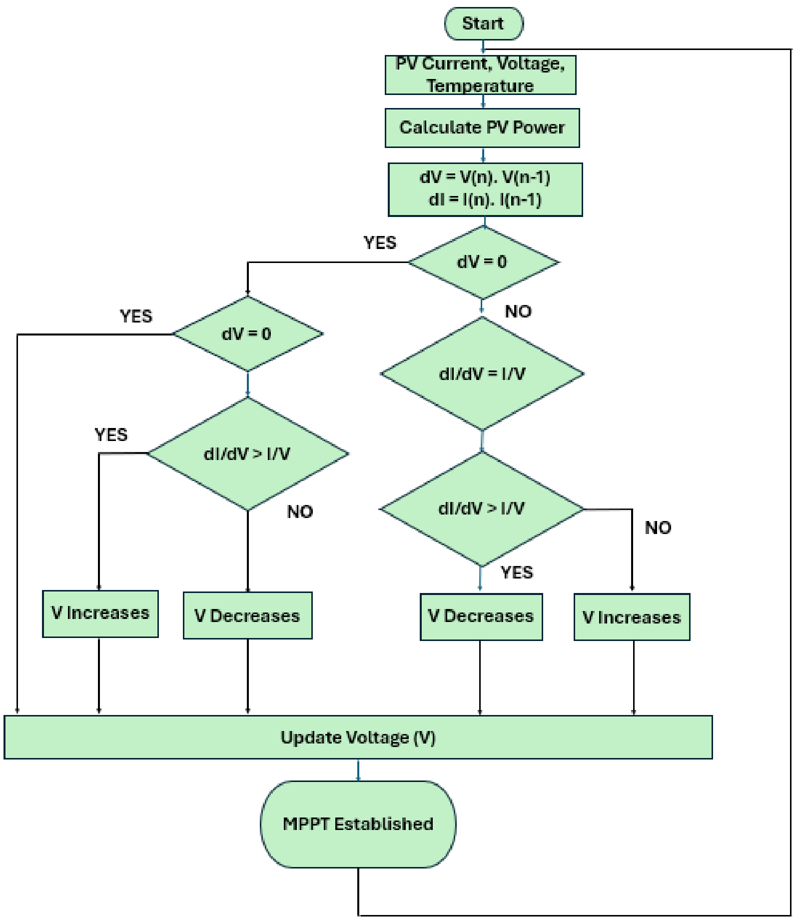

Figure 3.30: Incremental Conductance algorithm flowchart.

In incremental conductance method, for conductance $\left(I/V \right)$ and incremental conductance $d(VI)/dV$ peak power point in the P-V curve is obtained as [294]

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = V + \frac{dI}{dV}V = 0 . \tag{3.90}$$

And it appears as

$$\frac{dI}{dV} + \frac{I}{V} = 0 . \tag{3.91}$$

Mathematical formulation of IC methos is given by the following equations [294]

$$\begin{aligned} &At\ MPP, && \frac{V}{I} = -\frac{\Delta V}{\Delta I} \\ &At\ Leftside, && \frac{V}{I} < -\frac{\Delta V}{\Delta I} \\ &At\ Rightside, && \frac{V}{I} > -\frac{\Delta V}{\Delta I} \end{aligned} . \tag{3.92}$$

This method can be utilized for partial shading, dust or any other obstacle that restricts optimal power output. Existing conventional MPPT methods are not appropriate for the varying weather conditions, it may achieve MPPT closer to the exact point but not the exact point of MPP. These methods are suitable to use under uniform irradiance condition, but it is complicated to reach global MPP while there is varying and nonuniform irradiance [296].

Non-Iterative MPPT Method

Existing and conventional MPPT methods are developed based on different considerations such as speed of convergence, cost, required devices, range, speed and other relevant factors. In short, the existing solar PV systems MPPT methods are dependent on continuous iterations, increments and other optimization methods. Iterative method has higher convergence speed that helps to determine MPP voltage very quickly and provide better performance [296]. Non-iterative [296], [297] MPPT is the appropriate solution to resolve the complexity of conventional iterative techniques.

MPP is obtained in the non-iterative method using simple analytical approach that helps to reduce computational complexity. Moreover, the proposed algorithm offers extensive benefits in the case of digital platform implementation. A flowchart based on the operations of non-iterative method is provided in figure 3.31. It shows the steps of non-iterative MPPT algorithms. In the starting of the procedure, the power is calculated by the given voltage and current of the system.

The first step of the algorithm describes the four voltage samples V_1, V_2, V_3, V_4 including corresponding current samples I_1, I_2, I_3, I_4. Based on the provided samples related powers P_1, P_2, P_3, P_4 are calculated. Coefficients are obtained by the established equations are [296]

$$P_k = a_3 V_k^3 + a_2 V_k^2 + a_1 V_k + a_0 , \tag{3.93}$$

where a_0, a_1, a_2, a_3 are the coefficients.

Roots are obtained by the following equation

$$3a_3 V^2 + 2a_2 V + a_1 = 0 , \tag{3.94}$$

At the end, the roots V_{01} and V_{02} are determined using the equation 3.94. In the condition it shows that if the value $a_3 V_{01}$ is negative it chooses MPP as V_{01} and if the value is positive it chooses MPP as V_{02}. By this way, the MPP values is tracked without dedicating any iterative and complex method.

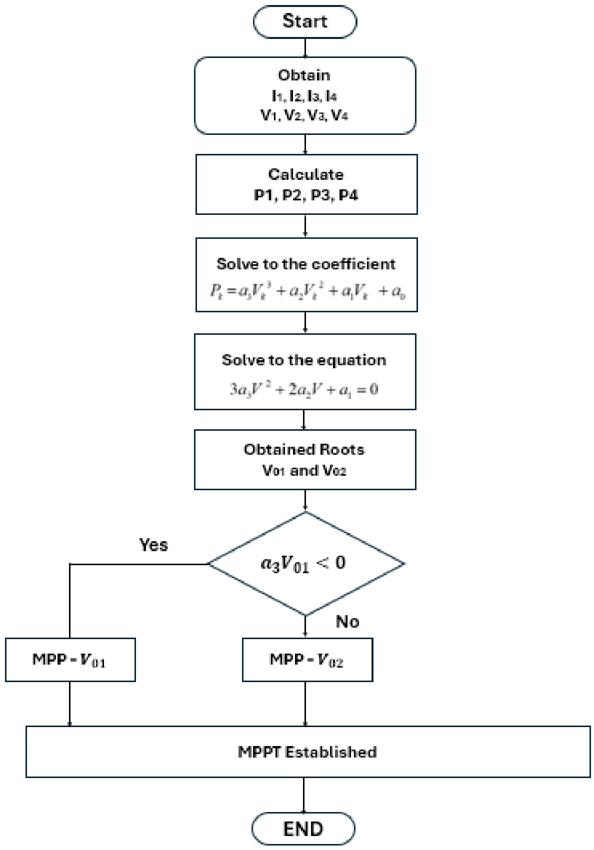

Figure 3.31: Non-iterative MPPT algorithm flowchart [296].

For power curve fitting purpose, third order polynomial is considered in this case. Optimal power point is achieved using these polynomials.

For better understanding of the MPPT methods, a comparison based on several criteria is provided by table 3.1.

Table 3.1: MPPT methods comparative analysis.

MPPT Methods	Analog/ Digital	Complexity	Convergence Speed	PV Array Dependency	Parameters
Incremental Conductance	Digital	Medium	Varies	No	Voltage, Current
Perturbation and Observation	Both	Low	Varies	No	Voltage, Current
Fuzzy Logic Control	Digital	High	Fast	Yes	Varies
Non-iterative Method	Both	Low	Instantaneous	No	Voltage, Current
Neural Network	Digital	High	Fast	Yes	Varies
Ripple Correlation Control	Analog	Low	Fast	No	Voltage, Current
Sliding Mode Control	Digital	Medium	Fast	No	Voltage, Current
FOCV	Both	Low	Medium	Yes	Voltage, Current

3.7 PVT System Monitoring & Fault Detection

Monitoring of PVT System

It is challenging to forecast and monitor a nonlinear system in real time [298]. Hybrid PVT is a nonlinear system that is mostly dependent on the ambient variables mainly irradiation, temperature and wind. The hybrid PVT system demonstrates huge potential to increase the performance of the photovoltaic module and provide thermal and electrical energy for household system or other use. The performance of a PVT system is enhanced by developing a low-cost embedded system that monitors it in real-time and extracts optimum energy by tracking maximum power point of the given system. Design of a low-cost embedded system for real-time monitoring is provided in the figure 3.32.

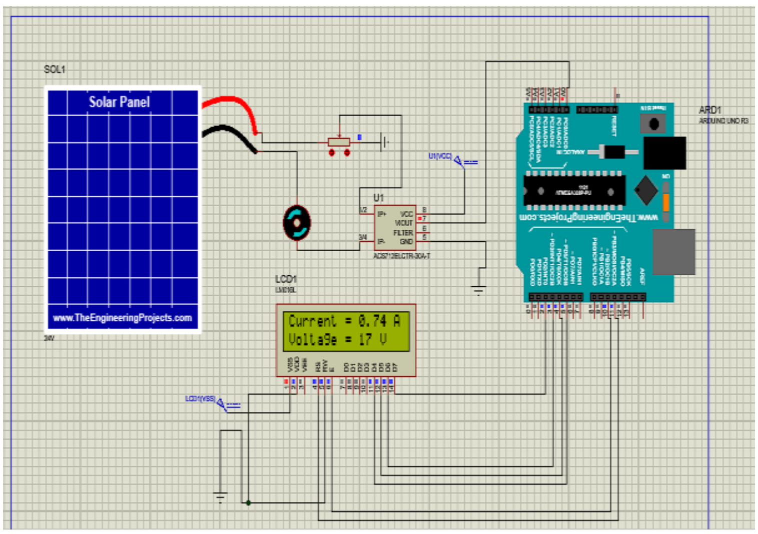

Figure 3.32: Low-cost embedded system.

Display unit mainly provides the output of current and voltage of the system from its electronic output section. A temperature sensor is also included in the system to sense the temperature and control the overall system to cool down the panel and on the other hand receive the thermal energy to utilize them for domestic or industrial use based on the system's placement. It is already proved in many works that reducing the temperature of a PV panel, always increases the performance of overall power generation.

The monitoring system is directly connected with a cloud server where all the information is gathered and analyzed. The information from the system is sent to the central cloud server to receive instant update about the system. All the data is going through Machine learning method to identify faults in the system and also train the system in real time. It has also an alert system that triggers during emergency situations. Machine learning system assists to classify the faults and suggests specific problematic situation [299-300]. This method assists in improving the performance of solar panel and includes a real time monitoring system. It is going to support the system about forecasting power generation from hybrid PVT. This will help to gain thermal power for domestic and industrial use which will reduce the cost of additional thermal power generation. Additionally, this monitoring system will help to contribute to the smart grid development that will help in the prediction of the power generation in advance and fault detection in real time.

MPPT techniques based on Internet of Thing (IoT) and fault detection are also possible to obtain using an experimental setup that will provide robust output of the PVT system.

Faults in PVT System

PVT system is one the main source of continuous electrical and thermal energy that uses sunlight, but energy generation can be degraded due to the faults in the internal and outer surface. For optimal output it is necessary to find out the faults and remedies to overcome this issue. Different types of faults may be encountered in the system and its negative impact will result in lower output. Most common types of PVT module faults are provided in the figure 3.33 [301].

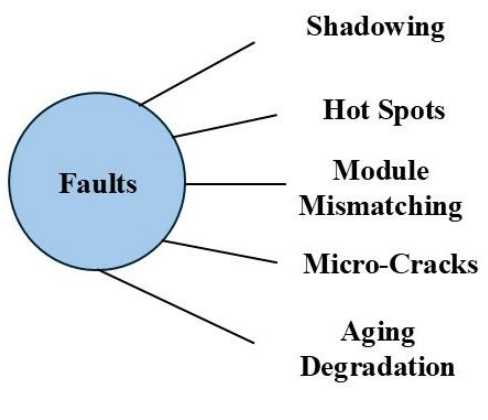

Figure 3.33: Common types of PVT module faults.

Shadowing in a PV module decreases efficiency and it occurs due to obstacles like trees, buildings, shade panels. Hotspots in the module may appear due to shading, aging and dusts issues. Hotspot occurs due to increased resistance leading to overheating in certain parts of a module. Module mismatching can be the reason for efficiency reduction and also the appearance of many hot spots. It causes due to mismatch in the modules during manufacturing and uneven aging. Mechanical stress may lead to micro-cracks in the module which also reduces efficiency. With the passing of time and use, PV module degrades gradually and power output decreases [301].

There are several reasons behind the PV modules' faults. Summary of the most common causes are provided in the figure 3.34 [301].

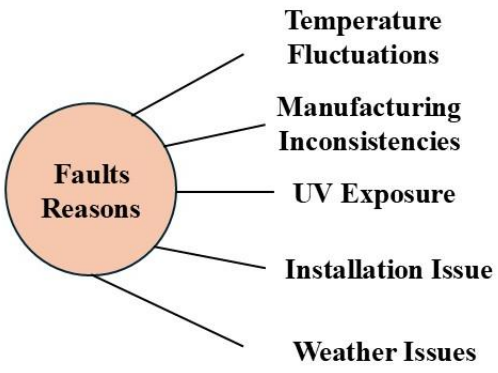

Figure 3.34: Common reasons for PVT module faults.

The most common reasons for photovoltaic module faults are temperature fluctuations, manufacturing inconsistencies, UV exposure, installation issues and weather conditions. The modules could be damaged due to temperature fluctuations leading to shrinking or expansion of materials. Module quality is compromised due to manufacturing inconsistencies which reduce overall performance. PV modules protection layers and upper portion are affected by the continuous UV exposure that reduces PV lifespan and efficiency. Faults also may occur due to defects during installation phase [301]. Weather conditions such as snow, continuous rain, earthquake and hailstorms also could be responsible for PV faults.

Minimizing fault requires efficient and effective fault detection. There are very popular strategies to mitigate PV faults. An overview of fault detection techniques is given in the figure 3.35 [301]. Effective sunlight absorption requires PV panels regular cleaning that helps to eliminate debris and remove dusts. Faults, problems, and aging issues are detected by periodic inspections of the module that enhances its lifespan as well. Faults due to shadowing of building and trees can be minimized by optimal panel positioning.

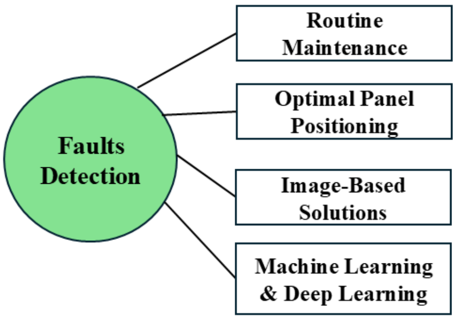

Figure 3.35: Fault detection techniques.

The panel orientation should be in such a way that it can receive maximum irradiation from the Sun. Fault detection is also achieved using the image processing based approaches in combination with deep learning techniques. Hot spots and micro-cracks are precisely located using infrared, thermographic images. Potential faults in the PV modules are effectively analyzed by using deep learning and machine learning also. Spot inconsistencies and data analysis of PV outputs can be studied using Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) [301].

Chapter 4: Results Analysis

4.1 Parameter Effect and Sensitivity Analysis

Efficiency of a PVT system can be increased or decreased with its parameters variation. Relevant external and internal parameters such as installation based, operation and maintenance parameters, environmental parameters are responsible for this effect. PVT systems performance is significantly dependent on these types of parameters value. These are categorized as highly sensitive, medium sensitive and low sensitive parameters based on their ability of impacting on the performance. A numerical simulation technic can be used to determine the sensitivity and parameter variation impact of the hybrid PVT system [302].

In a residential building based PVT system sensitivity [60, 61] study and optimization analysis derived and developed in [303]. Related parameters sensitivity study of a linear Fresnel reflector based novel PVT is presented in [304]. The increasing impact of ambient temperature and fluid velocity on thermal efficiency and improvement is discussed there. PVT panels behavior is analyzed and studied by parameters variation and sensitivity analysis. It also shows the variation in MPP of the system due to parameters variation.

Energy efficient solar system can be established by using an ideal classification, sensitivity analysis and parametric evaluation. Effective performance assessment is achieved by fundamental parametric analysis and optimization methods. Various research works focused on parametric, sensitivity and optimization study to improve and achieve higher performance [305]. A parametric research and analysis of hybrid PVT system to study the ambient parameters, geometrical properties, meteorological parameters are described in [21]. Ambient parameters are commonly referred to temperature, wind speed, and irradiance. Design parameters of a PVT module such as water inlet temperature, mass flow rate and other geometric variables are also significant for the efficiency analysis.

Impact of Irradiance

The sun emits electromagnetic energy or radiant energy in the form of sunlight or irradiance. It is actually the combined form of infrared, visible and ultraviolet spectrum effect. In a photovoltaic system, photocurrent is influenced by both irradiance and temperature. Photocurrent equation is obtained as [245]

$$I_{ph} = \left[I_s + k_i\left(T - 298\right)\right]\frac{I_{Irr}}{1000} \tag{4.1}$$

The equation describes that photocurrent value is proportional to the irradiance. The impact of varying irradiance in the PVT system output is provided in the figure 4.1. Open circuit voltage, short circuit current of the system changes as the irradiance value changes. The short circuit current value and open circuit voltage increases with increasing irradiance value. Irradiances values considered for simulation are 500 Wm^{-2}, 800 Wm^{-2}, 1100 Wm^{-2}, and 1300 Wm^{-2}. The result shows that current-voltage (I-V) curve has slight increasing tendency as irradiance value increases from 500 Wm^{-2} to 800 Wm^{-2}. Similarly, while irradiance changes from 800 Wm^{-2} to 1100 Wm^{-2} then it increases the value from the previous position. As same, the I-V curve increases while irradiance varies from 1100 Wm^{-2} to 1300 Wm^{-2}. So, increasing irradiance has an increasing current-voltage output value.

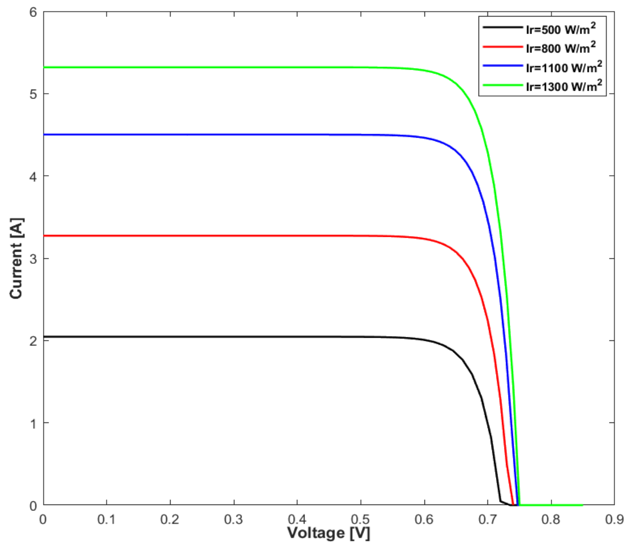

Figure 4.1: I-V curve for varying irradiance [245].

Similarly, power-voltage (P-V) curve for varying irradiance of a PVT module is provided in figure 4.2. It indicates that increasing irradiance value has increased the P-V curve which results in increasing overall output. As the P-V curve has an increasing tendency due to irradiance increases so the MPP value also increases. Considered irradiance values for P-V curve performance evaluation are 500 Wm^{-2}, 800 Wm^{-2}, 1100 Wm^{-2}, and 1300 Wm^{-2}.

As with the increasing irradiance P-V curve increases so MPP of the PVT system also increases. Change of MPP values with the irradiance variation is provided in table 4.1. The value of MPP of the PV cell is 1.22 W at irradiance value of 500 Wm^{-2}, at 800 Wm^{-2} MPP is 2.00 W. It describes that with the increasing irradiance value there is increasing MPP value. MPP decreases if irradiance in the PV module decreases and results in the overall output decrease. The performance of the PVT system is directly dependent on the irradiance value.

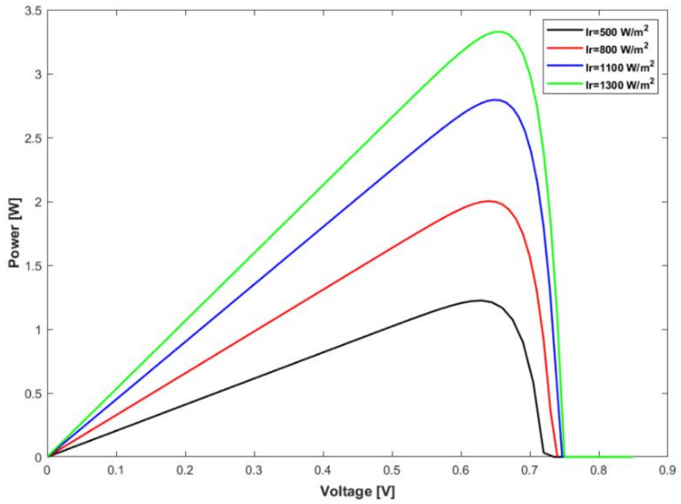

Figure 4.2: P-V curve for varying irradiance [245].

MPP value with regards to the irradiance reference is shown and compared in table 4.1.

Table 4.1. MPP values regarding variable irradiances.

Irradiance (Wm^{-2})	MPP (W)	MPP Difference (W)
500	1.22	0.00
800	2.00	0.78
1100	2.80	0.80
1300	3.33	0.53

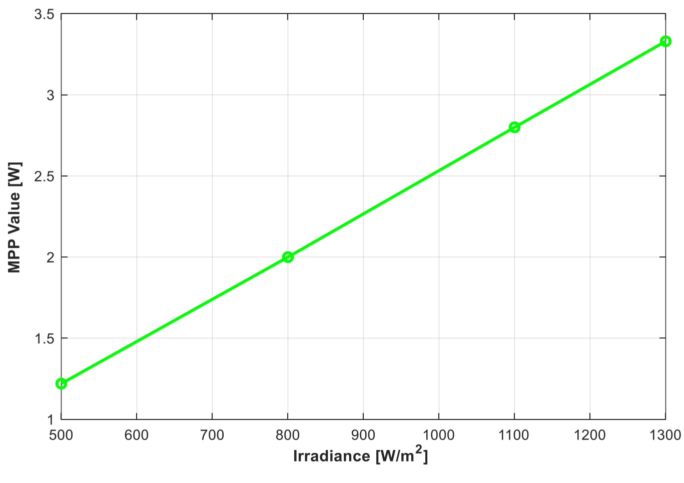

Figure 4.3: MPP for varying irradiances [245].

Three dimensional view and comparison of MPP value, MPP value differences with irradiances is provided in the figure 4.4.

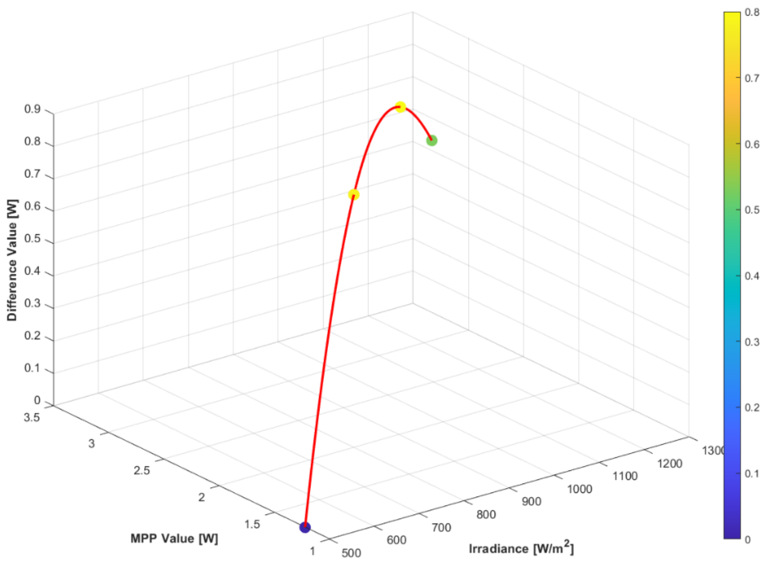

Figure 4.4: MPP for varying irradiances (3D view) [245].

Impact of Temperature

For Performance development, efficiency evaluation, designing of a PVT system, both inside and outside temperature plays a crucial role [21]. Temperature has continuous and effective influence on the output of PVT system performance, and it has the most sensitiveness compared to other parameters. PV Cell temperature and ambient temperature are the most influential factor of hybrid PVT system for optimal energy output. Ambient temperature and panel temperature relationship are described by the figure 4.5.

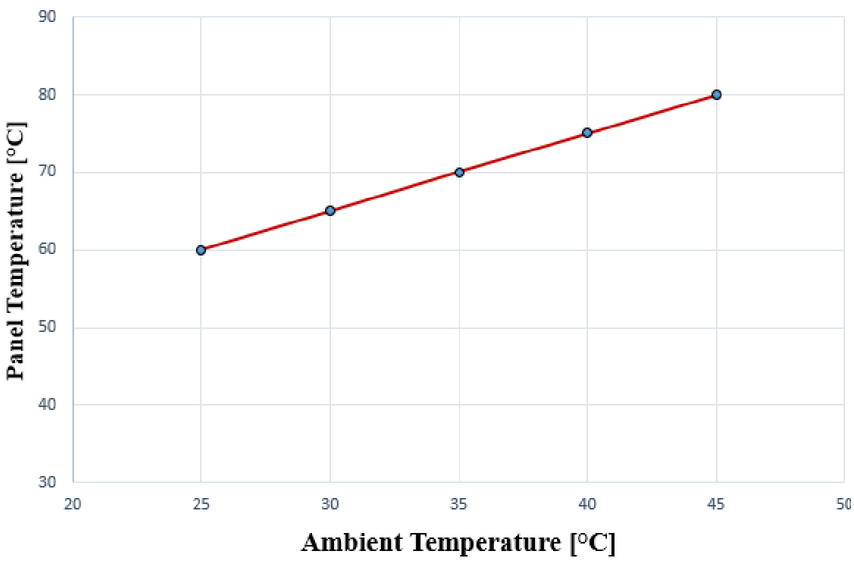

Figure 4.5: Panel temperature and ambient temperature correlation [245].

After a detailed data analysis and illustration provided in figure 4.5, it is evident that there is a direct relationship between the panel temperature and the ambient temperature.

Impact of Ambient Temperature

Ambient temperature has a direct impact on both the PVT module and cell temperature. Impact on the PVT system due to variation of ambient temperature value and obtained I-V curve is illustrated in the figure 4.6. In this analysis, current values of the I-V curve were multiplied by a factor of 10 for better visualization and understanding the system behavior.

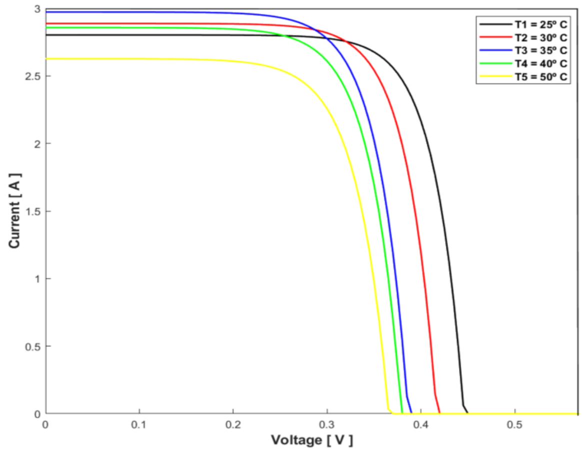

Figure 4.6: I-V characteristics for different ambient temperature [245].

From the figure 4.6 it is obtained that the I-V curve is decreasing with the increasing ambient temperature. It signifies that ambient temperature increase shows negative impact on the output of the system. It leads to a decrease in the optimum maximum power also. A three dimensional figure provides a clear concept regarding ambient temperature variation effect on the PVT system is given in the figure 4.7.

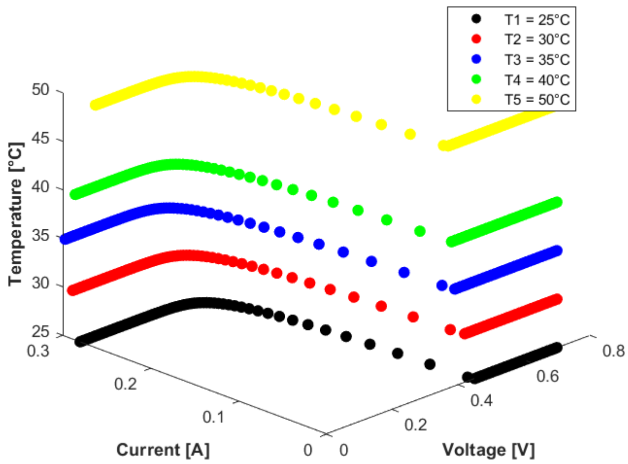

Figure 4.7: 3D representation of the I-V for varying ambient temperatures [245].

The ambient temperature varies from 25 ºC to 50 ºC and every increasing step it provides decreasing steps in the I-V curve. Relevant P-V curve for varying ambient temperature is shown in figure 4.7.

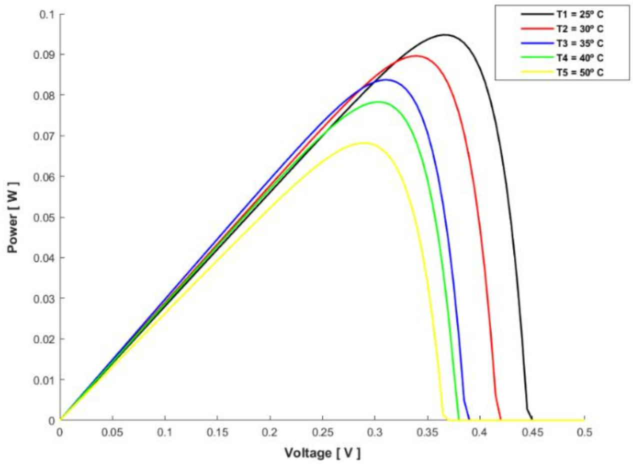

Figure 4.8: Power-voltage (P-V) characteristics for varying ambient temperature [245].

The power-voltage curve of a PV module varies and shows negative output due to variation of ambient temperature. The curve changes to inward position while the range of ambient temperature increases, and it results in a decrease of overall output. Impact of ambient temperature value variation in three-dimensional view is provided in the figure 4.9.

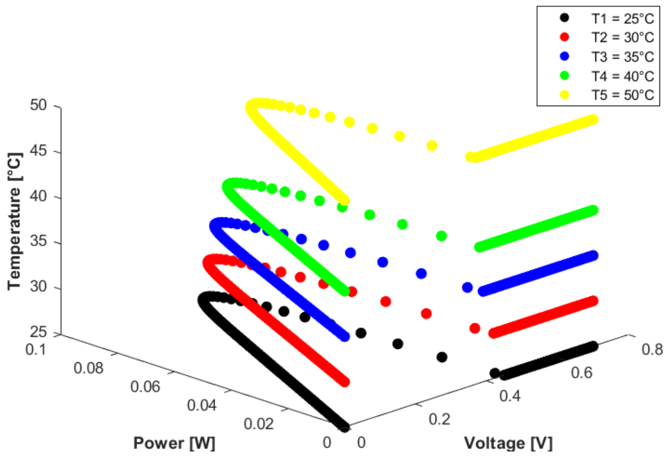

Figure 4.9: 3D representation of the P-V for varying ambient temperature [245].

From the figure 4.9 it can be overserved that maximum power point position changes and it reduces while the ambient temperature increases. And MPP increases if the value of ambient temperature decreases. The analysis concludes that increasing ambient temperature decreases MPP value and decreasing ambient temperature increases MPP value.

The point which has the maximum available power of a PVT module is regarded as the maximum power point (MPP). For developing an improved energy efficient PVT system, tracking MPP is one of the most significant tasks to accomplish. With the fluctuations of internal and ambient factors there is an impact on the output of the PVT system. It has already established the impact of external factor such as temperature. The behavior and impact of ambient temperature in regard to MPP is provided in the figure 4.10.

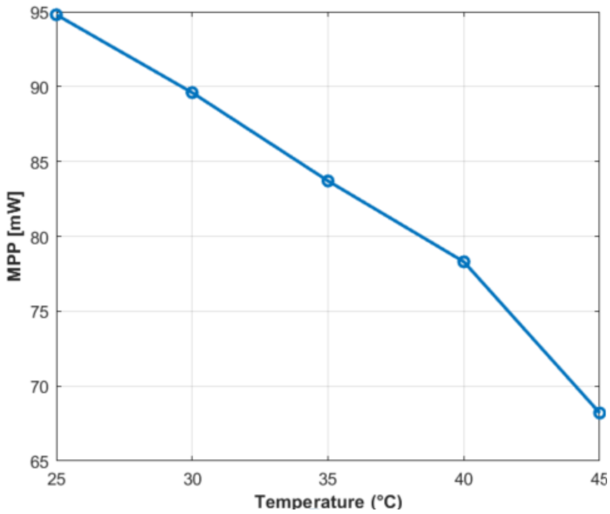

Figure 4.10: Ambient temperature influence on MPP values [245].

The figure 4.10 demonstrates that as the ambient temperature increases, MPP value decreases radically. MPP value, and MPP difference for changing ambient temperature is provided in table 4.2.

Table 4.2. MPP values regarding variable temperature.

Temperature (°C)	MPP (mW)	MPP Difference (mW)
25	94.80	0.00
30	89.60	5.20
35	83.70	5.90
40	78.30	8.40
45	68.20	10.10

Table 4.2 shows that increasing ambient temperature during PVT operation negatively affects the output as it reduces the electrical energy output of the system. This comparison of MPP and MPP difference in regard to ambient temperature variation is clearly provided by a three dimensional figure in 4.11.

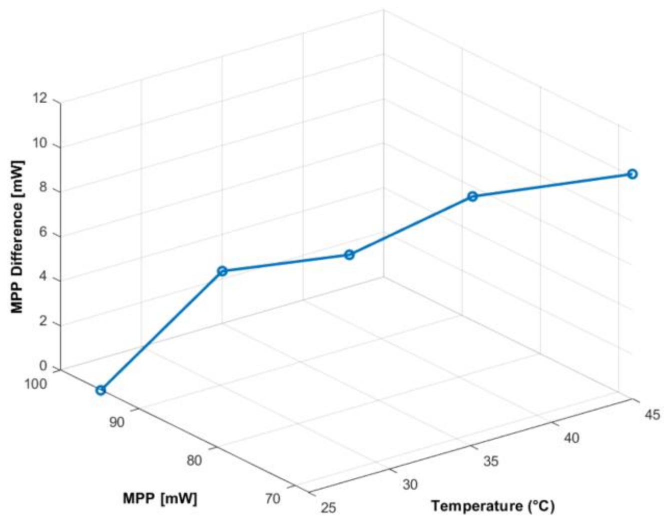

Figure 4.11: MPP variation due to ambient temperatures (3D view) [245].

Figure 4.11 describes that the value of MPP decreases while the ambient temperature rises from 35 ºC to 40 ºC and it keeps continuing the same while the ambient temperature continues. Ambient temperature variation has an impact on the efficiency of the PVT system is provided in the figure 4.12.

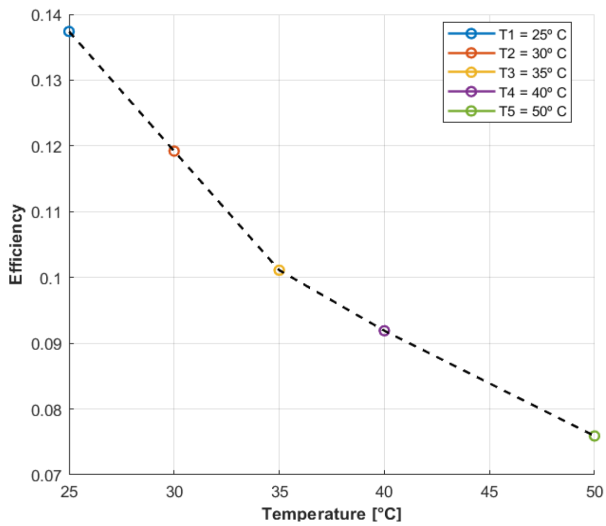

Figure 4.12: Efficiency and ambient temperature relation [245].

Figure 4.12 describes that increasing ambient temperature reduces electrical efficiency of the PVT system. It has similar pattern with the MPP value variation while with the increasing ambient temperature. Additionally, impact on efficiency due to ambient temperature variation is displayed by a three dimensional format in the figure 4.13.

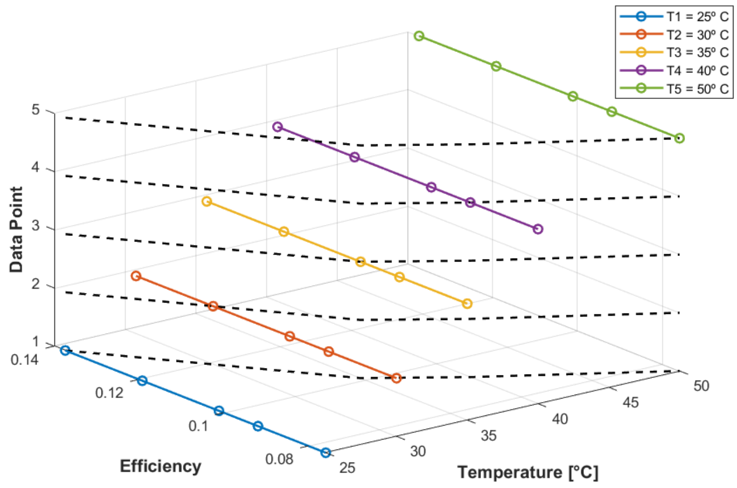

Figure 4.13: 3D view of ambient temperature and efficiency relation [245].

Ambient temperature and efficiency relationship in a three-dimensional view is illustrated in this figure 4.13. It acknowledges that with the rising ambient temperature electrical efficiency drops. It also indicates that as the ambient temperature rises from 25 ºC to 50 ºC, the gap between the efficiencies at these temperature level becomes more evident.

Impact of Panel Temperature

The fluctuation in the level of panel temperature impacts the solar module's electrical output. Temperature plays a crucial role in the module voltage, with an increase in temperature leading to a decrease in the voltage. Panel temperature variation impact in the I-V curve is provided in figure 4.14.

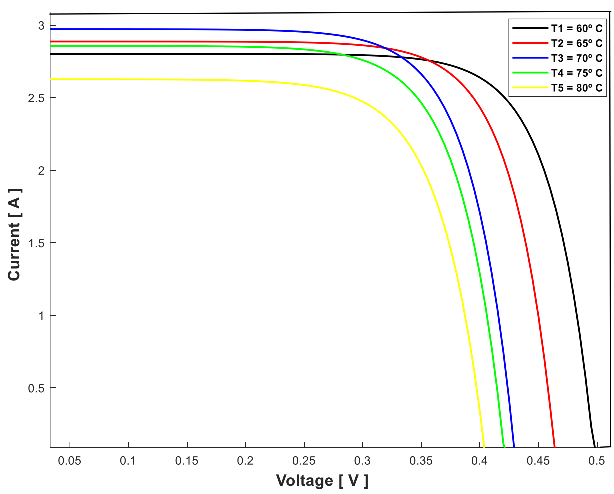

Figure 4.14: I-V curve for different panel temperature [245].

The selected values for panel temperature to analyze the variation effect are 60 ºC, 65 ºC, 70 ºC, 75 ºC and 80 ºC. As seen in the figure 4.13 an increase in panel temperature results in a decreasing trend in the current-voltage (I-V) curve. This incident leads to the decrease in the electrical output of the system. This situation is better explained by the figure 4.15.

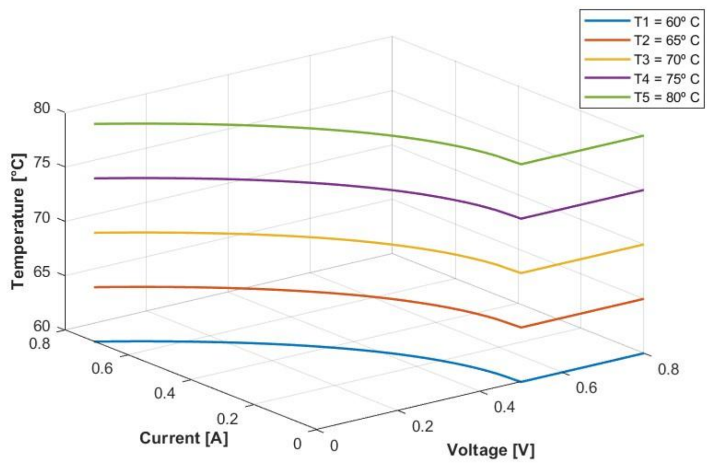

Figure 4.15: I-V curve for different panel temperature (3D view) [245].

Figure 4.15 provides the information regarding the panel temperature variation impact on the panel. It highlights that panel temperature variation has a negative effect on the PVT panel.

The P-V curve for varying temperature of the panel is provided with the figure 4.16. The obtained analysis from the result describes that P-V curve has decreasing tendency with the increasing panel temperature range. With this change, the electrical output of the system also reduces.

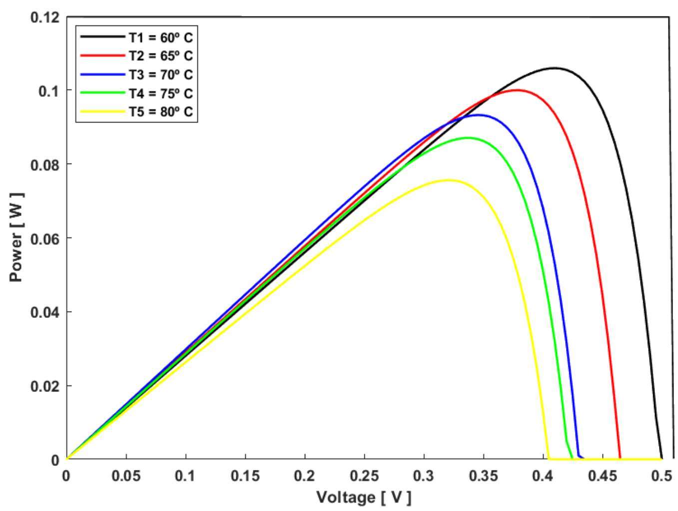

Figure 4.16: P-V curve for different panel temperature [245].

A three-dimensional view of the P-V curve based on panel temperature variation is provided in the figure 4.17.

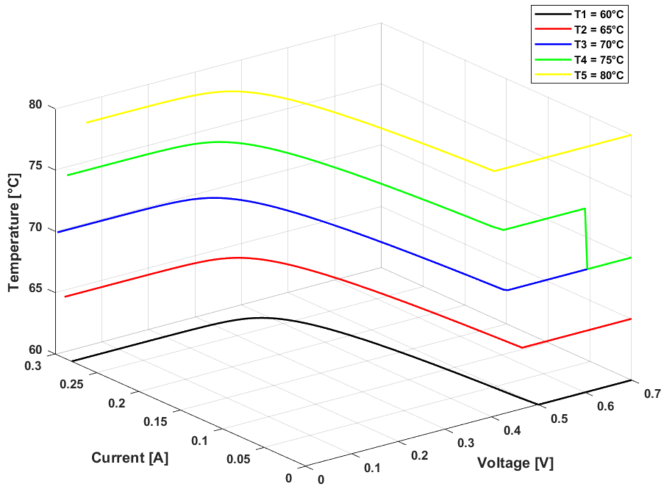

Figure 4.17: P-V curve for different panel temperatures (3D view) [245].

This figure 4.17 also provides the information that maximum power decreases with the increasing panel temperature. The MPP values and relevant difference for panel temperature variation are provided in table 4.3.

Table 4.3: MPP values regarding variable panel temperature [245].

Temperature (°C)	(Kelvin)	MPP (mW)	MPP Difference (mW)
60 °C	338.15 K	106	0
65 °C	343.15 K	100	6
70 °C	343.15 K	93	7
75 °C	348.15 K	87	6
80 °C	353.15 K	76	11

A graphical representation of the relevant MPP values with respect to the panel temperature is provided in the figure 4.18.

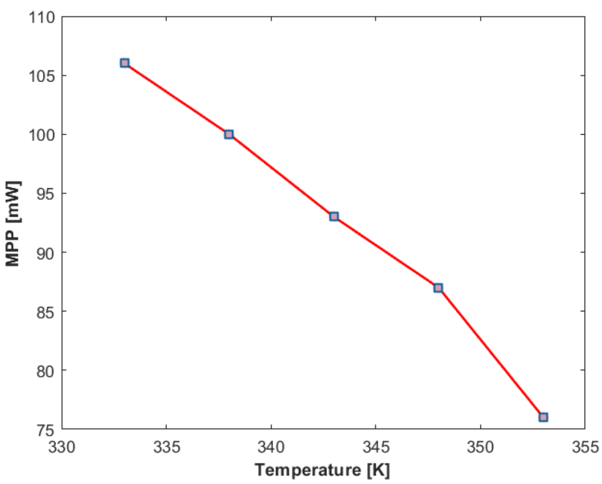

Figure 4.18: MPP curve for different panel temperature [245].

Figure 4.18 describes that MPP value is at peak while the panel temperature is the lowest whereas MPP value is the lowest while temperature is at the maximum. It confirms that increasing panel temperature has negative impact on the output of the panel and shows positive impact if this panel temperature is reduced by cooling or any other heat extraction method. Three dimensional representations of the MPP value dependency on the panel temperature is provided in the figure 4.19. The figure 4.19 clearly illustrates the difference in MPP values caused by panel temperature. The increase in panel temperature consistently reduces the overall electrical output of the PVT system.

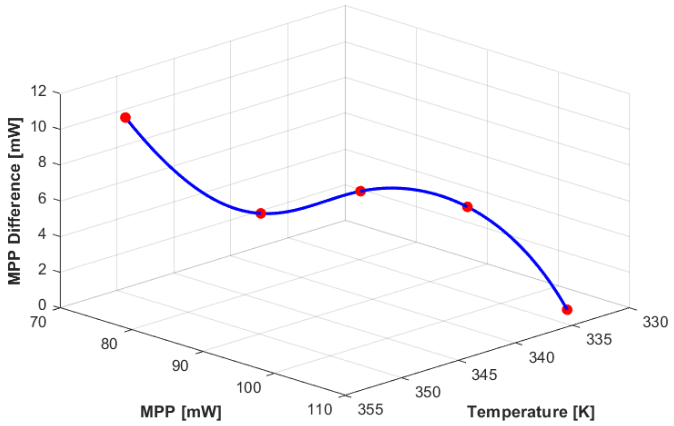

Figure 4.19: MPP curve for different panel temperature (3D view) [245].

Impact of Wind Speed

Energy conversion in the PV and PVT systems suffer with low conversion efficiency. Various factors have an effect on the output of the PVT system. Wind speed [306] is another environmental parameter that has an impact on the performance of the PVT system. The impact of varying wind speeds is discussed in this part. The figure 4.20 shows the behavior of I-V curve due to the variation of wind speeds.

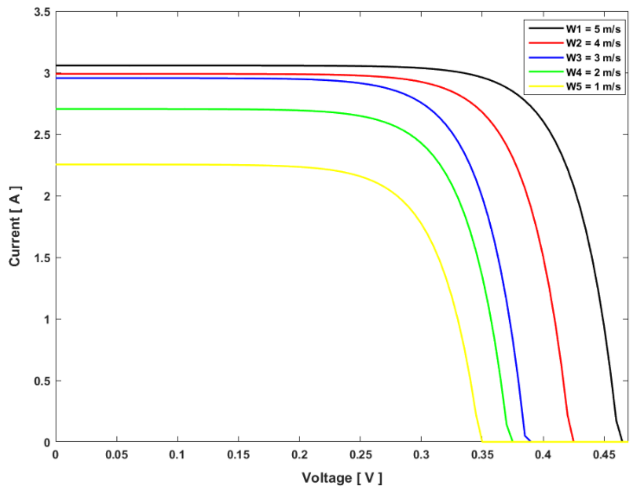

Figure 4.20: I-V curve for varying wind speeds [245].

The values of wind speed considered for simulation purpose in the figure 4.20 are 1 ms^{-1}, 2 ms^{-1}, 3 ms^{-1}, 4 ms^{-1}, and 5 ms^{-1}. The plot indicates that the system's electrical power increases by increasing open circuit voltage and short circuit current as wind speeds increases. Impact on P-V curve with the increasing wind speeds are provided in the figure 4.21.

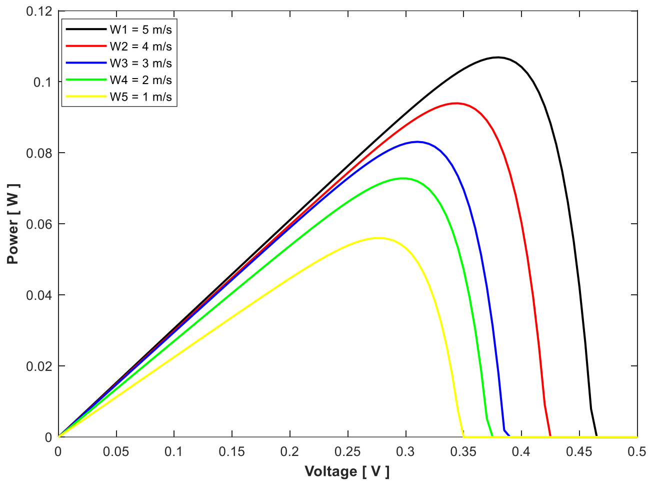

Figure 4.21: P-V curve for varying wind speed [245].

Wind speeds in a PV module have a direct influence on the P-V curve. The P-V curve rises with an increase in the wind speed and decreases with reducing wind speed. It explains that if there is less wind speed panel temperature rises, and it gets cooled with the higher wind speed value. MPP values in regard to wind speed are provided in the figure 4.22.

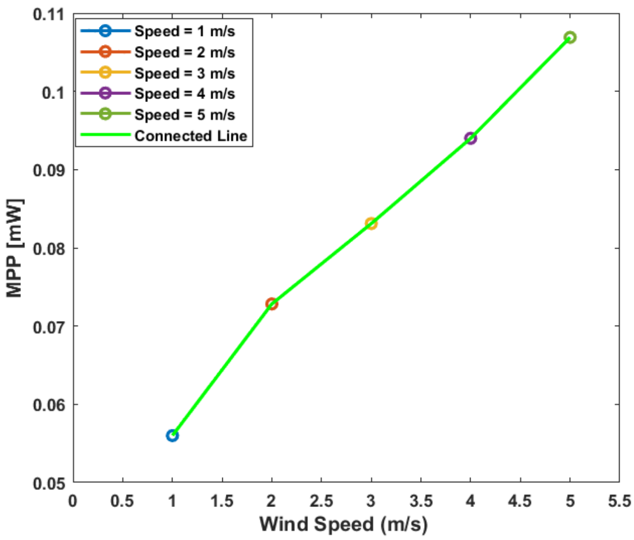

Figure 4.22: MPP variation due to varying wind speed [245].

The figure 4.22 describes the comparison of MPP values influenced by wind speed variations. This figure demonstrates that an increase in wind speed consistently results in a positive MPP gain. Three dimensional representations of this change with wind speed are provided in the figure 4.23.

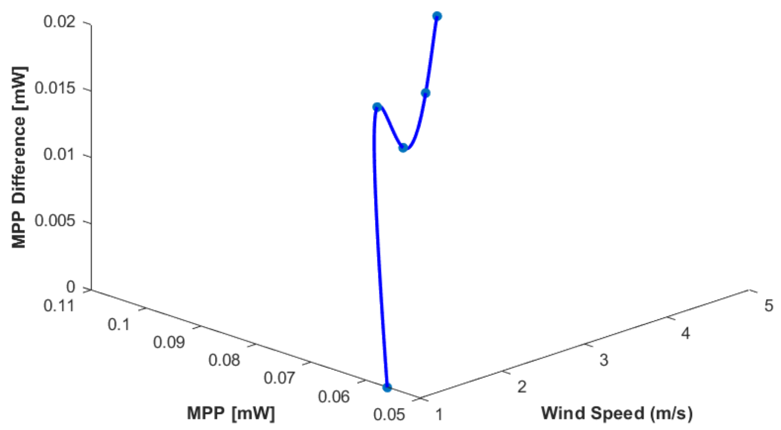

Figure 4.23: MPP variation due to varying wind speeds (3D view) [245].

Relevant MPP value with regards to the wind speed is provided in table 4.4.

Table 4.4. MPP values regarding variable wind speed [245].

Wind Speed (ms^{-1})	MPP (mW)	MPP Difference (mW)
1	0.05	0.00
2	0.07	0.02
3	0.08	0.01
4	0.09	0.01
5	0.10	0.01

MPP values variation for each wind speed value changes and difference of MPP values are provided in table 4.4. After analyzing the values, it reflects that wind speed increase results in positive impact on the maximum power value that also improve the efficiency of the system.

Overall electrical output is positively impacted by the wind speed increase. Additionally, in general the overall analysis also confirms that wind speed increase is positive for output of the PVT system and decrease has negative influence on the PVT panel.

Various other external factors also influence the performance and output of the PVT module. The key parameters taken into consideration for the efficiency analysis in many research works are humidity, wind speed and dust effects. The impact of humidity on PV panels has been studied and its impact are also analyzed in [307]. This study analyzes the panel's performance under different humid conditions. The findings of this study indicate that changes in humidity levels directly affect overall output of the system. The study also reveals that as humidity levels increase the maximum power decreases.

Additionally, environmental parameters such as ambient temperature, dust, wind speed and humidity greatly influence both the irradiance and temperature. Several research works studied and observed that shadowing and dust accumulation in the panels surface contribute to an increase in its internal temperature [308].

Humidity is the measure of water vapor contained in the air. The presence of humidity in the air creates a diffraction optical path for the incident sunlight. This leads to a reduction in the amount of effective solar radiation that reaches the surface of the panel [309].

Changing humidity level has an effect on the performance of the PVT panel. Irradiation from incoming sunlight is also impacted by the humidity variation. A study is performed regarding the PVT panels' output variation with the change of humidity. Figure 4.24 illustrates the relationship between humidity change and irradiation impact.

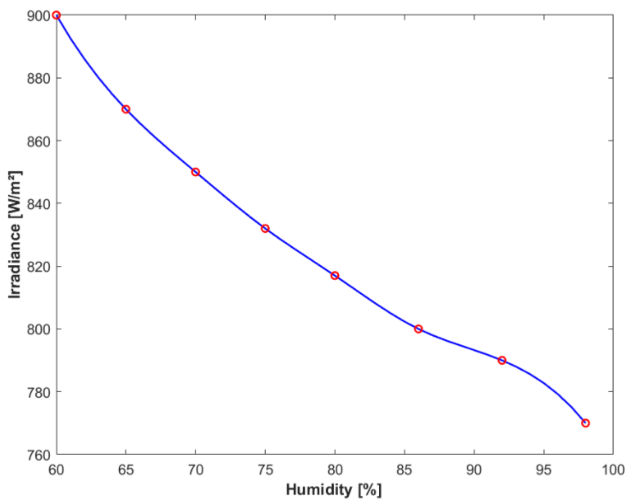

Figure 4.24: Irradiance and humidity correlation [245].

Figure 4.24 displays the changes in irradiance values corresponding to humidity variations in the PVT panel. As shown in the figure an increase in humidity levels leads to a decrease in the irradiance on the panel. Change in irradiance value with respect to humidity is provided in table 4.5.

Table 4.5. Irradiance values for varying humidity levels [245].

Humidity (%)	Irradiance (Wm^{-2})	Difference (Wm^{-2})
60	900	0
65	870	30
70	850	20
75	832	18
80	817	15
86	800	17
92	790	10
98	770	20

Table 4.5 indicates that irradiance changes significantly with the increasing humidity level in the PVT system. System overall output is also reduced while irradiance levels are reduced. As a result, the increasing humidity level decreases MPP of the PVT system. It is also observed that power output declines by nearly 50% with an 80% increase in humidity level.

Dust accumulation in the PVT panel is also another factor that influences the output. In [310], dust accumulation impact on both efficiency and output of the module are studied. Due to dust accumulation, panel temperature increases that results in a reduction of electrical power output. Overall study suggests that dust accumulation reduces productivity of the PVT system and accelerates panel degradation.

The essential parameters for improved PVT modeling are discussed in this section. Parameters variation effect, sensitivity analysis, performance variation is obtained using a MATLAB simulation. The external parameters of the PVT system are primarily considered, and results show that its effect is significant, which leads to a change in the total output. Irradiance and temperature are found in the analysis to be more sensitive. An increase in irradiance positively affects the system output, whereas temperature rise impacts negatively. Moreover, other parameters also influence the electrical power generation [245].

4.2 Thermal Loss Analysis

Performance analysis of a PVT system requires its thermal management mainly heat loss management. An electrical equivalent circuit of thermal loss is modeled and provided in the figure 3.21. And a single diode model electrical equivalent circuit is already explained in the figure 3.20. Produced I-V curve and P-V curve of a single diode model are provided in the figure 4.25.

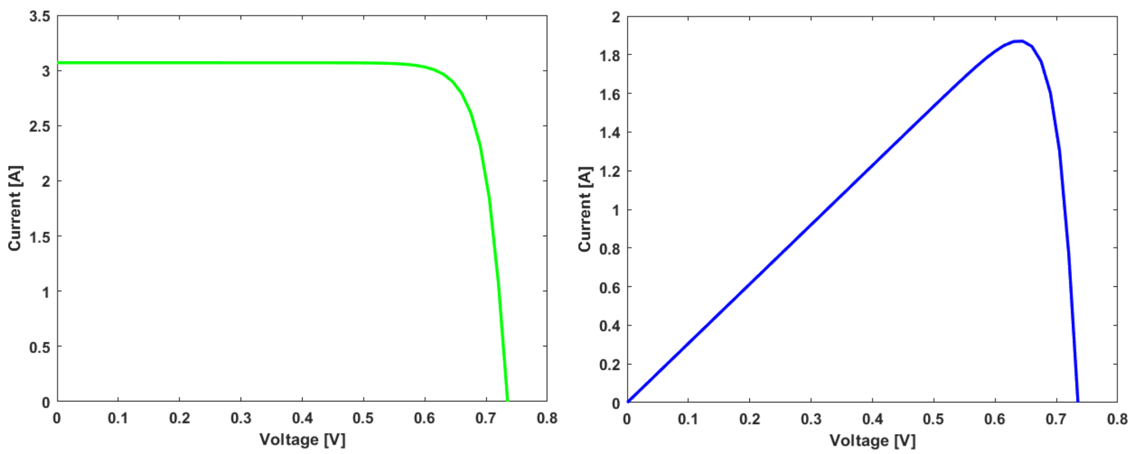

Figure 4.25: I-V curve (left) and P-V curve (right) from a single diode model.

An MPP curve of a single diode model shows the position where maximum power is located. An illustration of the MPP curve is provided in figure 4.26.

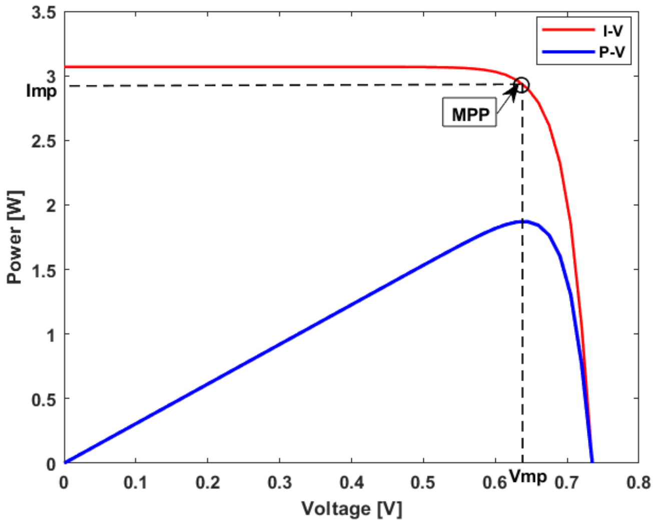

Figure 4.26: MPP curve from a single diode model.

Figure 4.26 shows the MPP position with current at maximum power and voltage at maximum power. Heat loss in PV system is modelled and an equivalent circuit is already provided. Produced I-V and P-V curve from heat loss model is provided in the figure 4.27.

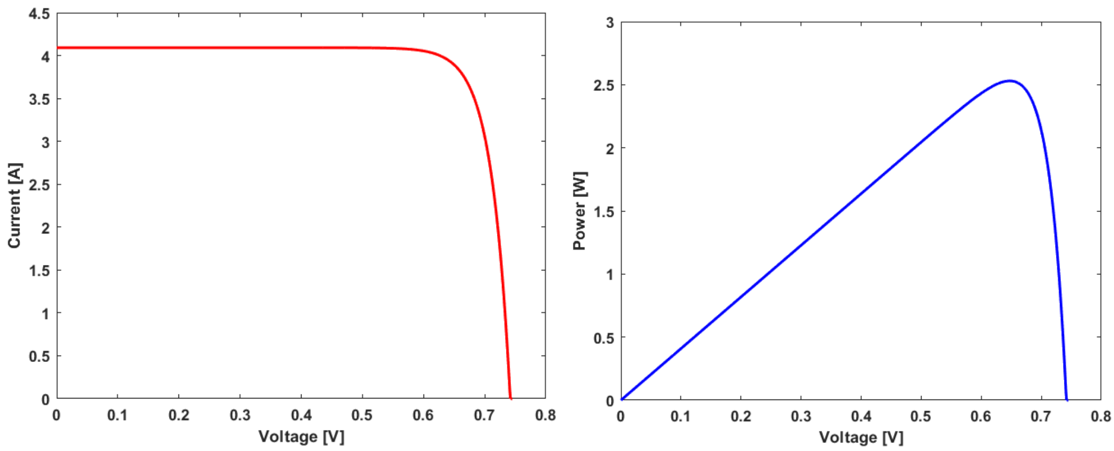

Figure 4.27: I-V curve (left) and P-V curve (right) from heat loss model.

MPP position and current, voltage value at maximum power is shown in figure 4.28.

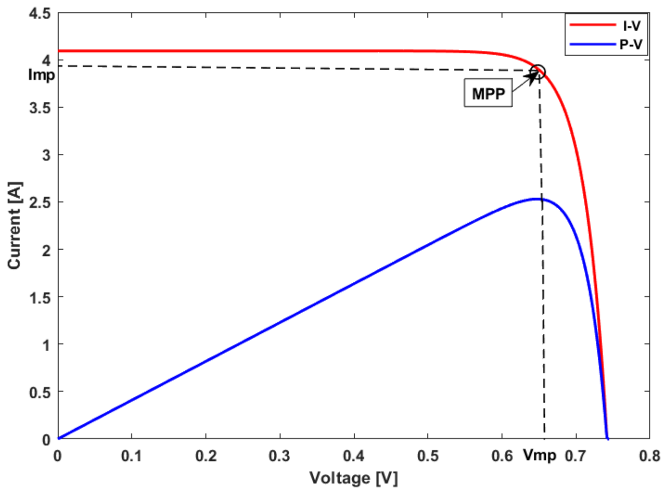

Figure 4.28: MPP curve from an equivalent loss circuit model.

The figure 4.28 shows the obtained MPP curve from the equivalent loss circuit model. This is considered as the equivalent of heat/thermal loss of a PV system. The value of MPP is obtained from the simulated data is 2.53 W. The simulation results show that heat loss equivalent output is higher than the PV cell conventional output. A comparison of the obtained simulated output of I-V and P-V curve is provided in the figure 4.29.

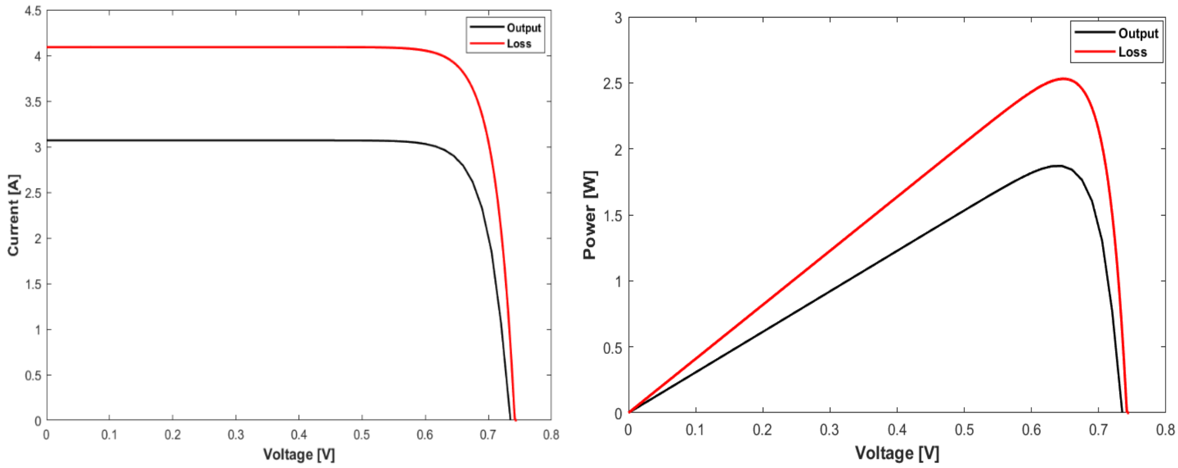

Figure 4.29: I-V curve (left) and P-V curve (right) comparison.

From the figure 4.29 it is described that the value of loss current is higher than the value of convenient output from the PV cell. Similarly, the P-V curve describes that loss P-V curve is higher than the P-V curve obtained from the existing PV cell model. It occurs as a higher portion of sunlight is not converted into electricity in the existing system. Obtaining maximum power in a PV system is inherent to reaching the optimum power. The comparison between MPP curve obtained from conventional system and MPP from loss model is provided in the figure 4.30. It shows the difference between MPP curve for conventional model (black P-V curve) and MPP curve for loss model (red P-V curve). It also describes that MPP obtained by loss mode is higher than the MPP of conventional PV cell model.

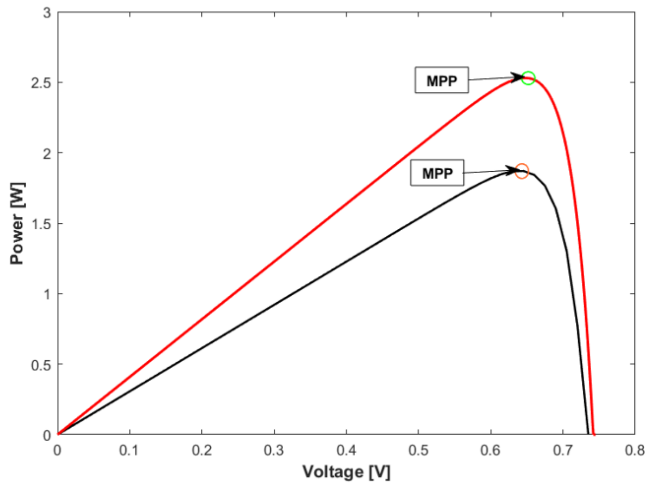

Figure 4.30: MPP curve difference between loss and conventional model.

Heat loss occurs in the PV panel that reduces electrical efficiency and overall performance of the system. Additionally, this heat transformation into a usable power is beneficial in the context of efficiency of the PV module. The excess heat is considered as a useful electrical power represented by the heat loss model as it adds extra electrical energy to the system. To sum up, the addition of this heat loss model with general electrical model provides an alternative solution to the PVT model that provides only electrical energy using any conventional thermoelectric generator. The simulated I-V curve and P-V curve for PV and equivalent PVT is provided in the figure 4.31.

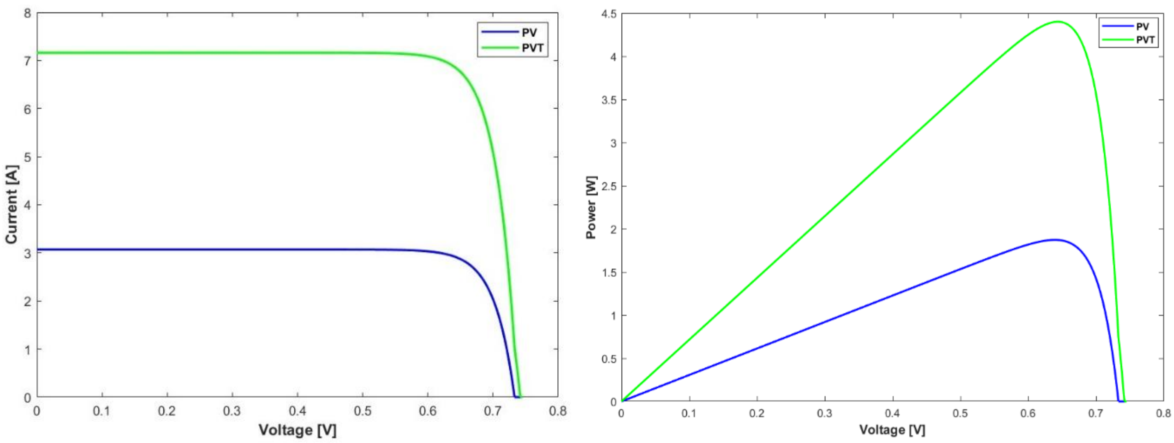

Figure 4.31: I-V curve (left) and P-V curve (right) comparison of equivalent PVT.

The MPP curve behavior and its difference between two systems is provided in the figure 4.32. The value of MPP of the PV cell is obtained by simulation is 1.87 W and the value of MPP of the equivalent electrical model of PVT system is obtained and it is 4.40 W.

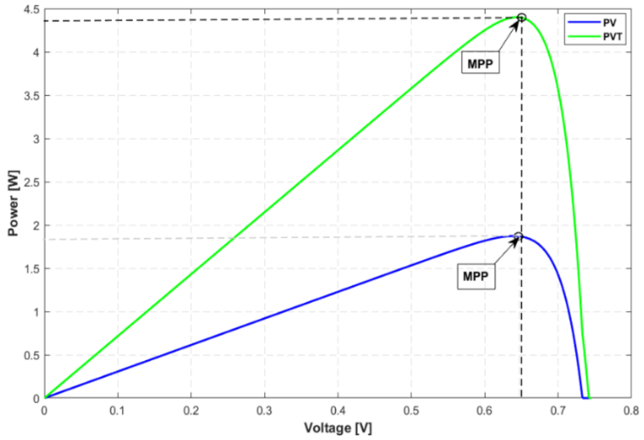

Figure 4.32: MPP curve difference between PV and equivalent PVT.

The result also describes that proposed equivalent PVT system based on thermal loss modeling has higher output than the output obtained from the equivalent electrical single diode cell model. Proposed thermal loss modeling analysis and equivalent PVT system also offers higher efficiency.

4.3 Simulation of PVT System

Simulation of a PVT system requires complete modeling, detailed study and performance analysis. Figure 4.33 represents the schematic of the proposed hybrid PVT system. It explains that the system consists of two primary components: the photovoltaic section and the thermal section. Solar radiation is converted to electrical energy in the PV section and this energy is stored locally or supplied to the grid. Most of the incident solar incident radiation is transformed into heat and later on converted to thermal energy in the thermal section of the PVT system. This extracted energy is useful in both residential and industrial consumer level [245].

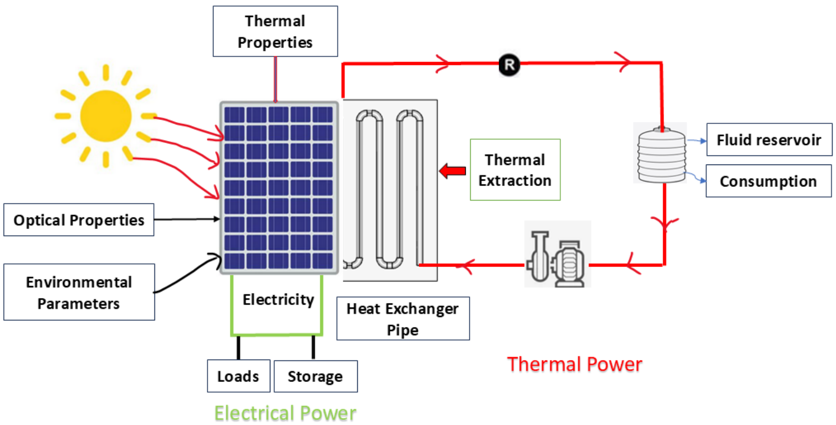

Figure 4.33: Hybrid PVT system illustration.

The figure 4.33 describes that the PV section of the PVT system consists of panel, loads and storage. Thermal section is composed of heat exchanger pipe (HEP), pump, fluid reservoir where it stores or supplies to the consumer. This PVT system is also influenced by optical parameters, environmental parameters, irradiance and related thermal properties. The improvement of PVT system has been continuing for many years. Designing an optimal and cost-effective PVT system that can operate efficiently in severe weather conditions is quite challenging and complicated. MATLAB/Simulink environment derived from [311] was used to develop and analyze this model is illustrated in the figure 4.34.

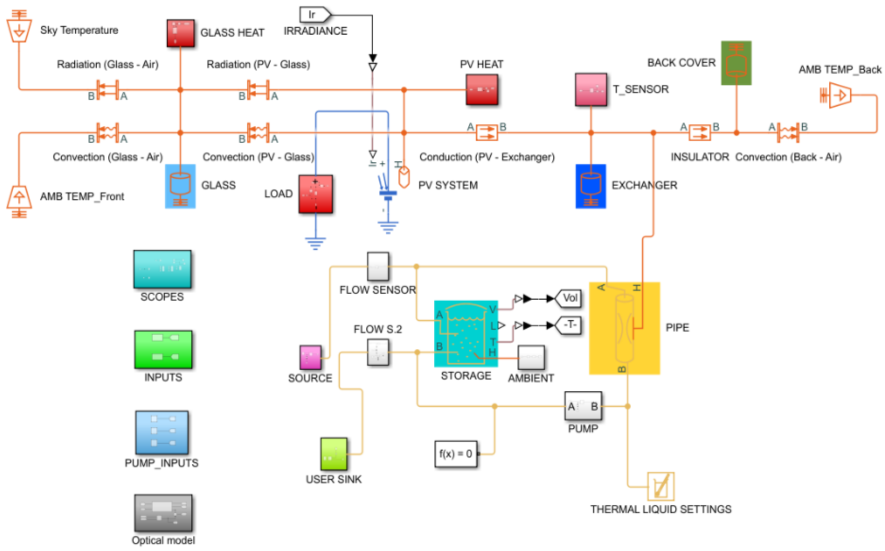

Figure 4.34: Simulation model of the proposed PVT system.

PVT System Analysis

Various cooling methods are discussed in many studies of temperature management of PVT system. The existing popular cooling technologies are water cooling, heat pipe cooling, air cooling, PCM cooling and bi-fluid cooling. Existing cooling techniques summary is provided in the table 4.6. It presents the categorization of the key materials used to cool the PVT panels. It describes the existing methods to cool and thermal energy management of the PVT system. Each category represents various strategies aimed at optimized energy utilization and enhancing the cooling efficiency of solar panels.

Table 4.6. PVT Cooling classification techniques based on primary materials.

Methods	Cooling Means/Ways	Examples
Water-Based	Water Circulation Cooling	Water channels, tanks, pumps, pipes, flow regulators.
	Spray-based cooling	Spray nozzles, solenoid valves, tanks, tubes.
	Evaporative cooling	Porous materials, burlap, cotton wick.
	Hybrid cooling	Nanofluids and water spray combination.
	Nanofluid assisted cooling	Heat exchangers, nanofluids, water channels, dispersion stabilizers.
Air-Based Methods	Air-Water Cooling	Water spray combined with air-cooled heat exchangers.
	Forced Airflow	Air ducts, metal sheets, fans, heat sinks.
	Natural Flow	Air ducts, heat sinks, passive ventilation systems.
PCM (Phase Change Material)	Active PCM Regeneration	Alternative heat sources from PCM regeneration process.
	Enhanced Cooling	Fans, pumps, Water pipes, enhanced thermal conductivity PCMs.
	Passive Cooling	Nanoparticles, PCM enclosures, heat sinks, thermal paste.
Other Cooling Strategies	Thermoelectric Cooling	Heat sinks, water pipes, fans, PCM, additional thermoelectric modules.
	Heat Pump Systems	Advanced refrigerant, conventional heat pumps.
	Advanced Thermal Coatings	Heat dissipation coatings, higher reflective
	Heat Pipe Cooling	Brass, Aluminum, thermosyphons, stainless steel.

Water cooling techniques offer an efficient and effective solution for reducing the adverse effects of high temperatures on PV systems. It is advantageous for PVT system as it continues to assist efficiency increase and maintain longevity. Among the different water based cooling methods evaporation based cooling, water based cooling, hybrid approach using water and nanofluids and tube water cooling are highly favored by the users for its better efficiency and ensuring optimal system performance. Heat transfer takes place through evaporation which supports maintaining low temperature in the PV panel. This method involves the application of water to a porous material, which helps regulate temperature at an optimal level, thereby improving efficiency [312].

In solar PVT systems, the use of specialized water based cooling method includes dedicated water pipes and cooling channels. In this method, water is circulated through heat exchangers pipe that is attached to the panels where it absorbs heat and cools the systems as liquid flows through the pipes. Subsequently, the heated water is collected and either stored or distributed to the end user.

In this work, a water based PVT [313] system is considered, studied and analyzed. The simulated model consists of two main components: an electrical system and a thermal system. The simulation of dynamic resistive load is properly investigated, and it is connected with an advanced cell block of PV cells. The process of complex heat exchange between thermal exchanger and environmental parameters, back cover, glass cover is covered and monitored by a thermal network. The radiation, conduction and convection method are used to model heat transfer of the PVT system.

Thermal liquid part is composed of storage tank, design components, precise pipes and adaptive pumps that control the liquid flow in an efficient manner. There are many existing PVT systems that use passive extraction system that do not require an extra pump. PVT system operation, methodology and other properties are summarized by a linear flowchart in the figure 4.35.

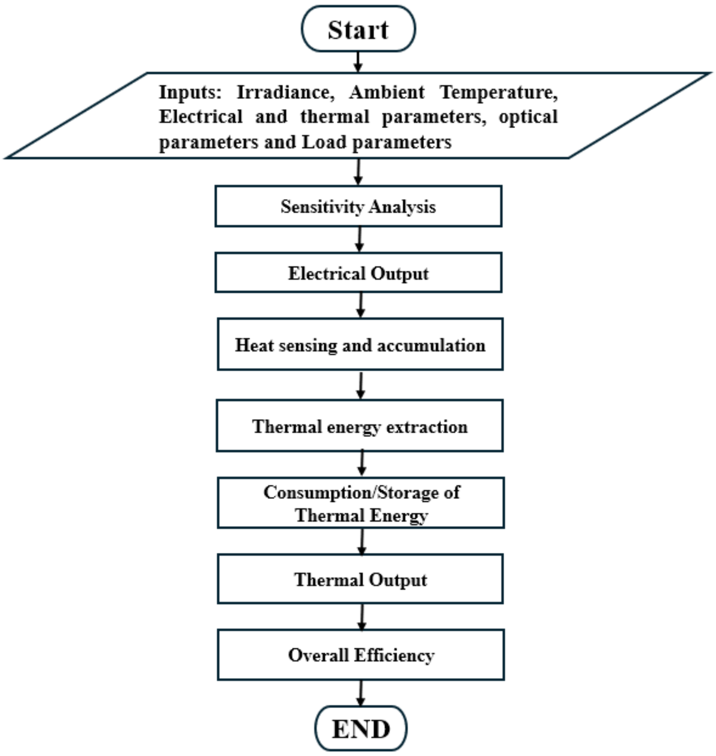

Figure 4.35: Operation of the PVT system.

Inputs of the PVT operations are mainly irradiance, ambient temperature, electrical and thermal parameters, optical parameters and load parameters. Sensitivity analysis is the important factor to study the parameter impact on the PVT system. Electrical energy is obtained from the incidence irradiance using PV effect on the top of the module. Thermal energy extraction takes place at the back of the system. Thermal output is obtained from the fluid flow, and it is stored in a storage. Overall efficiency is calculated using electrical and thermal output.

Input Parameters Analysis

A brief simulation and result analysis is obtained in this section. Input parameters with relevant output are analyzed and detailed description is discussed here. The considered load value for this simulation model is 5 Ω and it could differ depending on user requirements. The parameters are mainly cell electrical properties, temperature, panel optical properties, heat transfer properties and panel geometric properties. Initial temperature value for several components used for simulation is provided in the table 4.7.

Table 4.7. Initial temperature values.

Parameter	Value
Tank Water Temperature (Tw0)	295 K
Back cover temperature (Tb0)	295 K
Glass cover temperature (Tg0)	295 K
Heat exchanger temperature (Te0)	295 K
PV cells temperature (Tpv0)	295 K

Geometrical parameters of the solar panel are provided in the table 4.8. Thermal properties of the heat transfer process for simulation purpose are provided in the table 4.9.

Table 4.8. Geometrical properties of the panel.

Parameter	Value
Area of Cell (A_{cell})	0.02 m^2
Number of cells (N_{cell})	72

Table 4.9. Heat transfer properties.

Parameter	Value
Ambient Temperature (T_a)	295 K
Sky Temperature (T_{sky})	292 K
Glass Cover Mass (M_g)	4 kg
PV Cell Mass (M_{pv})	0.20 kg
Heat Exchanger Mass (M_e)	15 kg
Back Cover Mass (M_b)	5 kg
Specific Heat Glass (C_g)	800 J/kg/K
PV Cell Specific Heat (C_{pv})	200 J/kg/K
Heat Exchanger Specific Heat (C_e)	460 J/kg/K
Heat Exchanger Back Cover (C_b)	400 J/kg/K
Glass Emissivity	0.75
PV cell Emissivity	0.70
Glass-Air Convection Coefficient	10 $W/m^2/K$
PV-Glass Convection Coefficient	20 $W/m^2/K$
Back-Air Convection Coefficient	10 $W/m^2/K$
Heat Exchanger Thermal Conductivity	130 W/m/K
Heat Exchanger Thickness	0.04 m
Insulation Thermal Conductivity	0.10 W/m/K

Insulation Layer Thickness	0.03 m

PVT system overall output also depends on optical properties of the components. The used optical properties of the component for simulation purpose are provided in the table 4.10.

Table 4.10. Optical properties of the system.

Parameter	Value
Refractive Index ratio (glass/air)	1.52
Reflection Factor	0.15
Glass cover thickness	0.01 m
Absorption Coefficient glass	0.20 m^{-1}

Thermal properties of the PVT system are significantly considered for the heat transfer processes that influence the thermal output. The table 4.11 provides the thermal and heat transfer properties.

Table 4.11. System heat transfer properties.

Parameter	Value
Ambient Temperature (T_a)	295 K
Sky Temperature (T_{sky})	292 K
Glass Cover Mass (M_g)	4 kg
Heat Exchanger Thermal Conductivity	130 W/m/K
Heat Exchanger Thickness	0.04 m
Insulation Thermal Conductivity	0.10 W/m/K
Specific Heat Glass (C_g)	800 J/kg/K
PV Cell Specific Heat (C_{pv})	200 J/kg/K
Heat Exchanger Specific Heat (C_e)	460 J/kg/K
Heat Exchanger Back Cover (C_b)	400 J/kg/K
Glass Emissivity	0.75
PV cell Emissivity	0.70
Glass-Air Convection Coefficient	10 $W/m^2/K$
PV-Glass Convection Coefficient	20 $W/m^2/K$
Back-Air Convection Coefficient	10 $W/m^2/K$
PV Cell Mass (M_{pv})	0.20 kg
Heat Exchanger Mass (M_e)	15 kg
Back Cover Mass (M_b)	5 kg
Insulation Layer Thickness	0.03 m

Table 4.11 provides heat transfer properties of the system that includes different temperature, value of mass of different components, specific heat transfer properties, emissivity and other physical properties.

The manufacturer typically provides the electrical properties of the selected module in its datasheet. Table 4.12 provides the simulation parameters of electrical properties of the PV module.

Table 4.12. PV cell electrical properties.

Parameter	Value
Irradiance (I_{Irr})	1000 W/m^2
Quality Factor (N)	1.5
Series Resistance (R_s)	0 Ω
Shunt Resistance (R_{sh})	Close to infinity
Short-circuit current (I_{sc})	8.88 A
Open-circuit voltage (V_{oc})	0.62 V
Diode Saturation Current (I_s)	1e-6 A
Current (I_{ph})	8.88 A
Temperature Coefficient (Photo Current)	0 K^{-1}
Energy Gap	1.11 eV
Temperature Exponent (Saturation Current)	3
Temperature Exponent (Series Resistance)	0
Temperature Exponent (Shunt Resistance)	0
Measurement Temperature	298 K

Heat transfer occurs using a fluid that circulates in the heat exchanger pipe of a PVT system. Heat extraction and output characteristics depend on various types and sizes of pipes. The value of pipe parameters and other characteristics are provided in the table 4.13.

Table 4.13. Heat exchanger pipe parameters.

Parameter	Value
Pipe Length	5 m
Pipe Area	0.0007 m^2
Lower Renolds Number	4000
Shape Factor (Laminar flow viscous friction)	64
Nusselt Number	3.66
Upper Renolds Number	2000
Hydraulic Diameter	0.03 m
Pipe Resistance Length	1 m
Pipe Roughness (Internal surface)	15e-6 m

Thermal energy is stored and supplied to the consumers using a tank connected with the PVT system. The values and characteristics of the tank are provided in the figure 4.14.

Table 4.14. Tank input parameters.

Parameter	Value
Tank Area	0.30 m^2
Thermal Conductivity (Insulation layer)	0.10 W/m/K
Convection Coefficient (Tank and ambient air)	10 W/m^2/K
Initial Temperature	295.15 K

Thickness (Insulting layer)	0.05 m
Maximum Volume	0.25 m³
Initial Volume	0.10 m³

Pump flow input parameters for the simulation purpose are provided in the table 4.15.

Table 4.15. Pump flow input parameters.

Parameter	Description	Value
Supply Mass Flow	Supply mass flow rate	0.005 kg/s
Demand Mass Flow	Demand mass flow rate	0.005 kg/s
Internal Mass Flow	Internal circuit mass flow rate	0.022 kg/s

These given values are used in the simulation studies that analyze the output characteristics and performance of the PVT system. The simulated daily irradiance profile is shown in the figure 4.36.

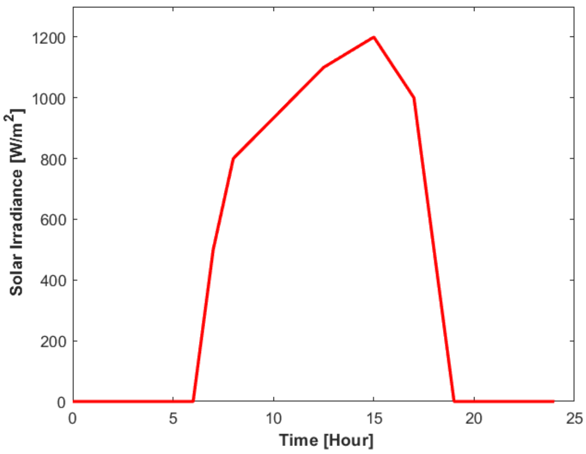

Figure 4.36: Daily irradiance profile.

Integration of the heat exchanger pipes in a PVT system provides improved performance due to the higher heat transfer rate and capacity of these pipes that functions in a passive system [314]. For the case of PCM, it provides higher heat transfer performance than the heat exchanger pipes even at low temperature difference. Heat exchanger pipes are used in heating, air conditioning and ventilation system as it results in effective heat transfer at lower temperature level [315].

Pipes are considered for the heat extraction purpose, and their material type is important in the heat transfer mechanism. Performance studies also required effective heat transfer fluid and operation. Pipes parameters are also a crucial part of this system that is considered for heat transfer analysis. Different types of heat extraction (HE) pipes provide different results related to thermal extraction are discussed here. Copper pipes based heat extraction method for a water heating PVT system is also significant [316]. The effect of using aluminum pipe and steel pipe as heat exchanger, design analysis is studied in

[317]. The figure 4.37 provides the design and layout overview of the attached pipe in the PVT system. Additionally, the pattern of the flow of heat transfer fluid is also identified by this analysis. The next section describes the output and performance variation of the different heat transfer pipes in the PVT system. Copper, aluminum and stainless steel pipes are considered in this analysis.

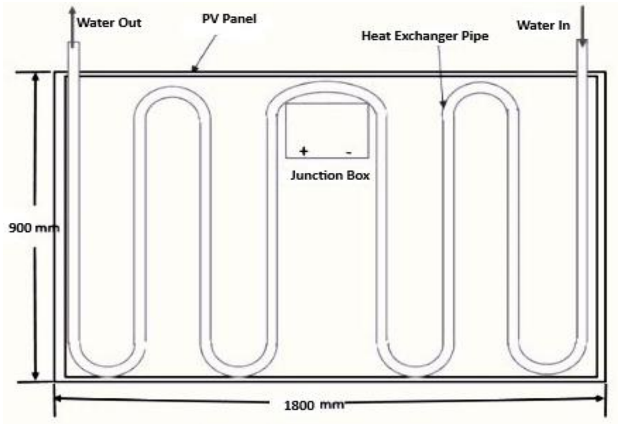

Figure 4.37: Heat Exchanger pipe layout in the PVT system [318].

4.4 Simulation Results Analysis

The panel's electrical and thermal properties are used to analyze the performance and improvement of the PVT system. The electrical analysis section is related to the equivalent electrical circuit model and related parameters. The study of various components like exchanger pipe, pump, storage tank and other thermal components are included in the modeling and analysis. Temperature profiling, comparison between several components temperature profile and efficiency are studied and simulated results are provided. Heat transfer using three types of pipes are copper, aluminum and stainless steel are used and compared in the PVT system. These pipes exhibit better mechanical strength, electrical and thermal properties, also these have improved corrosion resistance. Additionally, real world implementation in the PVT of these pipes is comparatively easy and these pipes have market availability also. Result analysis is obtained and discussed from [318].

Stainless Steel

For the simulation purpose, stainless steel pipe roughness is considered as 15e-6 m. Specific values of heat transfer properties of this pipe is provided in the table 4.16.

Table 4.16. Stainless-steel pipe heat transfer properties [318].

Parameter	Value
Heat Exchanger Specific Heat (C_e)	460 J/kg/K
Heat Exchanger Thermal Conductivity	130 W/m/K

Specific heat is considered as 460 J/kg/K and thermal conductivity is considered as 130 W/m/K. Temperature profile of various components with respect to time of the PVT system is provided in the figure 4.38.

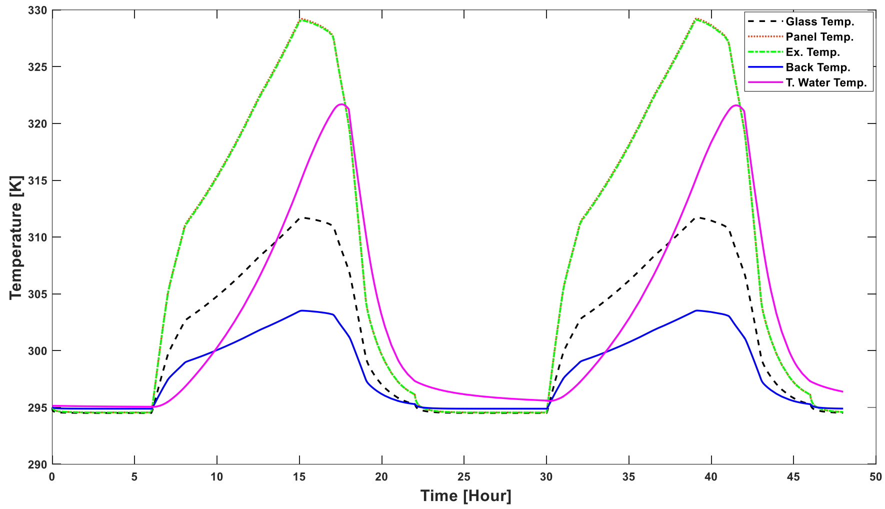

Figure 4.38: Temperature dynamics of various components [318].

This figure 4.38 illustrates temperature dynamics with time of the PVT system for panel, glass, back side, tank water and exchanger. Increasing irradiance increases temperature and the fluid temperature inside the pipe also elevates. Total electrical output and thermal output due to the use of stainless steel is provided in the figure 4.39. It illustrates the thermal and electrical output for a single period. Electrical power peaks at the time when the irradiance is higher and thermal power peaks at the time when it can extract the maximum power from the system.

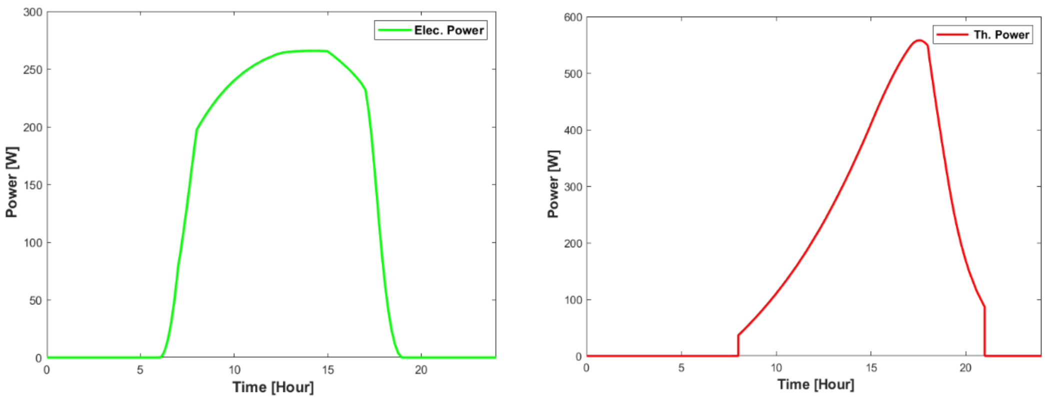

Figure 4.39: Electrical and thermal power output [318].

Temperature profile difference between PV panel and back side is provided in the figure 4.40. Temperature of the PV panel increases with the increasing irradiance value which occurs during the day. Back cover temperature is found to be lower than the panel temperature because of heat dissipation and insulating effect of the material. This figure provides an idea regarding the temperature variation of both panel and back side.

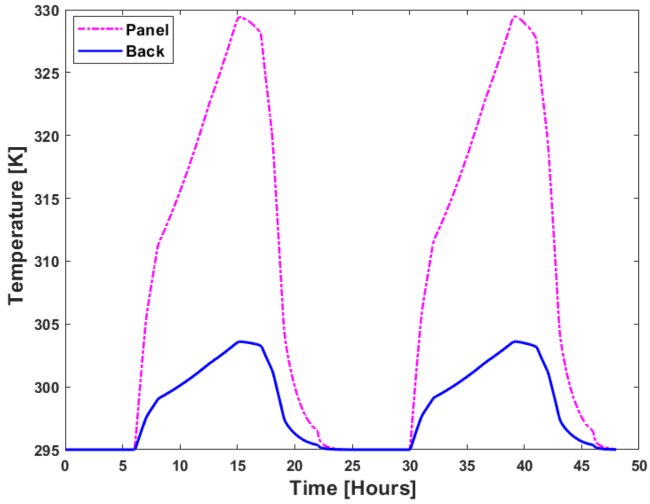

Figure 4.40: Back cover and PV panel temperature dynamics [318].

As tank water has thermal storage characteristics so temperature inside of it drops in a slower pattern but rises more gradually due to heat absorption characteristics. The temperature difference between the back cover and tank water is provided in the figure 4.41.

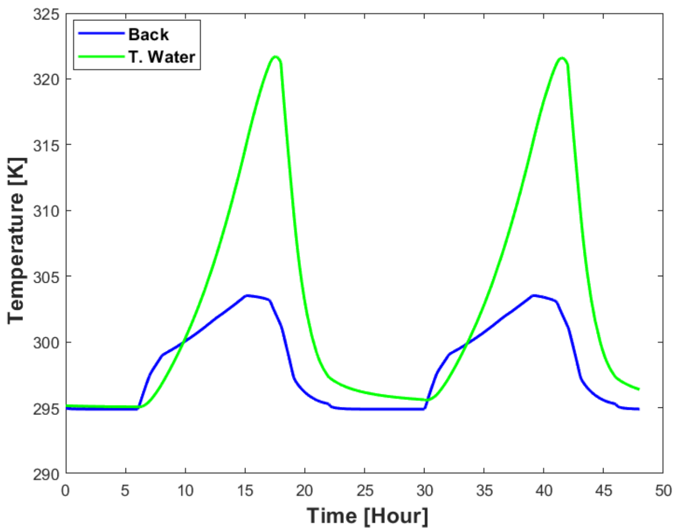

Figure 4.41: Back cover and tank water temperature dynamics [318].

Water volume of the tank is provided in the figure 4.42. Water volume pattern shows and provides the information regarding the used water in the system.

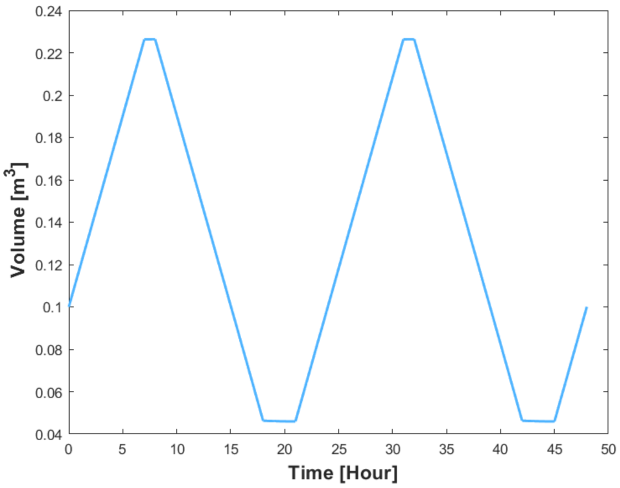

Figure 4.42: Flow of tank water [318].

Comparison between panel temperature and water temperature variation absorbed from surroundings heat is provided in the figure 4.43.

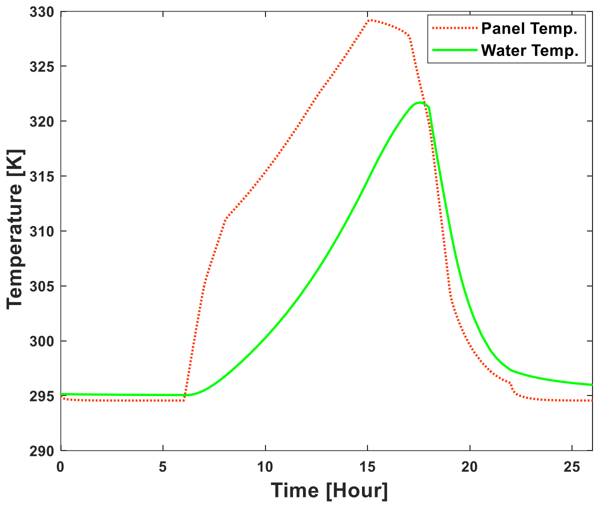

Figure 4.43: Panel temperature and water temperature [318].

The panel's effectiveness is dependent on the panel temperature that is the total heat absorbed by the panel from the irradiance and surroundings. Available tank water temperature for a 24-hour period is provided also by this figure.

Electrical power and thermal power output comparison of the PVT system is provided by the figure 4.44. Photovoltaic section provides electrical output while thermal section provides thermal output. Electrical output is available normally during the day as is related to the sunlight. Besides, PVT system provides higher thermal power around noon and decline starts around evening which exhibits higher output results of thermal inertia.

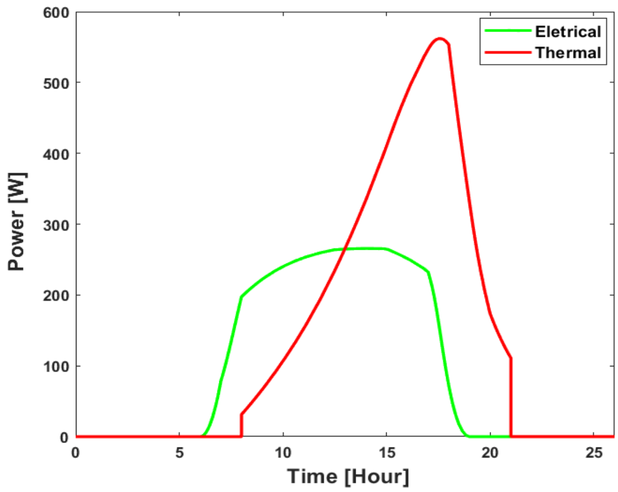

Figure 4.44: Electrical and thermal power output comparison.

Total input power and total output power comparison of the PVT system using stainless steel is provided in the figure 4.45. Two days (48 hours) observation period is considered for better elaboration and understanding. Overall input power of electrical and thermal is identified by the dotted red line in the figure. Input power is dependent on irradiance and external parameters while it varies mostly with the irradiance profile during the day. Output power in the figure 4.45 is depicted by the green line that provides the total power gain from the system. Losses in a system are calculated by the difference between input power and output power which is also obtained in this system [318].

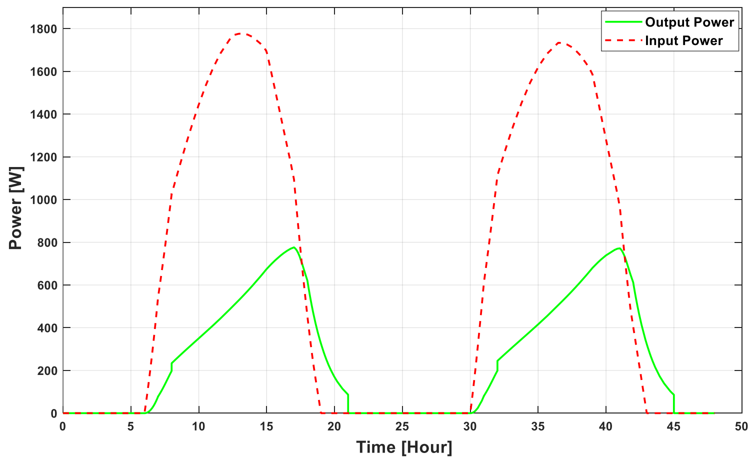

Figure 4.45: Comparison between total input and output power [318].

Efficiency Analysis (Stainless Steel)

The efficiency of the hybrid PVT system is provided by analyzing and comparing the total thermal and electrical usable energy and the total energy received by the system. The electrical energy proportion with respect to overall input energy is the electrical efficiency of the system. The usable thermal energy and the total input energy proportion is the thermal efficiency of the system.

The efficiency of the PVT system using stainless steel as a heat exchanger pipe is provided in the table 4.17. The values and information regarding electrical and thermal efficiency, total efficiency, input and output energies are given in this table. The obtained electrical efficiency of this system is 0.16, thermal efficiency of this system is 0.24 and finally obtained total efficiency of the PVT system is 0.40 while stainless steel is used as heat exchanger pipe [318]. An overview of the total efficiency including electrical and thermal is provided in figure 4.46.

Table 4.17. Efficiency analysis using stainless-steel pipe [280].

Parameter	Value	Unit
Sun Input Energy (2 days)	31.23	kWh
Sun Input Energy (daily)	15.61	kWh
Electrical Energy Supplied (2 days)	5.16	kWh
Electrical Energy Supplied (daily)	2.58	kWh
Supplied Thermal Energy (2 days)	19.32	kWh
Used Thermal Energy (daily)	11.92	kWh
Total Used Thermal Energy (2 days)	7.40	kWh
Thermal Energy (daily)	3.70	kWh
Electrical Efficiency	0.16	
Thermal Efficiency	0.24	
Total Efficiency	0.40	

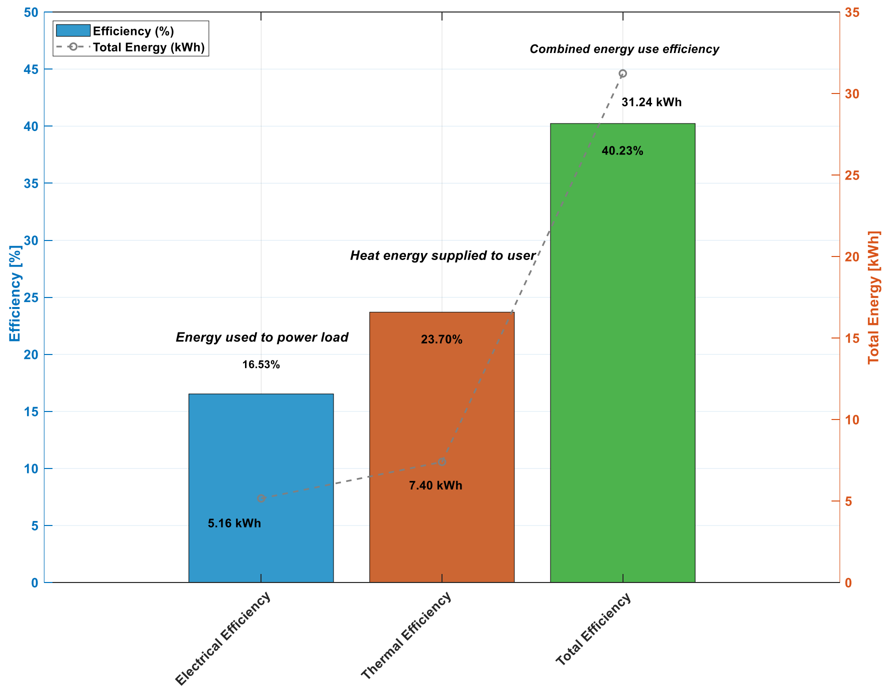

Figure 4.46: Hybrid PVT efficiency with stainless steel [318].

Aluminum

Different heat transfer pipes can be utilized in the hybrid PVT system, where aluminum is one of them. Simulation of aluminum using heat exchanger pipe is considered and related output is discussed here. Pipe roughness of the aluminum pipe is considered as 1.5e^{-6} m. Table 4.18 provides the considered thermal properties of the aluminum pipe.

Table 4.18. Aluminum pipe heat transfer properties [318].

Parameter	Value
Sky Temperature (T_{sky})	295 K
Heat Exchanger Specific Heat (C_e)	897 J/kg/K
Heat Exchanger Thermal Conductivity	237 W/m/K

This part discusses heat transfer analysis and electrical analysis using aluminum as a heat exchanger pipe. Temperature dynamics behavior of different components of the PVT system while aluminum as heat exchanger pipe is provided in the figure 4.47.

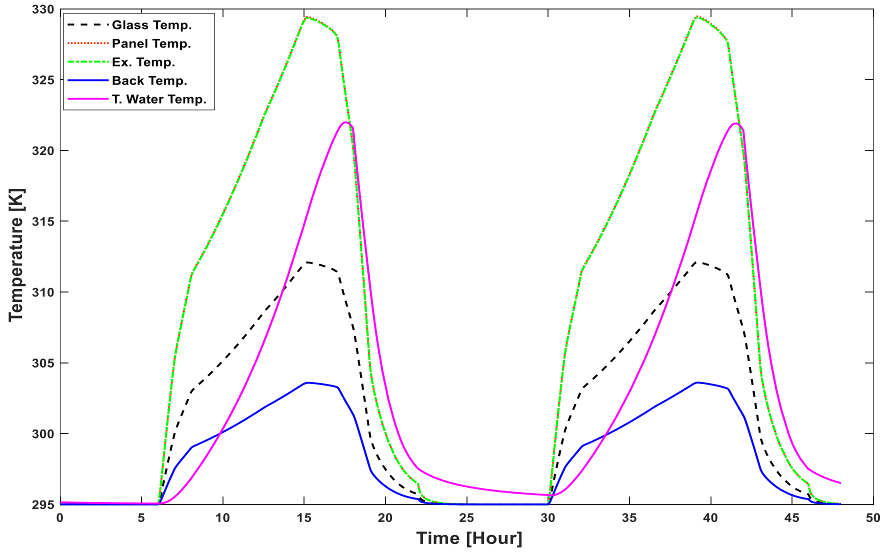

Figure 4.47: Temperature profile for different components [318].

This figure 4.47 provides the temperature profile for various components of the PVT system where panel temperature, glass temperature, back temperature, exchanger temperature and tank water temperature are considered. It describes that with the sunrise or increasing irradiance the temperature of the components increases, and it is at the peak while the value of irradiance is high. The fluid temperature inside the pipe also increases as the heat transfer occurs with the passing of time. Considering the ideal situation, the temperature value of the panel and exchanger is the same as depicted in this figure also. It can also be observed from the figure that tank water temperature also rises gradually with the rise of panel temperature. And the temperature of the back side of the panel is slightly lower than the temperature of the other components.

The variation in electrical power output and thermal power output resulting from the use of an aluminum heat exchanger pipe is provided in the figure 4.48. It indicates the electrical and thermal power output for a day period. It discovers that the electric power output peaks around noon as the irradiance also peaks at that moment. Thermal power output starts with the sunrise very slowly, but peaks while the fluid absorbs the maximum power from the system and almost falls with the sunset [318].

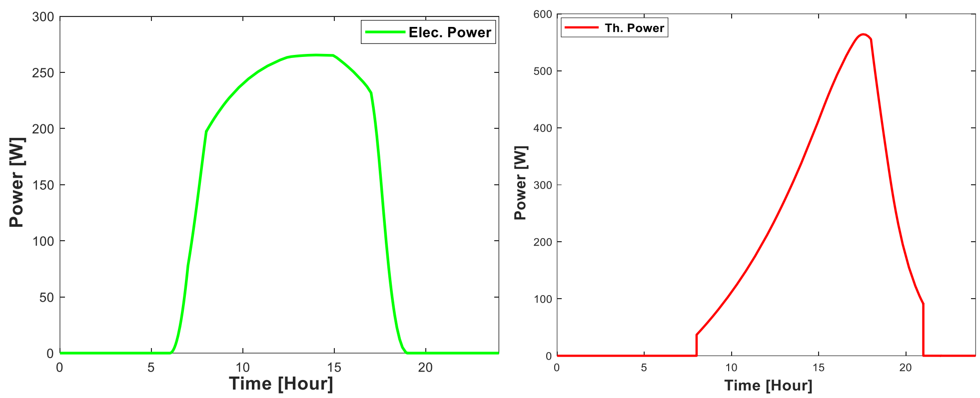

Figure 4.48: PVT system’s electrical and thermal power output [318].

Temperature behavior of the panel and the back cover is provided in the figure 4.49. The figure depicts that due to materials insulating effect properties and heat dissipation there is difference between the panel and back cover temperature.

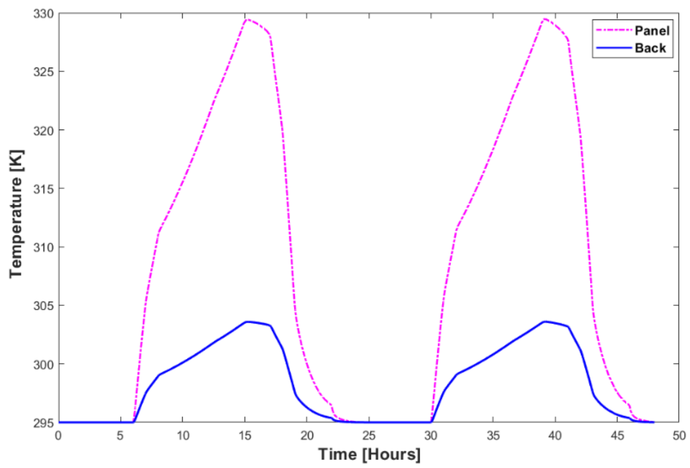

Figure 4.49: Temperature profile of the PV panel and back cover [318].

Figure 4.50 shows the temperature difference between back cover surface and tank water.

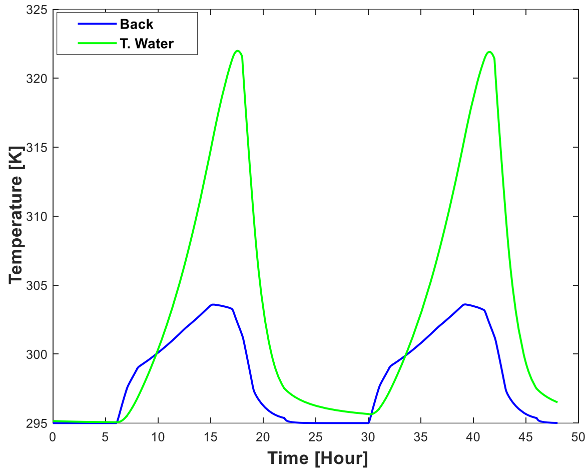

Figure 4.50: Temperature profile of the tank water and back cover [318].

Back cover and tank water temperature both are related with the incident irradiation mainly and other internal and external parameter also. Due to the heat absorption over time from the panel, tank water increases gradually. Due to thermal insulation and heat storage capacity, it can maintain temperature to a certain level for a specific period of time. Storage tank's water volume and its pattern are provided in the figure 4.51.

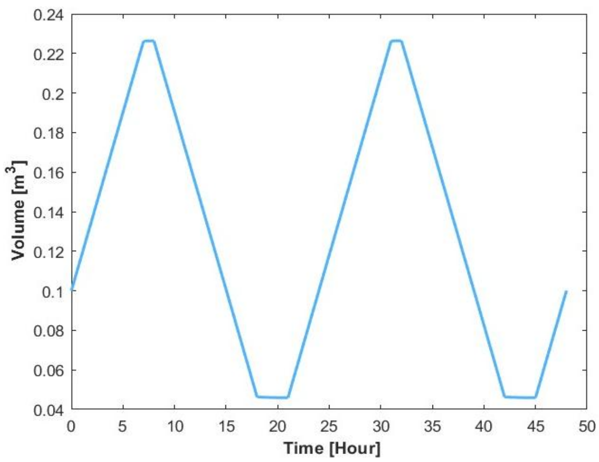

Figure 4.51: Tank water volume dynamics over time [318].

This figure 4.51 helps to understand the water volume dynamics over time. This phenomenon will regularize the controlling of PVT system during its operation. The water volume varies throughout the day, decreases with the usage and rises during replenishment. Obtained Electrical and thermal power output using aluminum as heat exchanger pipe in the PVT system is provided and compared in the figure 4.52 [318].

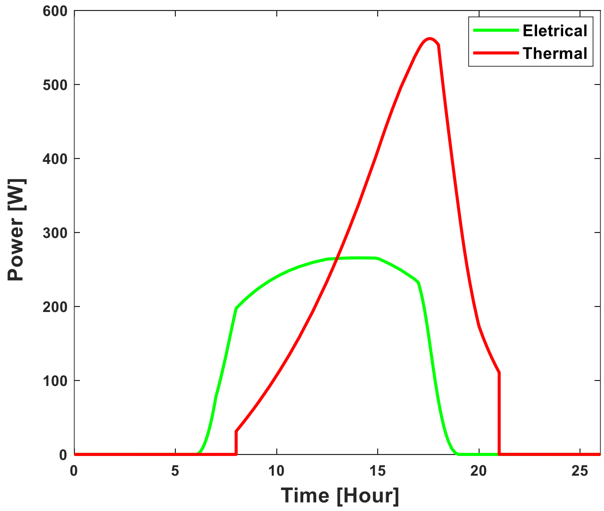

Figure 4.52: Comparison of electrical and thermal power output [318].

It provides the obtained electrical and thermal power output comparison of the PVT system while aluminum is used as heat exchanger pipe. It also describes the electrical power output and thermal output deviation because electrical power is instantaneous, and thermal power requires time to process. That is why the electrical power generation starts as soon as the irradiance incident on it and thermal power starts later on after sufficient heat consumption by the pipe and fluid. Electrical power output is extracted from the PV panel and maximum power output is obtained while the irradiance value is intense and maximum. Thermal output is obtained using thermal component that extract the dissipated heat from the PVT system. In general, there is no output at nighttime. However, due to thermal inertia, the high output persists for a longer duration, with thermal power peaking around midday and gradually declines after sunset. The comparison of water temperature and panel temperature obtained from surroundings and heat absorption is provided in the figure 4.53.

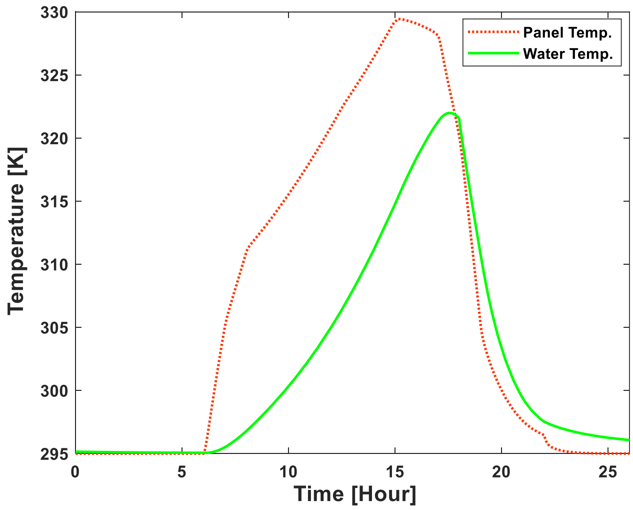

Figure 4.53: Panel temperature and water temperature comparison [318].

Panel temperature represented by the red dotted line shows the behavior for a day and water temperature represented by the green line shows the daily dynamic behavior of the absorbed heat by the water. Measurement of thermal and electrical efficiency of the PVT system requires to know the temperature level of the different parts [318].

Figure 4.54 represents a comparison of input and output power of the PVT system while aluminum pipe is used as heat exchanger in here.

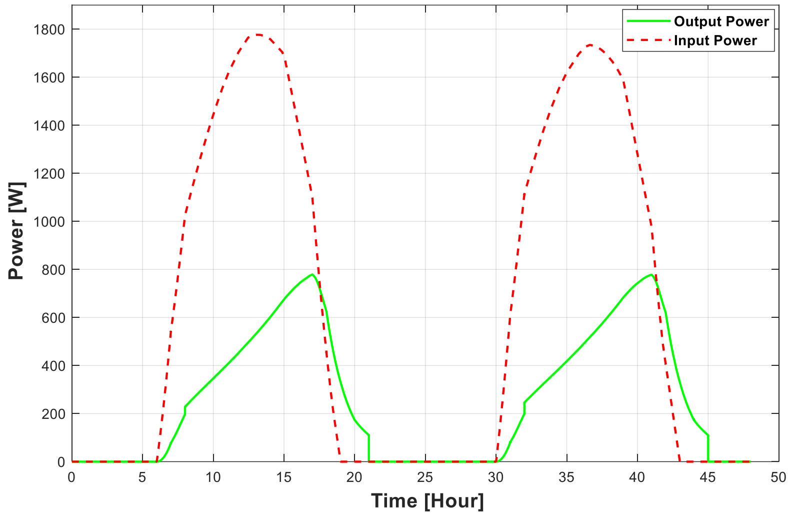

Figure 4.54: Input and output power comparison of the PVT system [318].

For easier comprehension two days (48 hours) observation are considered for simulation purpose what is depicted in the figure 4.54. Total output of the PVT system that includes electrical and thermal power is represented by the output power in the figure and total power input that is included irradiance and other external factors are represented by the red dotted line in this figure. Total power input and output typically varies with the available irradiance that increases in the day period and decreases at the end of the day. The output of the system is determined by the losses and generation in it [318].

Efficiency Analysis (Aluminum)

Efficiency analysis of the PVT system is determined by analyzing the total received energy by the system and the total generated useful electrical and thermal energy. The results and values of efficiency analysis of the hybrid PVT system using aluminum heat exchanger pipe is provided in the table 4.19.

Table 4.19. Efficiency values for PVT system using aluminum **[280]**.

Parameter	Value	Unit
Electrical Energy Supplied (2 days)	5.15	kWh
Electrical Energy Supplied (daily)	2.57	kWh
Supplied Thermal Energy (2 days)	19.41	kWh
Used Thermal Energy (daily)	11.92	kWh
Total Used Thermal Energy (2 days)	7.49	kWh
Thermal Energy (daily)	3.74	kWh
Electrical Efficiency	0.17	
Thermal Efficiency	0.24	
Total Efficiency	0.41	

From the table 4.19 it is seen that the electrical efficiency of the system is 0.17, thermal efficiency is 0.24 and total efficiency is 0.41. An overview of the electrical, thermal and total efficiency is provided in the figure 4.55.

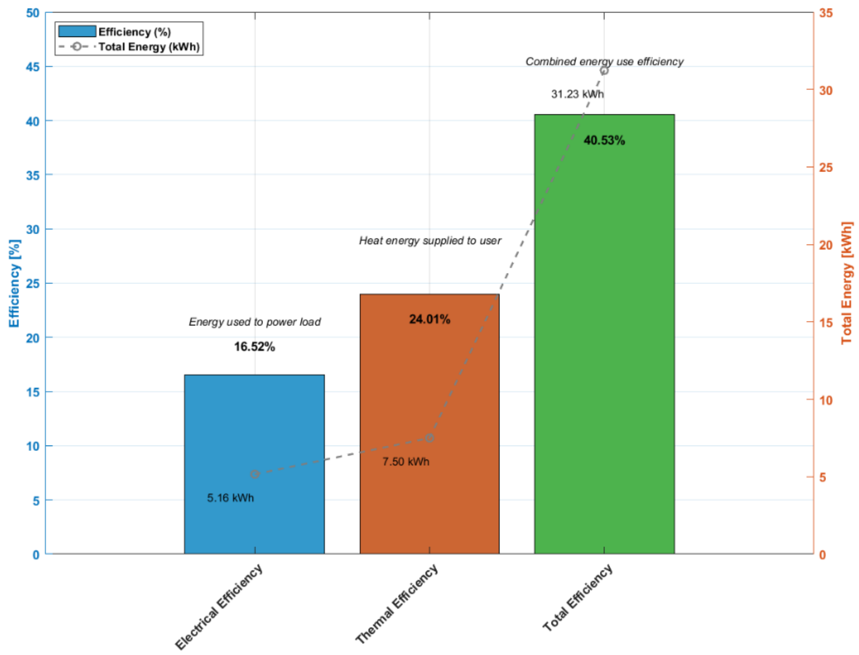

Figure 4.55: Electrical, thermal and total efficiency for aluminum [318].

Copper

Copper as a heat exchanger pipe in the PVT system is considered and studied in this section. It describes obtained outputs, thermal profiling and efficiency of the PVT while copper is used in the system. The parameters including geometric, thermal and electrical are used as same as the previous one. Absolute roughness of the internal surface is considered, and the value is 1.5e-6 m, the Nusselt number for heat transfer in laminar flow is 4.36. The properties of the used pipe are shown in the table 4.20.

Table 4.20. Copper pipe's heat transfer properties [280].

Parameter	Value
Heat Exchanger Specific Heat (C_e)	400 J/kg/K
Heat Exchanger Thermal Conductivity	398 W/m/K

This part discusses simulation results and comparison obtained by using copper as heat exchanger pipe. Temperature dynamics of the various components of PVT system for this case are provided in the figure 4.56.

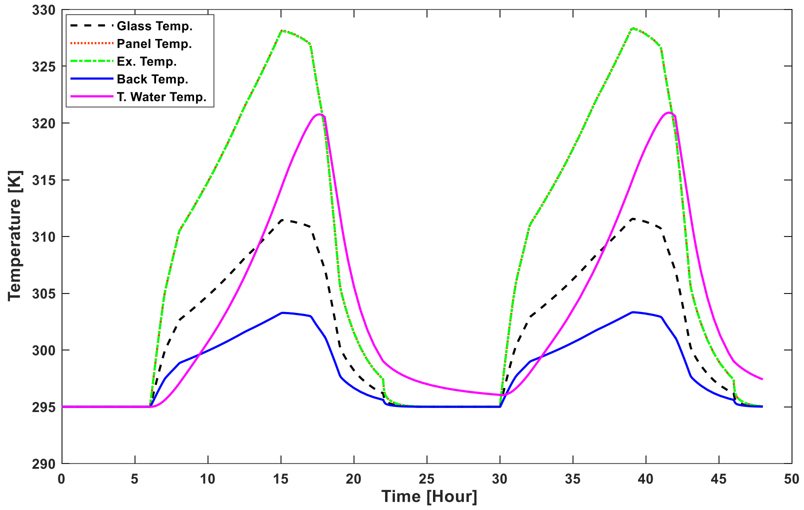

Figure 4.56: Temperature variations of different parts using copper pipe [318].

This figure 4.56 provides temperature dynamics for PVT components while copper is used as heat exchanger pipe. Temperature of these components increases while the irradiance increases. At the same time, as long as the water flow in the pipe continues heat energy also continues to transfer to the fluid in a timely manner.

The values and illustration of obtained electrical and thermal power using copper pipe is represented by the figure 4.57. Electric power increases very rapidly and maintains output for a certain time and then decreases. It is directly dependent on the irradiance from the Sun where thermal power rises gradually and dependent on system temperature and thermal properties.

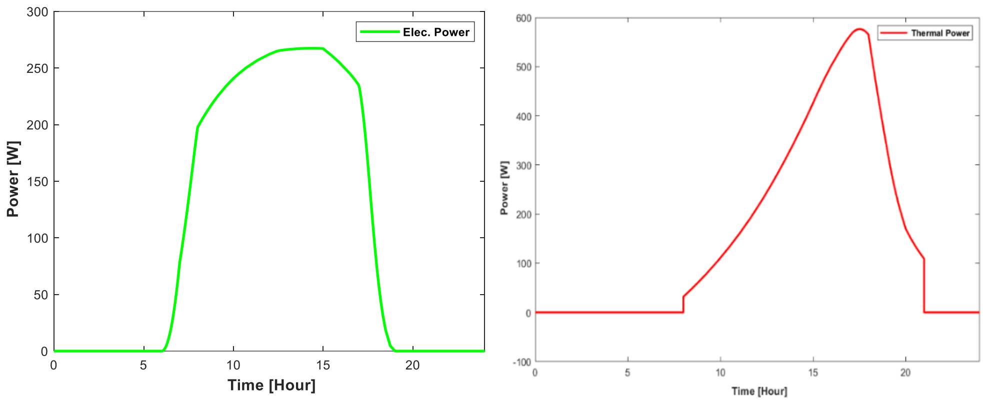

Figure 4.57: Obtained electrical and thermal power output [318].

The comparison between PV panel temperature and back part is provided in the figure 4.58. It describes that the panel temperature is higher than the back part temperature because panel is directly exposed to sunlight. The comparison between tank water and back part during operation simulation is provided in the figure 4.59.

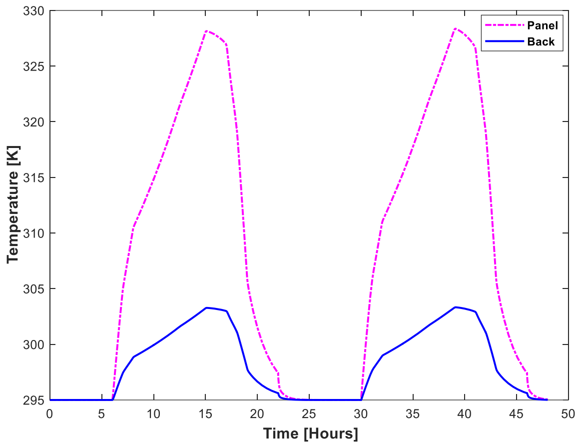

Figure 4.58: Back part and PV panel temperature comparison [318].

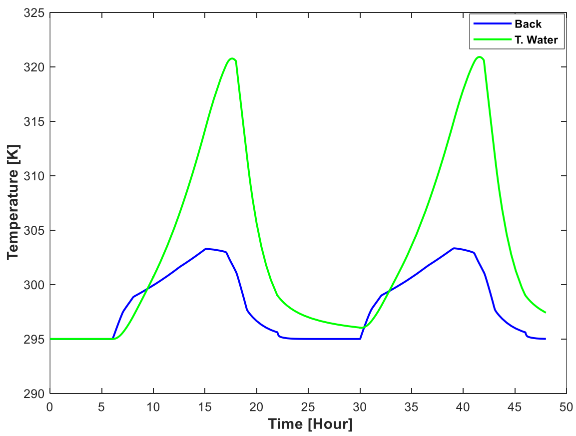

Figure 4.59: Tank water and back part temperature comparison [318].

Temperature increase or decrease of the tank water depends on the irradiance profile and heat extraction by the heat exchanger pipe. Water flow volume pattern for this case is provided in the figure 4.60.

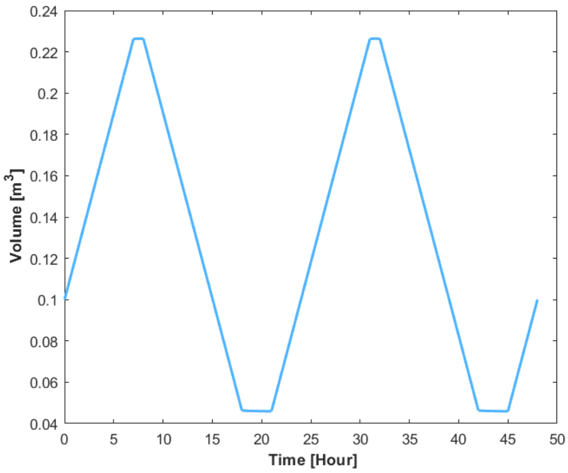

Figure 4.60: Tank water dynamics of the system [318].

Electrical and thermal power output of the PVT system depends on various parameter characteristics. The parameters are mainly internal and external parameters. Comparison between electrical and thermal power output is represented in the figure 4.61.

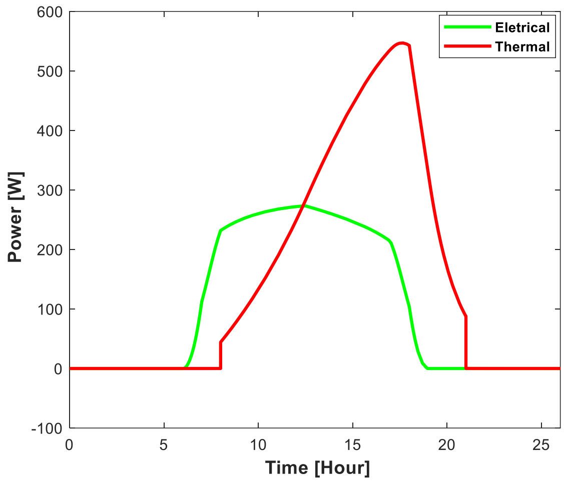

Figure 4.61: Electrical and thermal power comparison for copper pipe [318].

This comparison represents that the thermal power output of the PVT is higher than the electrical power output. Copper as heat exchanger pipe is used here that helps to keep the panel cool resulting in better electrical output and extracting the thermal energy that accumulates thermal power. Active power regime is mainly considered when there is sufficient radiation and thermal extraction. Thermal extraction is dependent on the temperature and water temperature as water absorbs thermal energy from the system. Panel temperature and water temperature difference of the system is provided by the figure 4.62.

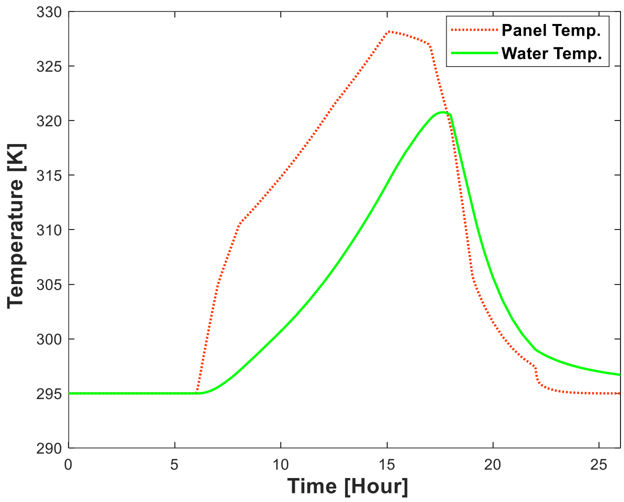

Figure 4.62: Panel temperature and water temperature comparison [318].

In the figure 4.62, panel temperature is represented by the red dotted line and has higher values than the water temperature which is represented by the green line. Panel temperature is represented by the total heat absorption from the surroundings and irradiance. Water temperature is the absorbed thermal energy from the system is also required to obtain its efficiency. This figure 4.62 mainly demonstrates the temperature gain and thermal energy received by the interaction of the panel temperature and the water inside the pipe and storage tank. Useful power of a system is calculated by the difference between input and output power. The comparison of input and output power is provided in the figure 4.63.

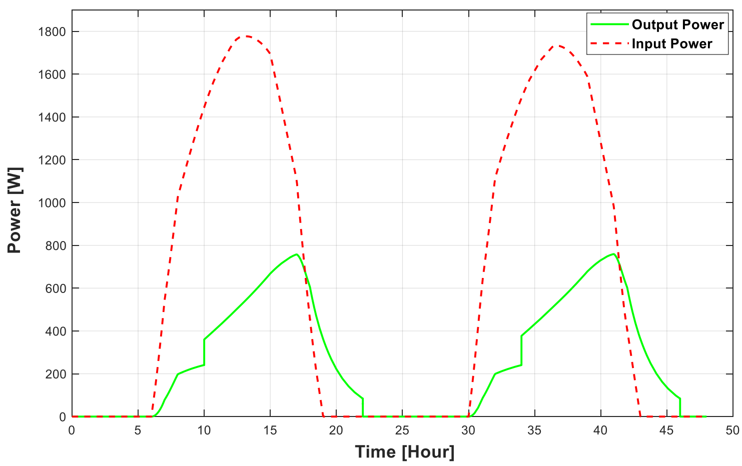

Figure 4.63: Output and input power comparison obtained using copper pipe [318].

This figure 4.63 describes that the value of output power is lower than the value of input power. To increase the system's efficiency, output power should be higher, and it is dependent on significant improvement of the electrical and thermal parameters.

Efficiency Analysis (Copper)

The efficiency of the PVT system is calculated by analyzing the produced electrical and thermal energy in regard to the total input energy. The efficiency table using copper heat exchanger pipe is provided in the table 4.21.

Table 4.21. Efficiency table for copper heat exchanger pipe [318].

Parameter	Value	Unit
Electrical Energy Supplied (2 days)	5.17	kWh
Electrical Energy Supplied (daily)	2.58	kWh
Supplied Thermal Energy (2 days)	19.6	kWh
Used Thermal Energy (daily)	11.92	kWh
Total Used Thermal Energy (2 days)	7.40	kWh
Thermal Energy (daily)	3.85	kWh
Electrical Efficiency	0.17	
Thermal Efficiency	0.25	
Total Efficiency	0.42	

The obtained electrical efficiency of the PVT system while copper is used as heat exchanger pipe is 0.165 and thermal efficiency is 0.246 that results in total efficiency 0.412. The representation of the efficiency analysis is provided in the figure 4.64.

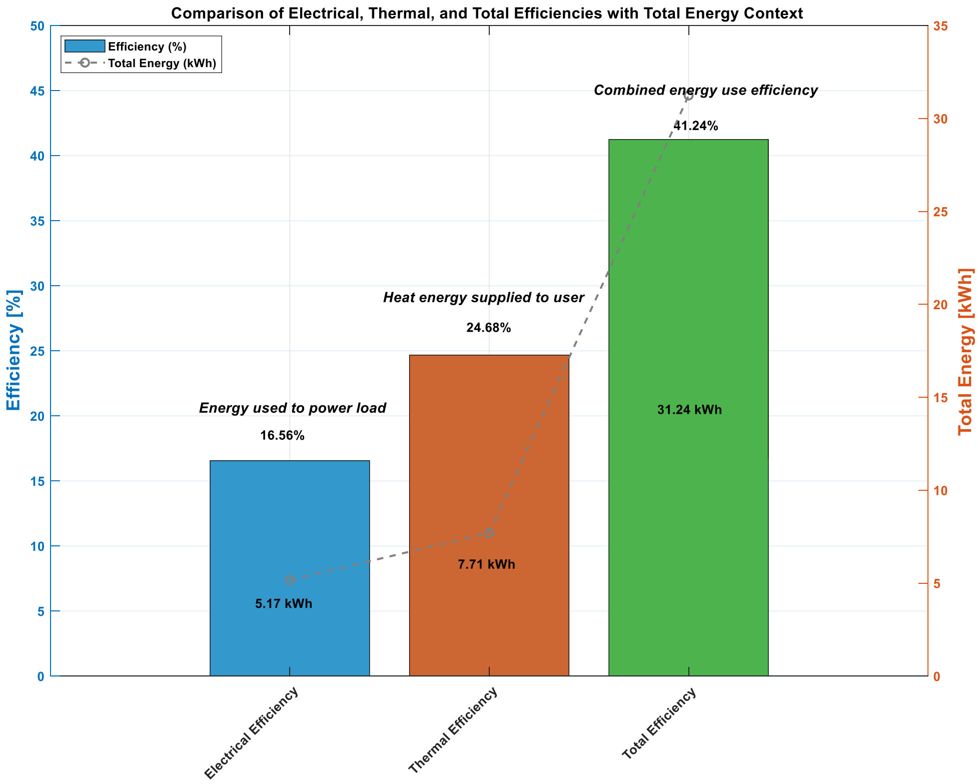

Figure 4.64: Electrical, thermal and total efficiency comparison [318].

Output and Efficiency Comparison

The previous section discusses related output including temperature profile and efficiency analysis for three different heat exchanger pipes. In this section, the comparison of thermal output, electrical output and total output for these three heat exchanger pipes is discussed. It will not only help the research community but also the residential and industrial entities choosing an appropriate heat exchanger pipe for the installation of the PVT system [318].

Electrical & Thermal Efficiency Comparison

Electrical efficiency is calculated by the ratio of the total incident energy and total electrical energy output. From the results it is obtained that electrical power output for steel is 5.16 kWh, for aluminum is 5.16 kWh and for copper is 5.174 kWh. It resulted in electrical efficiency of copper is 16.56%, for aluminum is 16.52% and for stainless steel is 16.53%. The numerical representations are provided by the figure 4.65 [318].

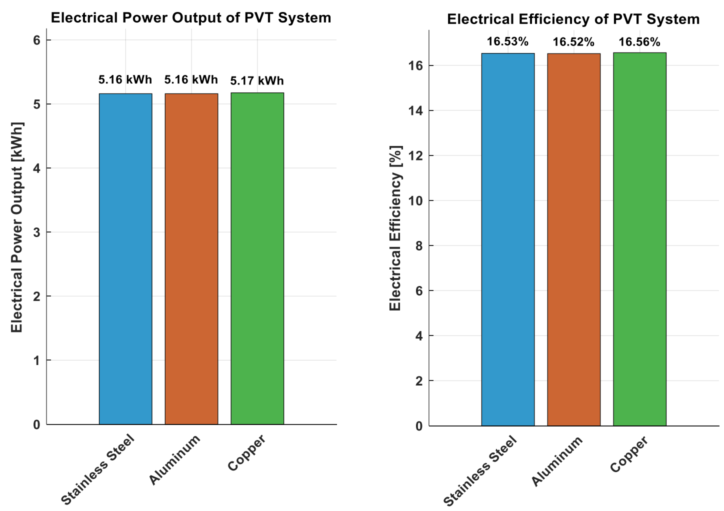

Figure 4.65: Comparison of electrical efficiency [318].

The results show that the electrical efficiency obtained using the copper as heat exchanger pipe is the maximum and electrical efficiency for stainless steel and aluminum is similar to each other and lower than copper. So, in these three heat exchangers pipes the copper provides the better performance while used in the PVT system.

Thermal energy output for copper pipe is 19.629 kWh, for stainless steel is 19.324 kWh and for aluminum is 19.419 kWh. And, obtained thermal efficiency for copper is 24.68%, for stainless steel is 23.70% and for aluminum is 24.01%. Figure 4.66 represents a thermal output comparison obtained from three types of heat exchanger pipe, namely stainless steel, aluminum and copper. The results show that the thermal efficiency of copper is 24.68%, aluminum is 24.01% and stainless steel is 23.70%. The copper has maximum thermal output and the aluminum and then stainless steel [318].

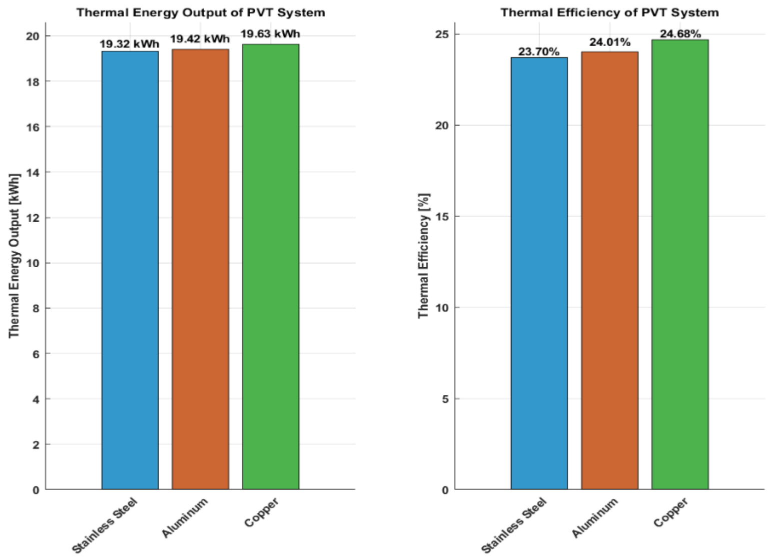

Figure 4.66: Comparison of thermal efficiency [318].

Overall output is obtained by combining electrical and thermal output. It provides an overview of the total performance and energy potential of the system. Total output of the copper heat exchanger pipe is 24.80 kWh, aluminum is 24.58 kWh and for stainless steel is 24.48 kWh. The calculated efficiency of copper is 41.24%, for aluminum it is 40.53% and for stainless steel is 40.23%. A comparison of these three heat exchanger pipes is provided in the figure 4.67.

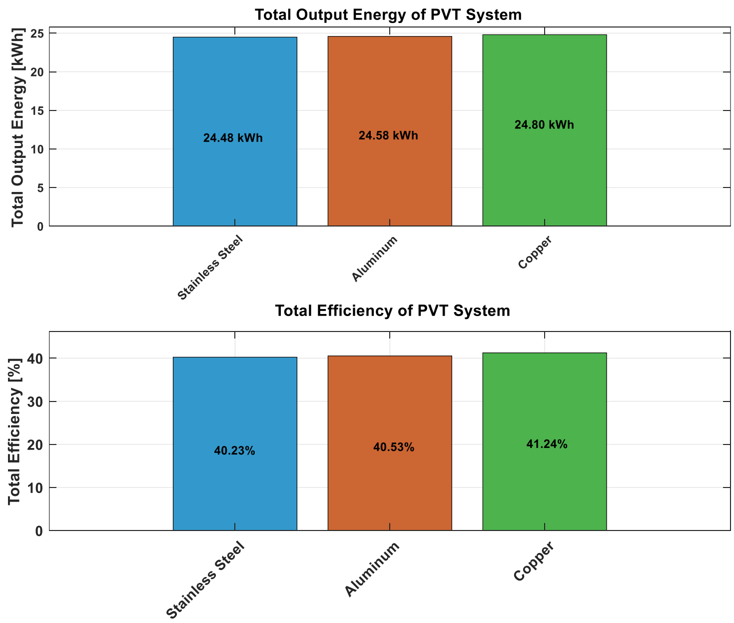

Figure 4.67: Comparison of total efficiency [318].

After analyzing the results, it is observed that copper pipe provides the maximum efficiency and output in comparison to stainless steel and aluminum. Copper has significantly higher thermal conductivity compared to other heat exchanger pipe material. Copper has better thermal conductivity, durability and corrosion resistance. It has also flexibility in shaping, designing and implementing in the hybrid PVT system. Therefore, using copper pipes in the PVT system is recommended over the other two types, although other factors may also need to be considered.

4.5 Non-Iterative MPPT

Non-iterative MPPT algorithm is obtained by root findings method which is already discussed in the previous chapter, additionally flowchart and algorithm are also discussed there. Obtained results and related outputs are discussed in this section. Three different options are considered to track MPP of the PVT module. Firstly, the MPP is obtained considering the points from both sides of the reference, then MPP is obtained considering the points from left side of the reference, finally the MPP is obtained considering the points from the right side of the reference.

In the figure 4.68, MPP is obtained considering four different points from both sides of the reference. The MPP value obtained in simulation is 2.3965 W and the manufacturer provided the value of MPP for this system is 2.3969 W which is very close to each other [296].

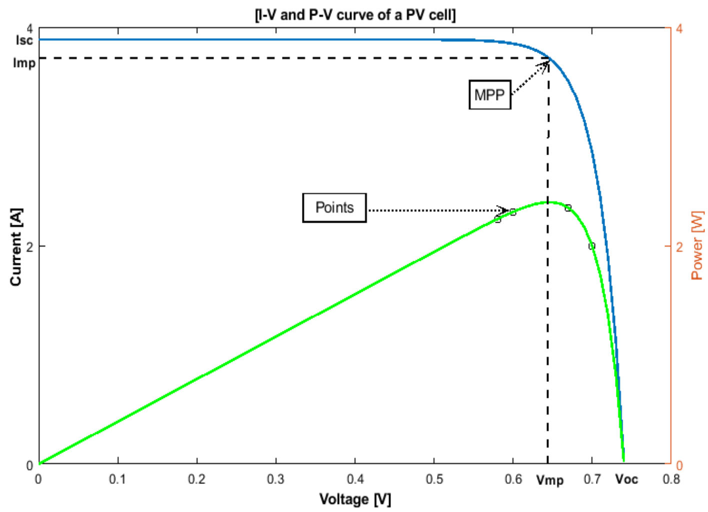

Figure 4.68: MPP determination considering both side points [296].

Figure 4.69 provides the MPP determination using both side points from measured data of a panel. It is also compared and found that for the measured data, the value of MPP given by the manufacturer and obtained using this approximation is similar.

Nex part it is about the discussion of the MPP obtained from left side of the reference point. The main purpose of this method is to obtain MPP by considering these values from the left side of the reference point while ($\frac{dp}{dv} > 0$).

Figure 4.69 provides the MPP determination of the PVT system using left side ($\frac{dp}{dv} > 0$) reference values. By this way, the simulated MPP is obtained as 2.39695 W, and the manufacturer provided the value for MPP is 2.39690 W. By comparing this result, it is found that the MPP value obtained in the simulation using this technique is closer to the given value of the system [296].

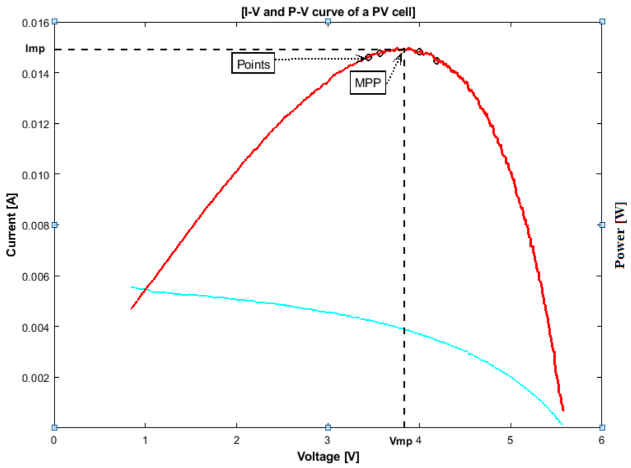

Figure 4.69: MPP determination considering both side points (experimental data) [296].

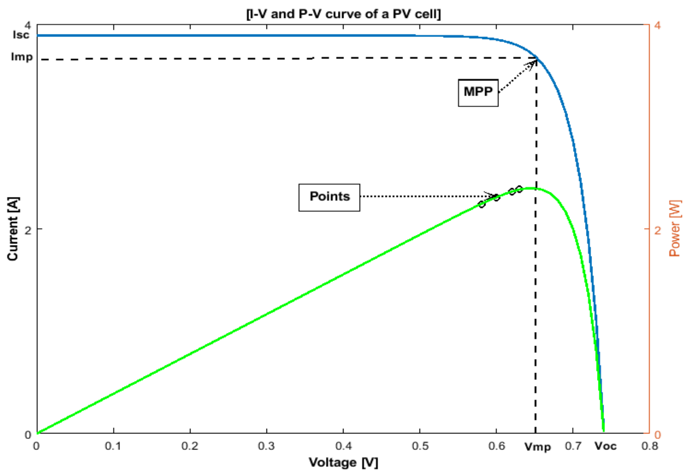

Figure 4.70: MPP determination considering left side points [296].

And MPP is determined by using the left side values from the measured data is shown in the figure 4.71.

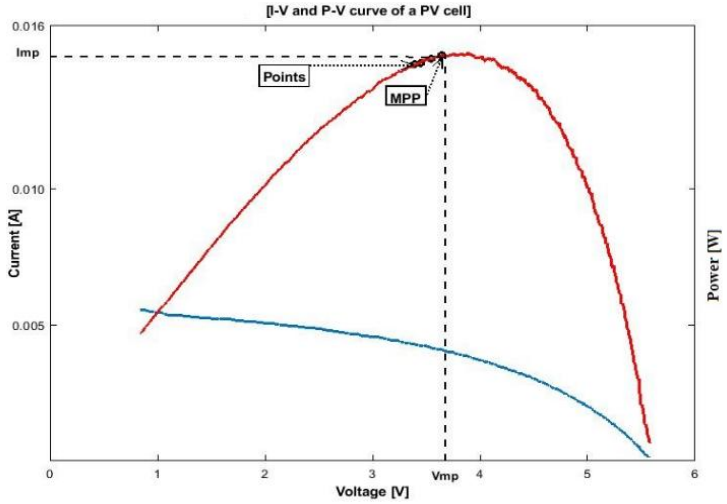

Figure 4.71: MPP determination considering left side points (measured) [296].

The obtained MPP using non-iterative method is closer to the MPP provided by the manufacturer. Figure 4.72 shows the MPP curve obtained using the values from the right side ($\frac{dp}{dv} < 0$) of the reference MPP point. The simulated result for MPP is obtained as 2.3967 W and the value of MPP provided by the manufacturer is 2.3969 is closer to the result obtained here.

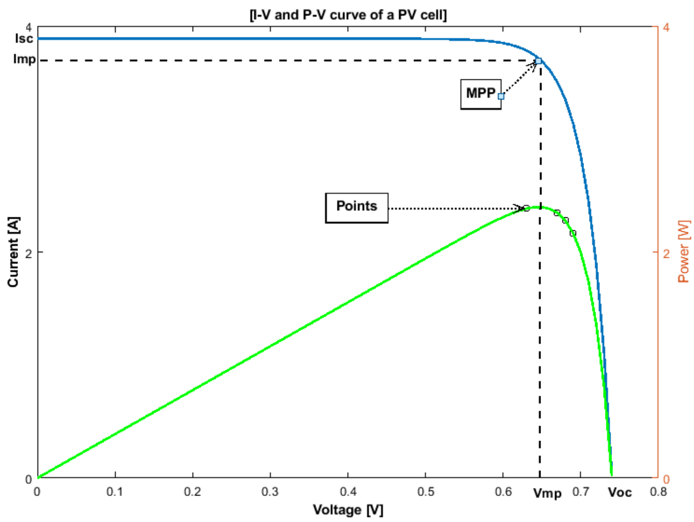

Figure 4.72: MPP determination considering right side points [296].

As same, the right side points method is implemented in the experimental values and is provided in the figure 4.73.

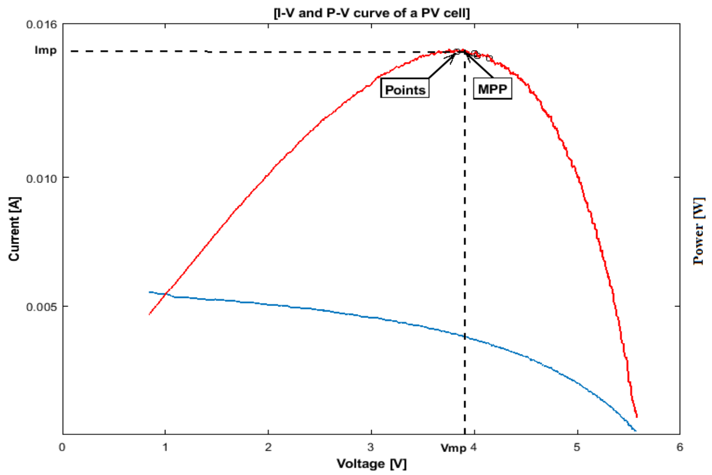

Figure 4.73: MPPT determination considering right side points (measured) [296].

MPPT Comparison

This section provides a comparison of the MPP tracking mechanisms. A conventional method such as perturb & observe (P&O) is used and compared with the non-iterative method. The figure 4.74 provides a comparison of MPP algorithms where for non-iterative method values are chosen from both side of the reference.

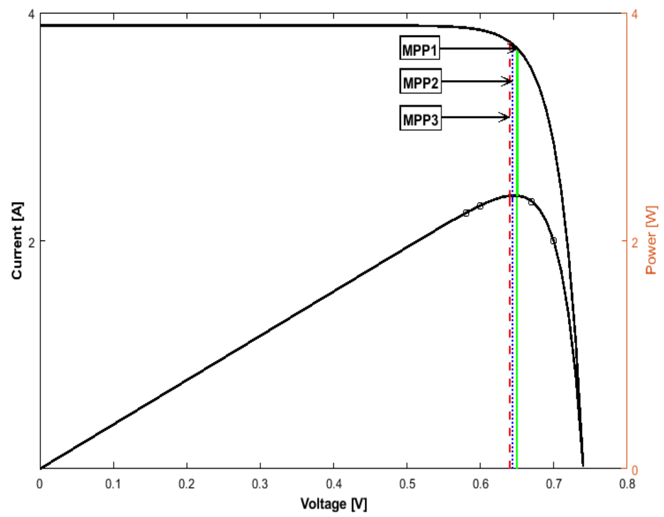

Figure 4.74: MPP comparison considering both side values [296].

In the figure 4.74, MPP1 is the rated value, MPP2 is the value obtained by the non-iterative method and MPP3 is the value obtained by the conventional method. Obtained values (MPP2 = 2.3965 W, MPP3 = 2.3960 W) using both methods are compared with MPP1. The comparison shows that obtained value with non-iterative method is higher than the value obtained using the conventional method [296].

The same method is used in the experimental values of the module that is illustrated in the figure 4.75.

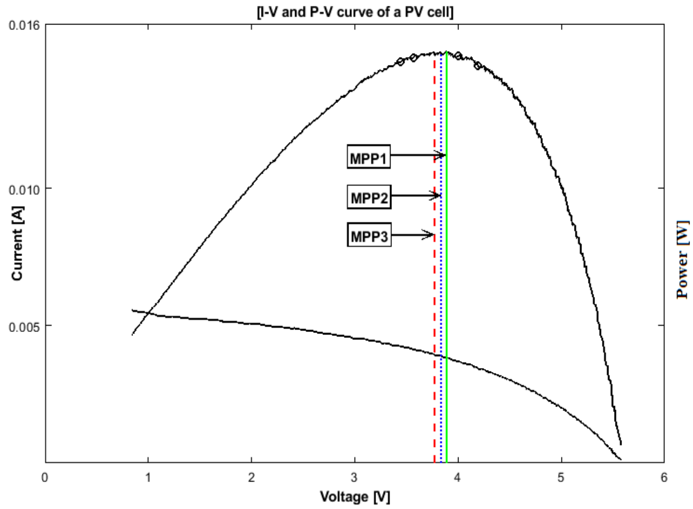

Figure 4.75: MPP comparison considering both side values using experimental data [296].

The comparison also shows that MPP value obtained using non-iterative method is higher than the conventional method.

MPPT comparison is analyzed in the figure 4.76 while proposed MPPT considers the values from the left side ($\frac{dp}{dv} > 0$) of the reference point. MPP1 is the MPP value provided by the manufacturer, MPP2 is obtained using non-iterative method and MPP3 is obtained by using the conventional method. The given value of MPP1 is 2.3969 W, the value for MPP2 is 2.3959 W and for MPP3 the value is 2.3949. The results describe that MPP obtained by the non-iterative method is closer to the rated MPP and is also higher than the MPPT of conventional method.

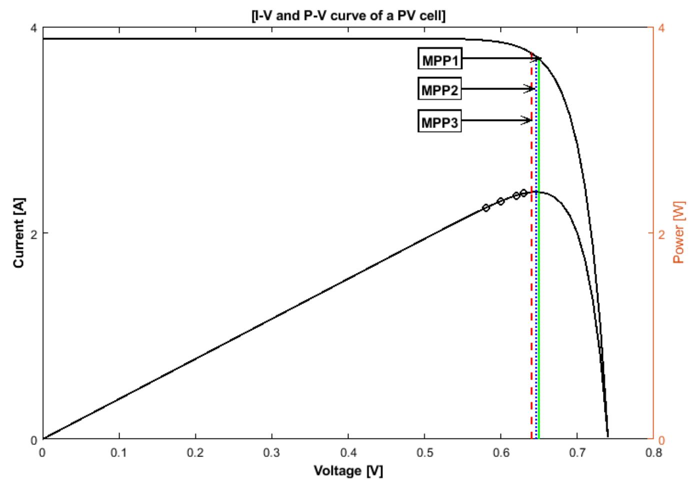

Figure 4.76: MPP comparison considering left side values [296].

Figure 4.77 provides a detailed comparison of MPPT using left side values implemented in the measured values.

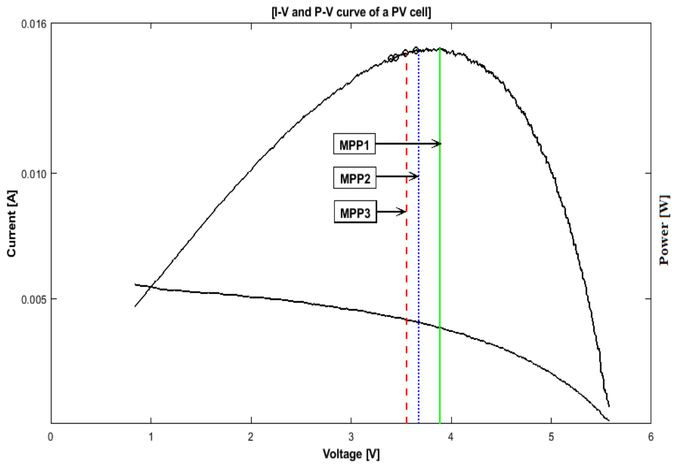

Figure 4.77: MPP comparison considering left side values (measured) [296].

Here, MPP1 is the rated MPP value, MPP2 is the obtained value using proposed non-iterative method and MPP3 is the value obtained using conventional method. The figure 4.77 illustrates that MPP obtained using non-iterative method has higher precision than the iterative method.

The simulated result for the MPPT method comparison using right side values ($\frac{dp}{dv} < 0$) is provided in the figure 4.78.

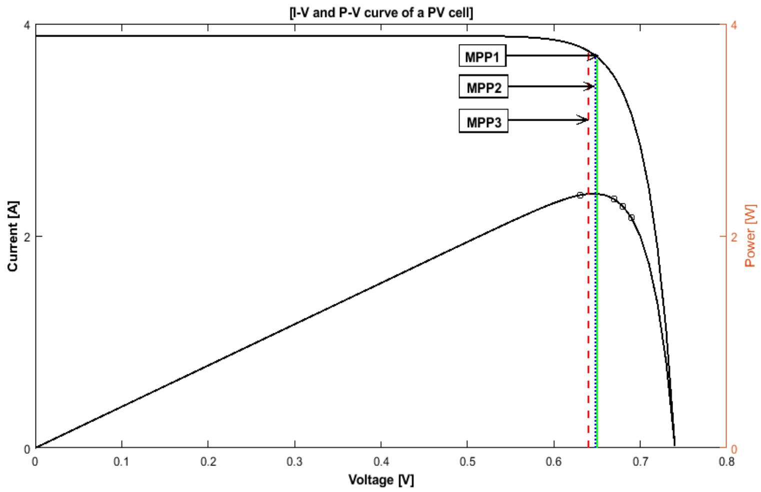

Figure 4.78: MPP comparison considering right side values [296].

Here also, MPP2 is the MPP obtained by non-iterative method, MPP3 is the MPP obtained by the conventional (P&O) method and MPP1 is the given value. The figure 4.78 describes that the MPP obtained using a non-iterative method is closer to the given MPP and higher than the MPP of the conventional method [296].

MPPT comparison using right side values for the experimental data is provided in the figure 4.79.

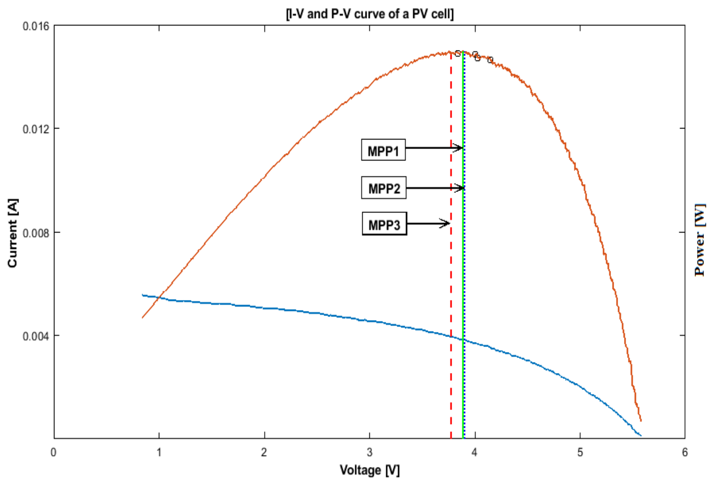

Figure 4.79: MPPT comparison considering right side values (measured) **[257]**.

This figure 4.79 shows that the MPP value (MPP2) obtained using non-iterative method provides better output in comparison to the MPP value (MPP3) obtained conventional method. Additionally, MPP obtained using the proposed method also closer to the rated MPP value.

4.6 Monitoring and Fault Detection of PVT System

Modern energy management system requires continuous monitoring and fault detection mechanisms. Due to the exponential increase in the PV plants continuous monitoring, maintenance and observation is required. Unpredictable weather and non-linear solar cell characteristics complicate fault detection with conventional methods. Monitoring of PVT systems and fault detection can be obtained using IoT systems. Additionally, Integration of artificial intelligence is becoming a common choice to address monitoring and fault detection challenges [319].

An automatic, low-cost virtual monitoring and data acquisition system with fault detection for hybrid PVT system is obtained by an established system of Neural Solar. The system is able to store, monitor and display data of environmental variables and electrical output parameters. Faults are detected by analyzing I-V and P-V curves with stored data. It includes high-precision I/O modular field points, a data acquisition card, and a graphic programming package. Typically, the system's robustness and effectiveness are obtained using a grid simulator. Monitoring of a PV system using IoT is summarized by the figure 4.80 [319].

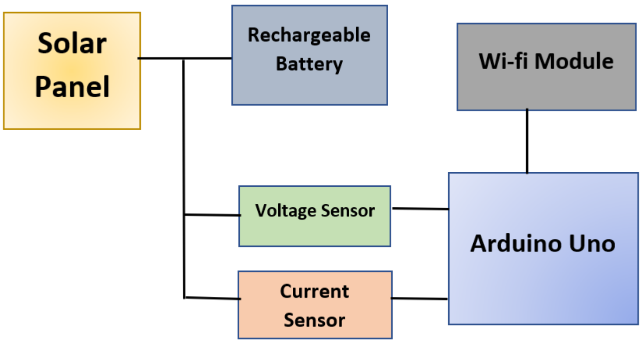

Figure 4.80: IoT based monitoring system.

This monitoring system involves solar panel, rechargeable battery, voltage sensor, current sensor, temperature sensor, a microcontroller system and a Wi-fi module. The converted energy by the solar panels is stored in a rechargeable battery. Voltage and current sensors are used to measure the voltage and current produced by the solar panel. Additionally, temperature sensor measures the temperature of the system. The readings are processed by the microcontroller and sensors are connected to the microcontroller. A Wi-Fi module transmits real-time data from the microcontroller to the ThingSpeak platform. ThingsSpeak platform allows access to real-time data from any internet connected devices [319] .

Mainly power anomaly and temperature anomaly is detected in the preliminary phase of the monitoring that indicates the fault in the system. Power anomaly is provided and summarized by the flowchart shown in the figure 4.81.

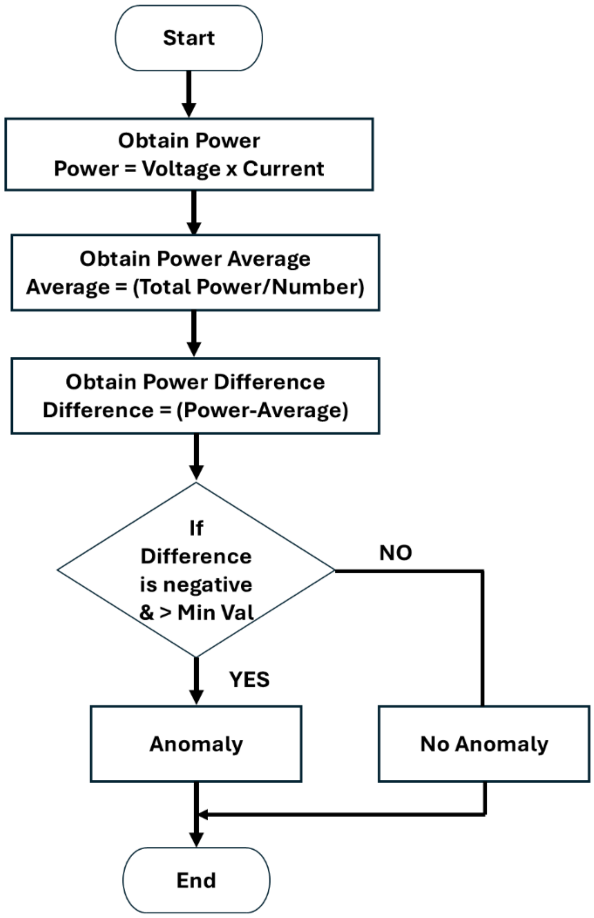

Figure 4.81: Power anomaly detection [319].

Power anomaly or fault in the power generation is provided using a flowchart in the figure 4.81. The first step is obtaining power is calculated using the generated current and voltage from the system. Then, power average is calculated considering total number of panels in series. Power difference is the difference between the power of the reference panel and the average obtained in the previous step. Conditional step checks if the power difference value is negative and greater than the minimum value set by the user. If it fulfills the condition there should be an anomaly in the generation, if not no anomaly is detected.

Temperature anomaly of a photovoltaic system and its operation is summarized by the figure 4.82. First temperature is obtained using temperature sensor from the developed system. Temperature average is obtained using the total temperature of the panels divided by the total number of the panel. Temperature difference is obtained by the obtained temperature of the reference panel and average temperature of the panel. There are two conditions in the temperature anomaly detection system. The first condition verifies if the obtained difference is greater than the minimum difference set by the user. If this condition is true, then there is temperature anomaly detected. If this condition is not true, then it checks for the second condition is to check if the panel temperature is greater than the maximum temperature set by the system. If it satisfies the condition then temperature anomaly is detected, if not then there is no anomaly detected [319].

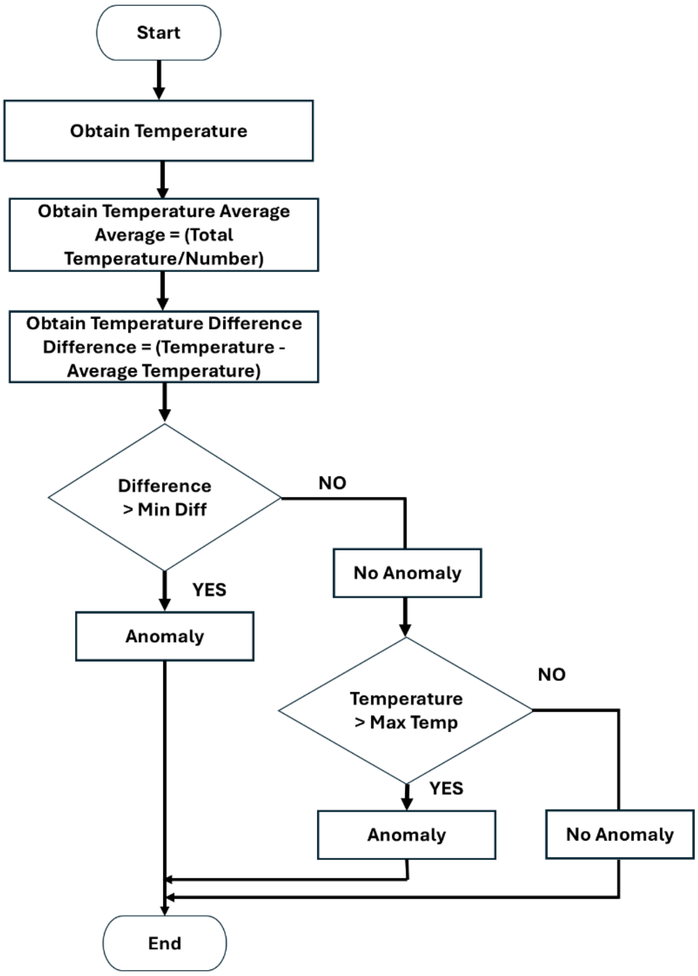

Figure 4.82: Temperature anomaly detection [319].

The experimental output is provided in this section that describes overall anomaly detection of the system. The output obtained by the system is provided in the figure 4.83.

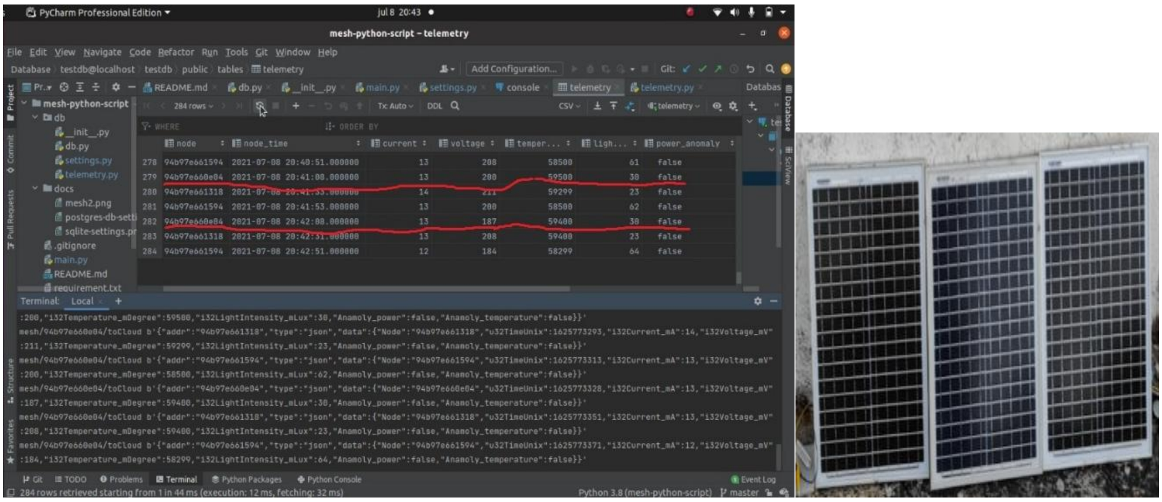

Figure 4.83: Power anomaly detection (phase 1) [319].

In the first phase of the test, it shows that power anomaly detection is false as there is no shading, no obstruction appears that reduces the power output of the system. Three panels (20 watts) are used in series to obtain and execute the experimental procedure. The second phase of the test and its output is shown in the figure 4.84.

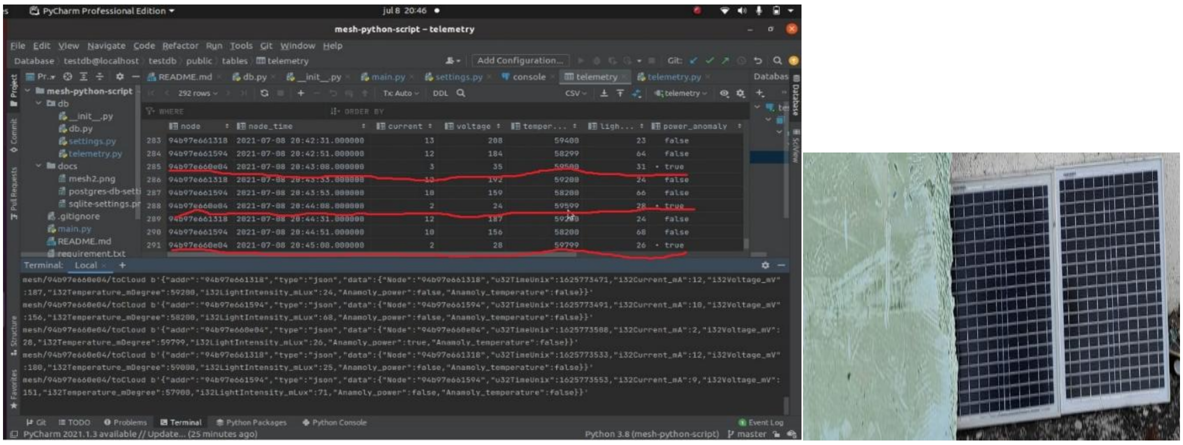

Figure 4.84: Power anomaly detection (phase 2) [319].

In the second phase of the experimental test, we added an obstacle to one of the panels. The purpose is to identify if there is any anomaly in the system. As we can see from the figure, the output is highlighted in red which shows anomaly as ‘true’. It means that the algorithm identified the fault/power abnormality due to the inclusion of an obstacle. The third phase of the experiment using this method is provided in the figure 4.85.

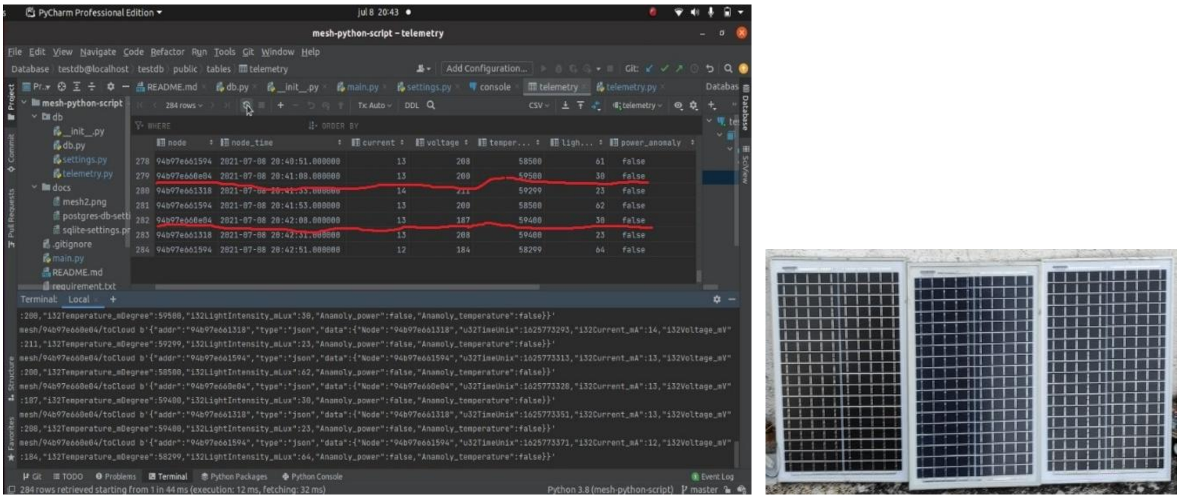

Figure 4.85: Power anomaly detection (phase 3) [319].

Again, in the third phase of the experiment the obstacle was removed, and the algorithm was implemented to see if the anomaly still exists. The result shows that there is no anomaly in the output.

This provided section described the output and fault monitoring system that will enable us to develop and establish an efficient energy management system.

Chapter 5

Conclusions

Climate change and its global impacts are driven by the excessive use of fossil fuels on a massive scale. The purpose of integrating and improving solar energy technology in the existing energy generation system is to reduce carbon emission and provide a pollution free environment. The objective of this work is to develop, improve and establish an energy efficient, innovative, low-cost and technologically advanced hybrid photovoltaic thermal system. Additionally, it will also contribute to and optimize economic development and industrialization of the solar energy sector. In this motivation, it is studied, analyzed and discussed the possible modeling including technological investigation and outcomes of the hybrid PVT system.

Design configurations and structural analysis provide the perspective regarding the related components of the PVT system. An analysis of solar system classification is conducted and obtained results are discussed. This provides insights into the existing types, classes and specifications of hybrid PVT system. Mathematical model of electrical equivalent circuit and its parameters of this system are the key factor to studying and analyzing this system. The factors related to PV panel efficiency are also discussed in this work that helps to choose appropriate parameters. Temperature analysis shows the possible drawbacks of existing PV system. Additionally, discussed temperature loss models identify the potential for effective utilization of temperature in the form of thermal energy. Various cooling methods can also be employed to mitigate the effects of excessive temperature on the PV module. A detailed study on the classification of PVT systems based on ongoing literature provides a comprehensive overview of the existing hybrid PVT system. The proposed innovative and effective classification presented in this work will enhance the selection of optimal parameters for the hybrid PVT system. Additionally, it discussed the challenges associated with selecting the appropriate design structure and parametric evaluation also need to be considered. The developed classification model based on parametric analysis and optimization highlights significant parameters related to performance and efficiency improvement of the hybrid PVT system.

An introduction to PVT system provides the idea regarding its formulation, key parameters, interrelations between PV and PVT systems in multiple perspectives, structural overview and involved thermal management mechanisms are incorporated to evaluate preliminary performance. Design overview and structural parameters orientation analysis including flow of heat transfer fluids of various types of PVT system are also provided in this work. It includes different types and shape of heat transfer pipe, and kinds of heat transfer fluid that contribute to choosing an appropriate design, structure and fluid for the hybrid PVT system. A brief discussion on PVT system's application, feasibility and effectiveness is the motivation for research on this topic. PVT systems modeling is the primary focus of this research work that represents both electrical and thermal system in the aspects of mathematical formulation. It also incorporates operation and performance analysis depending on the performed activities during operation of both the upper and lower section. PVT system layout provides the physical phenomena of the proposed innovative system. Mathematical model for performance analysis is also obtained in this work that discusses the output concept of the system. An enhanced mathematical model of electrical and thermal system is studied, analyzed and considered in this work. Electrical model of the electrical equivalent circuit of the photovoltaic part, electrical equivalent thermal loss model is also analyzed that is used to simulate the equivalent electrical and thermal output of the system. Analysis of parameters effect and sensitivity study of the hybrid PVT system provides characteristics and performance overview. Modeling and study of several MPPT methods are also discussed and provided in this work. A developed low-cost monitoring & fault detection system with existing challenges is also discussed in this research.

Parameters and sensitivity study is very crucial in the context of analyzing the optimal output of the PVT system. The impact of different parameters has different level of output variation. Various internal and external parameters are studied, and their sensitivity analysis is observed. The efficiency relation of these parameters change is also discussed in this thesis. Irradiance and temperature have the most significant impact on the overall performance of the proposed PVT system. Additionally, other external parameters like wind speed and humidity are also considered where the internal parameters for both electrical and thermal model is also evaluated. Results obtained from the thermal loss equivalent model also show effective outcome and increased efficiency from the system. A developed mathematical and simulation model is presented in this thesis that evaluates the overall output and enhancements of the hybrid PVT system. Three types of heat exchanger pipe for the proposed PVT system, namely stainless steel, aluminum and copper are simulated and obtained results are studied. The results include irradiance profile, temperature dynamics of various components, electrical and thermal output assessment and finally total efficiency comparison. A non-iterative MPPT method is also developed and compared with the existing iterative method that demonstrates promising results in terms of efficiency and performance.

In conclusion the author aims to emphasize that this thesis will contribute to the modeling, development and performance optimization of the hybrid PVT system. Additionally, it will also contribute to modernization and digitalization of the hybrid PVT system through monitoring, fault identification and the development of a robust system. A brief experimental work is going on in this model for the enhancement purpose. It will help with the parameter extraction from measurement and experiment data. The development of a portable plug & play system for commercial use after patent request is also expected to be accomplished.

References

1. Kalogirou, S.A. *Solar Energy Engineering: Processes and Systems*; Elsevier: Amsterdam, The Netherlands, 2023.
2. Halmann, M.M.; Steinberg, M. *Greenhouse Gas Carbon Dioxide Mitigation: Science and Technology*; CRC Press: Boca Raton, FL, USA, 1998.
3. Lashof, D.A.; Ahuja, D.R. Relative Contributions of Greenhouse Gas Emissions to Global Warming. *Nature* 1990, *344*, 529.
4. Colombo, U. Development and the Global Environment. In Hollander, J.M. (Ed.), *The Energy-Environment Connection*; Island Press: Washington, DC, USA, 1992; pp. 3–14.
5. NASA. Global Temperature. Available online: https://climate.nasa.gov/vital-signs/global-temperature/?intent=121 (accessed on *20th February 2025*).
6. Tester, J.W.; Drake, E.M.; Driscoll, M.J.; Golay, M.W.; Peters, W.A. *Sustainable Energy: Choosing Among Options*, 2nd ed.; The MIT Press: Cambridge, Massachusetts, London, England, 2012.
7. Falope, T.; Lao, L.; Hanak, D.; Huo, D. Hybrid energy system integration and management for solar energy: A review. *J. Clean. Prod.* 2025, *245*, 118694.
8. Bollen, M.H.J.; Moreno-Munoz, A. The Power Grid as Part of a 100% Renewable Energy System. *In* Moreno-Munoz, A. (Ed.) *Large Scale Grid Integration of Renewable Energy Sources*; Institution of Engineering and Technology: 2017; pp. 1–27.
9. Das, U.K.; Tey, K.S.; Seyedmahmoudian, M.; Mekhilef, S.; Idris, M.Y.I.; van Deventer, W.; et al. Forecasting of Photovoltaic Power Generation and Model Optimization: A Review. *Renew. Sustain. Energy Rev. 2018*, *81*, 912–928.
10. Yao, X.; Yi, B.; Yu, Y.; Fan, Y.; Zhu, L. Economic Analysis of Grid Integration of Variable Solar and Wind Power with Conventional Power System. *Appl. Energy 2020*, *264*, 114706.
11. Bollen, M.H.J.; Moreno-Munoz, A. The Power Grid as Part of a 100% Renewable Energy System. *In* Moreno-Munoz, A. (Ed.) *Large Scale Grid Integration of Renewable Energy Sources*; Institution of Engineering and Technology: 2017; pp. 1–27.
12. Hoeven, M.J.I.E.A. Solar Thermal Electricity–Technology Roadmap; International Energy Agency: Paris, France, 2014; pp. 1–52.
13. Solargis. Solar Resource Map © 2021. Available online: https://solargis.com (accessed on 5 February 2025).
14. Pourasl, H.H.; Vatankhah Barenji, R.; Khojastehnezhad, V.M. Solar Energy Status in the World: A Comprehensive Review. *Energy Reports* 2023, *10*, 3474–3493.
15. Bahrami, M.; Gavagsaz-Ghoachani, R.; Zandi, M.; Pharranasak, M.; Maranazanaa, G.; Nahid-Mobarakeh, B.; Pierfederici, S.; Meibody-Tabar, F. Hybrid maximum power point tracking algorithm with improved dynamic performance. *Renew. Energy* 2019, *130*, 982–991.
16. Abbassi, R.; Abbassi, A.; Jemli, M.; Chebbi, S. Identification of unknown parameters of solar cell models: A comprehensive overview of available approaches. *Renew. Sustain. Energy Rev.* 2018, *90*, 453–474.
17. Herez, A.; El Hage, H.; Lemenand, T.; Ramadan, M.; Khaled, M. Review on Photovoltaic/Thermal Hybrid Solar Collectors: Classifications, Applications and New Systems. *Solar Energy* 2020, *207*, 1321–1347.
18. Lamnatou, C.; Chemisana, D. Photovoltaic/Thermal (PVT) Systems: A Review with Emphasis on Environmental Issues. *Renewable Energy* 2017, *105*, 270–287.
19. Da Silva, R.M.; Fernandes, J.L.M. Hybrid Photovoltaic/Thermal (PV/T) Solar Systems Simulation with Simulink/Matlab. *Solar Energy* 2010, *84*, 1985–1996.
20. Mattia, D.R.; Giorgio, R.; Cecilia, R.; Federico, S.; Luca, A.T. Dynamic Thermal Model for Hybrid Photovoltaic Panels. *Energy Procedia* 2015, *81*, 345–353.
21. Good, C. Environmental Impact Assessments of Hybrid Photovoltaic-Thermal (PV/T) Systems—A Review. *Renew. Sustain. Energy Rev.* 2016, *55*, 234–239.

22. Herrando, M.; Markides, C.N. Hybrid PV and Solar-Thermal Systems for Domestic Heat and Power Provision in the UK: Techno-Economic Considerations. *Appl. Energy* 2015, *161*, 512–532.
23. Moshksar, E.; Ghanbari, T. A Model-Based Algorithm for Maximum Power Point Tracking of PV Systems Using Exact Analytical Solution of Single-Diode Equivalent Model. *Solar Energy* **2018**, *162*, 117–131.
24. Zhang, F.; Maddy, J.; Premier, G.; Guwy, A. Novel Current Sensing Photovoltaic Maximum Power Point Tracking Based on Sliding Mode Control Strategy. *Solar Energy* 2015, *118*, 80–86.
25. Eldahab, Y.E.A.; Saad, N.H.; Zekry, A. Enhancing the Maximum Power Point Tracking Techniques for Photovoltaic Systems. *Renew. Sustain. Energy Rev.* 2014, *40*, 505–514.
26. Jiang, L.L.; Srivatsan, R.; Maskell, D.L. Computational Intelligence Techniques for Maximum Power Point Tracking in PV Systems: A Review. *Renew. Sustain. Energy Rev.* 2018, *85*, 14–45.
27. Abdel-Salam, M.; El-Mohandes, M.-T.; Goda, M. An Improved Perturb-and-Observe Based MPPT Method for PV Systems under Varying Irradiation Levels. *Solar Energy* 2018, *171*, 547–561.
28. Husain, M.A.; Tariq, A.; Hameed, S.; Arif, M.S.B.; Jain, A. Comparative Assessment of Maximum Power Point Tracking Procedures for Photovoltaic Systems. *Green Energy Environ.* 2017, *2*, 5–17.
29. Ahmed, M.T.; Gonçalves, T.; Tlemcani, M. Real-Time Estimation of MPPT with Non-Iterative Algorithm. In Proceedings of the *International Conference on Advanced Materials for Photonics, Sensing and Energy Applications (AMPSECA' 2017)*, Agadir, Morocco, 28–30 March 2017.
30. Bankupalli, P.T.; Ghosh, S.; Kumar, L.; Samanta, S.; Dixit, T.V. A Non-Iterative Approach for Maximum Power Extraction from PEM Fuel Cell Using Resistance Estimation. *Energy Convers. Manag.* 2019, *187*, 565–577.
31. Askarian, A.; Baranwal, M.; Salapaka, S. DC Bus Voltage Regulation Using Photovoltaic Module: A Non-Iterative Method. In Proceedings of the *American Control Conference (ACC)*, Seattle, WA, USA, 24–26 May 2017; pp. 4099–4104.
32. Obbadi, A.; Errami, Y.; Elfajri, A.; Agunaou, M.; Benhmida, M.; Sahnoun, S. Photovoltaic (PV) Parameter Estimation of a Multicrystalline Panel Using Developed Iterative and Non-Iterative Methods. In Proceedings of the *3rd International Renewable and Sustainable Energy Conference (IRSEC)*, Marrakech, Morocco, 10–13 December 2015; pp. 1–6.
33. Cristaldi, L.; Faifer, M.; Rossi, M.; Toscani, S.; Catelani, M.; Ciani, L.; Lazzaroni, M. Simplified Method for Evaluating the Effects of Dust and Aging on Photovoltaic Panels. *Measurement* 2014, *54*, 207–214.
34. Toivola, M.; Halme, J.; Peltokorpi, L.; Lund, P. Investigation of Temperature and Aging Effects in Nanostructured Dye Solar Cells Studied by Electrochemical Impedance Spectroscopy. *Int. J. Photoenergy* 2009, *2009*, 15.
35. Zhu, H.; Lu, L.; Yao, J.; Dai, S.; Hu, Y. Fault Diagnosis Approach for Photovoltaic Arrays Based on Unsupervised Sample Clustering and Probabilistic Neural Network Model. *Sol. Energy* 2018, *176*, 395–405.
36. Harrou, F.; Sun, Y.; Taghezouit, B.; Saidi, A.; Hamlati, M.E. Reliable Fault Detection and Diagnosis of Photovoltaic Systems Based on Statistical Monitoring Approaches. *Renew. Energy* 2018, *116*, 22–37.
37. Rouibah, N.; Barazane, L.; Mellit, A. A Low-Cost Monitoring System for Maximum Power Point of a Photovoltaic System Using IoT Technique. In Proceedings of the *International Conference of Wireless Technologies, Embedded and Intelligent System*, Fez, Morocco, 3–4 April 2019; pp. 1–5.

38. Fuentes, M.; Vivar, M.; Burgos, J.M.; Aguilera, J.; Vacas, J.A. Design of an Accurate Low-Cost Autonomous Data Logger for PV System Monitoring Using Arduino That Complies with IEC Standards. *Sol. Energy Mater. Sol. Cells* 2014, *130*, 529–543.
39. Hammoumi, A.E.; Motahhir, S.; Chalh, A.; Ghzizal, A.E.; Derouich, A. Low-Cost Virtual Instrumentation of PV Panel Characteristics Using Excel and Arduino in Comparison with Traditional Instrumentation. *Renewables Wind Water Sol.* 2018, *5*, 3.
40. Young, C.; Thelen, J.; Nehrir, H. Design and Implementation of a Low-Cost Solar Photovoltaic Experimental Station for Education Enhancement. In Proceedings of the *North American Power Symposium (NAPS)*, Pullman, WA, USA, 7–9 September 2014; pp. 1–5.
41. Kumar, G.V.B.; Kaliannan, P.; Padmanaban, S.; Holm-Nielson, J.B.; Blaabjerg, F. Effective Management System for Solar PV Using Real-Time Data with Hybrid Energy Storage System. *Appl. Sci.* 2020, *10*, 3.
42. Aktas, A.; Kircicek, Y. *Solar Hybrid Systems: Design and Application*; Academic Press: Cambridge, MA, USA, 2021.
43. Khatib, T.; Mohamed, A.; Sopian, K. A review of solar energy modeling techniques. *Renew. Sustain. Energy Rev.* 2012, *16*, 2864–2869.
44. Kreider, J.F.; Kreith, F. *Solar Heating and Cooling: Active and Passive Design*; CRC Press: Boca Raton, FL, USA, 1982.
45. Ångström, A. Computation of Global Radiation from Records of Sunshine. *Ark. Geofys.* 1956, *2*.
46. Benson, R.; Paris, M.; Sherry, J.; Justus, C. Estimation of Daily and Monthly Direct, Diffuse and Global Solar Radiation from Sunshine Duration Measurements. *Sol. Energy* 1984, *32*, 523–535.
47. Collares-Pereira, M.; Rabl, A. The Average Distribution of Solar Radiation: Correlations Between Diffuse and Hemispherical and Between Daily and Hourly Insolation Values. *Sol. Energy* 1979, *22*, 155–164.
48. Al-Ezzi, A.S.; Ansari, M.N.M. Photovoltaic Solar Cells: A Review. *Appl. Syst. Innov.* 2022, *5*, 67.
49. Zhang, C. High Efficiency GaAs-Based Solar Cells Simulation and Fabrication; Arizona State University: 2014.
50. Barker, P.P.; Bing, J.M. Advances in Solar Photovoltaic Technology: An Applications Perspective. *In* Proceedings of the IEEE Power Engineering Society General Meeting, San Francisco, CA, USA, 12–16 June 2005; IEEE: Piscataway, NJ, USA, 2005; pp. 1955–1960.
51. Green, M.A. Photovoltaic Principles. *Physica E: Low-Dimensional Systems and Nanostructures* 2002, *14*, 11–17.
52. Kannan, N.; Vakeesan, D. Solar Energy for Future World: A Review. *Renewable and Sustainable Energy Reviews* 2016, *62*, 1092–1105.
53. Ahmed, M.T.; Rashel, M.R.; Islam, M.; Islam, A.K.; Tlemcani, M. Classification and Parametric Analysis of Solar Hybrid PVT System: A Review. *Energies* 2024, *17*, 588.
54. Schindler, F.; Michl, B.; Krenckel, P.; Riepe, S.; Benick, J.; Muller, R.; Richter, A.; Glunz, S.W.; Schubert, M.C. How to achieve efficiencies exceeding 22% with multi-crystalline n-type silicon solar cells. *Energy Procedia* 2017, 124, 777–780.
55. Tiwari, G.N.; Mishra, R.K.; Solanki, S.C. Photovoltaic modules and their applications: A review on thermal modelling. *Appl. Energy* 2011, 88, 2287–2304.
56. Debberma, M.; Sudhakar, K.; Baredar, P. Thermal modeling, exergy analysis, performance of BIPV and BIPVT: A review. *Renew. Sustain. Energy Rev.* 2017, 73, 1276–1288.
57. Xie, K.; Guo, M.; Liu, X.; Huang, H. Enhanced efficiencies in thin and semi-transparent dye-sensitized solar cells under low photon flux conditions using TiO2 nanotube photonic crystal. *J. Power Source* 2015, 293, 170–177.
58. Shaikh, J.S.; Shaikh, N.S.; Sheikh, A.D.; Mali, S.S.; Kale, A.J.; Kanjanaboos, P.; Patil, P.S. Perovskite Solar Cells: In Pursuit of Efficiency and Stability. *Mater. Des.* 2017, 136, 54–80.
59. Leva, S.; Dolara, A.; Grimaccia, F.; Mussetta, M.; Ogliari, E. Analysis and Validation of 24 Hours Ahead Neural Network Forecasting of Photovoltaic Output Power. *Math. Comput. Simul.* 2017, *131*, 88–100.

60. Chaichan, M.T.; Kazem, H.A. Experimental analysis of solar intensity on PV in hot and humid weather conditions. *Int. J. Sci. Eng. Res.* 2016, 7, 91–96.
61. Diwania, S.; Agrawal, S.; Siddiqui, A.S.; Singh, S. Photovoltaic–thermal (PV/T) technology: A comprehensive review on applications and its advancement. Int. J. Energy Environ. Eng. 2020, 11, 33–54.
62. Kaundinya, D.P.; Balachandra, P.; Ravindranath, N.H. Grid-Connected versus Stand-Alone Energy Systems for Decentralized Power—A Review of Literature. *Renew. Sustain. Energy Rev.* 2009, *13*, 2041–2050.
63. Kumar, N.M.; Subathra, M.P.; Moses, J.E. On-Grid Solar Photovoltaic System: Components, Design Considerations, and Case Study. *Proceedings of the 2018 4th International Conference on Electrical Energy Systems (ICEES)*, Chennai, India, 7–9 February 2018; IEEE, pp. 616–619.
64. Orioli, A.; Di Gangi, A. A Procedure to Evaluate the Seven Parameters of the Two-Diode Model for Photovoltaic Modules. *Renewable Energy* 2019, *139*, 582–599.
65. Ayeng'o, S.P.; Axelsen, H.; Haberschusz, D.; Sauer, D.U. A Model for Direct-Coupled PV Systems with Batteries Depending on Solar Radiation, Temperature, and Number of Serially Connected PV Cells. *Sol. Energy* 2019, *183*, 120–131.
66. Nayak, B.; Mohapatra, A.; Mohanty, K.B. Parameter Estimation of Single Diode PV Module Based on GWO Algorithm. *Renew. Energy Focus* 2019, *30*, 1–12.
67. Humada, A.M.; Darweesh, S.Y.; Mohammed, K.G.; Kamil, M.; Mohammed, S.F.; Kasim, N.K.; Mekhilef, S. Modeling of PV System and Parameter Extraction Based on Experimental Data: Review and Investigation. *Sol. Energy* 2020, *199*, 742–760.
68. Ahmed, M. T. Modelization and Characterization of Photovoltaic Panels. Master's Thesis, Universidade de Évora, Évora, Portugal, 2017.
69. Dolara, A.; Leva, S.; Manzolini, G. Comparison of Different Physical Models for PV Power Output Prediction. *Sol. Energy* 2015, *119*, 83–99.
70. Chan, D.S.; Phang, J.C. Analytical methods for the extraction of solar-cell single-and double-diode model parameters from IV characteristics. *IEEE Transactions on Electron Devices* 1987, *34*, 286–293.
71. Pranahita, B.S.; Kumar, A.S.; Babu, A.P. A Study on Modelling and Simulation of Photovoltaic Cells. *Int. J. Res. Eng. Technol.* 2014, *3*, 2319–1163.
72. Gow, J.A.; Manning, C.D. Development of a Photovoltaic Array Model for Use in Power-Electronics Simulation Studies. *IEE Proc.-Electr. Power Appl.* 1999, *146*, 193–200.
73. Rashel, M.R. Modeling Photovoltaic Panels under Variable Internal and Environmental Conditions with Non-Constant Load. Ph.D. Thesis, Universidade de Évora, Évora, Portugal, 2018.
74. Tian, H.; Mancilla-David, F.; Ellis, K.; Muljadi, E.; Jenkins, P. Detailed Performance Model for Photovoltaic Systems; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2012; No. NREL/JA-5500-54601.
75. De Soto, W.; Klein, S.A.; Beckman, W.A. Improvement and Validation of a Model for Photovoltaic Array Performance. *Sol. Energy* 2006, *80*, 78–88.
76. Ahmed, M.T.; Gonçalves, T.; Tlemcani, M. Single Diode Model Parameters Analysis of Photovoltaic Cell. In *Proceedings of the 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*; IEEE: 2016; pp. 396–400.
77. Dewi, T.; Risma, P.; Oktarina, Y. A Review of Factors Affecting the Efficiency and Output of a PV System Applied in Tropical Climate. *IOP Conf. Ser. Earth Environ. Sci.* 2019, *258*, 012039.
78. Hasan, K.; Yousuf, S. B.; Tushar, M. S. H. K.; Das, B. K.; Das, P.; Islam, M. S. Effects of Different Environmental and Operational Factors on the PV Performance: A Comprehensive Review. *Energy Sci. Eng.* 2022, *10*(2), 656–675.
79. Rahman, M.M.; Hasanuzzaman, M.; Abd Rahim, N. Effects of Operational Conditions on the Energy Efficiency of Photovoltaic Modules Operating in Malaysia. *J. Clean. Prod.* 2017, *143*, 912–924.
80. Dubey, S.; Sarvaiya, J.N.; Seshadri, B. Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World—A Review. *Energy Procedia* 2013, *33*, 311–321.

81. Moretón, R.; Lorenzo, E.; Pinto, A.; Muñoz, J.; Narvarte, L. From Broadband Horizontal to Effective In-Plane Irradiation: A Review of Modelling and Derived Uncertainty for PV Yield Prediction. *Renew. Sustain. Energy Rev.* 2017, *78*, 886–903.
82. Abiola-Ogedengbe, A.; Hangan, H.; Siddiqui, K. Experimental Investigation of Wind Effects on a Standalone Photovoltaic (PV) Module. *Renew. Energy* 2015, *78*, 657–665.
83. Said, S.A.M.; Hassan, G.; Walwil, H.M.; Al-Aqeeli, N. The Effect of Environmental Factors and Dust Accumulation on Photovoltaic Modules and Dust-Accumulation Mitigation Strategies. *Renew. Sustain. Energy Rev.* 2018, *82*, 743–760.
84. Rajput, P.; Sastry, O.S.; Tiwari, G.N. Effect of Irradiance, Temperature Exposure, and an Arrhenius Approach to Estimating Weathering Acceleration Factor of Glass, EVA, and Tedlar in a Composite Climate of India. *Sol. Energy* 2017, *144*, 267–277.
85. Sun, C.; Zou, Y.; Qin, C.; Zhang, B.; Wu, X. Temperature Effect of Photovoltaic Cells: A Review. *Adv. Compos. Hybrid Mater.* 2022, *5*, 2675–2699.
86. Ahmed, H.; Elshabasi, M.; Ohland, J.; Stölzel, M.; Weber, A.; Lechner, R.; & Heise, S. J. Temperature Coefficient Characterization of CIGSSe Solar Cells with Layer Modifications. *Sol. Energy Mater. Sol. Cells* 2021, *225*, 111059.
87. Petrović, A.; Gojanović, J.; Matavulj, P.; Islam, M.; Živanović, S. Temperature Dependence of P3HT: ICBA Polymer Solar Cells. In *Proceedings of the 2017 International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD)*, 2017, pp. 133–134. IEEE.
88. Amrouche, B.; Guessoum, A.; Belhamel, M. A simple behavioural model for solar module electric characteristics based on the first-order system step response for MPPT study and comparison. *Applied Energy* 2012, *91*, 395–404.
89. Fan, J.C.C. Theoretical temperature dependence of solar cell parameters. *Solar Cells* 1986, *17*, 309–315.
90. Chakraborty, P.K.; Mondal, B.N. A note on anomalous bandgap variations in semiconductors with temperature. *Indian Journal of Physics* 2018, *92*, 303–306.
91. Dupré, O.; Vaillon, R.; Green, M.A. Physics of the Temperature Coefficients of Solar Cells. *Sol. Energy Mater. Sol. Cells* 2015, *140*, 92–100.
92. Emery, K.; Burdick, J.; Caiyem, Y.; Wanlass, M.W. Temperature Dependence of Photovoltaic Cells, Modules and Systems. *IEEE Photovolt. Spec. Conf.* 1996, *5520347*.
93. Hossain, M.I.; Bousselham, A.; Alharbi, F.H.; Tabet, N. Computational Analysis of Temperature Effects on Solar Cell Efficiency. *J. Comput. Electron.* 2017, *16*(3), 1–11.
94. Mäckel, H.; MacKenzie, R.C.I. Determination of Charge-Carrier Mobility in Disordered Thin-Film Solar Cells as a Function of Current Density. *Phys. Rev. Appl.* 2018, *9*(3), 034020.
95. Ebenhoch, B.; Thomson, S.A.J.; Genevičius, K.; Juška, G.; Samuel, I.D.W. Charge Carrier Mobility of the Organic Photovoltaic Materials PTB7 and PC71BM and Its Influence on Device Performance. *Org. Electron.* 2015, *22*, 62–68.
96. Sarkar, A.; Rahaman, A.; Chakraborty, K.; Pal, T.; Ghosh, S.; Banerjee, D. Organic Heterojunctions of Phthalocyanine-Reduced Graphene Oxide above Percolation Threshold for Photovoltaic Application. *Mater. Chem. Phys.* 2020, *253*, 123418.
97. Quilettes, D.W.; Vorpahl, S.M.; Stranks, S.D.; Nagaoka, H.; Eperon, G.E.; Ziffer, M.E. Impact of Microstructure on Local Carrier Lifetime in Perovskite Solar Cells. *Science* 2015, *348*, 683–768.
98. Vargas, C.; Yan, Z.; Coletti, G.; Chan, C.E.; Rayne, D.N.R.; Jensen, M.A.; Hameiri, Z. Recombination Parameters of Lifetime-Limiting Carrier-Induced Defects in Multicrystalline Silicon for Solar Cells. *Appl. Phys. Lett.* 2017, *110*, 092106.
99. Kopidakis, N.; Benkstein, K.D.; Yuan, Q.; Schiff, E.A. Temperature Dependence of the Electron Diffusion Coefficient in Electrolyte-Filled TiO2 Nanoparticle Films: Evidence Against Multiple Trapping in Exponential Conduction-Band Tails. *Phys. Rev. B* 2006, *73*, 045326.
100. Roy, P.; Kumar Sinha, N.; Tiwari, S.; Khare, A. A Review on Perovskite Solar Cells: Evolution of Architecture, Fabrication Techniques, Commercialization Issues, and Status. *Sol. Energy* 2020, *198*, 665–688.
101. Li, D.; King, M.; Dooner, M.; Guo, S.; Wang, J. Study on the Cleaning and Cooling of Solar Photovoltaic Panels Using Compressed Airflow. *Sol. Energy* 2021, *221*, 433–444.

102. Carvalho de Oliveira, M.C.; Alves Cardoso Diniz, A.S.; Viana, M.M.; Cunha Lins, V.D.F. The Causes and Effects of Degradation of Encapsulant Ethylene Vinyl Acetate Copolymer (EVA) in Crystalline Silicon Photovoltaic Modules: A Review. *Renew. Sustain. Energy Rev.* 2018, *81*, 2299–2317.
103. Seyyed, A.S.; Jamal, F.; Mohammad, N.; Abbas, K. The Experimental Analysis of Dust Deposition Effect on Solar Photovoltaic Panels in Iran's Desert Environment. *Sustain. Energy Technol. Assess.* 2021, *47*, 101542.
104. Alves dos Santos, S.A.; Torres, J.P.N.; Fernandes, C.A.F.; Marques Lameirinhas, R.A. The Impact of Aging of Solar Cells on the Performance of Photovoltaic Panels. *Energy Convers. Manag.* 2021, *10*, 100082.
105. Mohamed, A.; Khatib, T. Correlation for Estimating Solar Cell Temperature Based on a Tropical Field Operation of a Photovoltaic System. In *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, 2014; pp. 1–5.
106. Cotfas, D. T.; Cotfas, P. A.; Machidon, O. M. Study of temperature coefficients for parameters of photovoltaic cells. *International Journal of Photoenergy*, 2018, 1, 5945602.
107. Manju, S.; Sagar, N. Progressing towards the development of sustainable energy: A critical review on the current status, applications, developmental barriers and prospects of solar photovoltaic systems in India. *Renewable and Sustainable Energy Reviews*, 2017**,** *70*, 298-313.
108. Sudhakar, P.; Kumaresan, G.; & Velraj, R. Experimental analysis of solar photovoltaic unit integrated with free cool thermal energy storage system. *Solar Energy*, 2017, *158*, 837-844.
109. Xu, L.; Li, S.; Jiang, J.; Liu, T.; Wu, H.; Wang, J.; Li, X. The influence of dust deposition on the temperature of soiling photovoltaic glass under lighting and windy conditions. *Sol. Energy* 2020, *199*, 491–496.
110. Tiano, F.A.; Rizzo, G.; Marino, M.; Monetti, A. Evaluation of the Potential of Solar Photovoltaic Panels Installed on Vehicle Body Including Temperature Effect on Efficiency. *ETransportation* 2020, *5*, 100067.
111. Khanna, S.; Sundaram, S.; Reddy, K.S.; Mallick, T.K. Performance Analysis of Perovskite and Dye-Sensitized Solar Cells under Varying Operating Conditions and Comparison with Monocrystalline Silicon Cell. *Appl. Therm. Eng.* 2017, *127*, 559–565.
112. Pan, B.; Weng, J.; Chen, S.; Huang, Y.; Dai, S. The Effect of Partial Shading on Dye-Sensitized Solar Cell Module Characteristics. *J. Phys. D Appl. Phys.* 2014, *47*(47), 475503.
113. Bahaidarah, H.M.; Baloch, A.A.; Gandhidasan, P. Uniform cooling of photovoltaic panels: A review. *Renew. Sustain. Energy Rev.* 2016, *57*, 1520–1544.
114. Royne, A.; Dey, C. J.; Mills, D. R. Cooling of photovoltaic cells under concentrated illumination: A critical review. *Solar Energy Mater. Sol. Cells* 2005, *86*, 451–483.
115. Lu, X.; Zhao, Y.; Wang, Z.; Zhang, J.; Song, Y. Influence of environmental temperature and device temperature difference on output parameters of c-Si solar cells. *Sol. Energy* 2016, *136*, 333–341.
116. Zhai, H.; Zhang, J.; Wu, Z.; Xie, H.; Li, Q. Investigation on non-uniform temperature distribution in a solar cell with associated laser beam heating. *Solar Energy* 2021, *213*, 172–179.
117. Nasby, R. D.; Sanderson, R. W. Performance measurement techniques for concentrator photovoltaic cells. *Solar Cells* 1982, *6*(1), 39–47.
118. Skoplaki, E. P. J. A.; Palyvos, J. A. Operating temperature of photovoltaic modules: A survey of pertinent correlations. *Renew. Energy* 2009, *34*(1), 23–29.
119. Koehl, M.; Heck, M.; Wiesmeier, S.; Wirth, J. Modeling of the nominal operating cell temperature based on outdoor weathering. *Sol. Energy Mater. Sol. Cells* 2011, *95*(7), 1638–1646.
120. Santiago, I.; Trillo-Montero, D.; Moreno-Garcia, I. M.; Pallarés-López, V.; Luna-Rodríguez, J. J. Modeling of photovoltaic cell temperature losses: A review and a practice case in South Spain. *Renew. Sustain. Energy Rev.* 2018, *90*, 70–89.
121. Skoplaki, E.; Boudouvis, A. G.; Palyvos, J. A. A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting. *Sol. Energy Mater. Sol. Cells* 2008, *92*(11), 1393–1402.
122. Bardhi, M.; Grandi, G.; Tina, G. M. Comparison of PV cell temperature estimation by different thermal power exchange calculation methods. *Renew. Energy Power Qual. J.* 2012, *10*(5).

123. Kurnik, J., Jankovec, M., Brecl, K., & Topic, M. (2011). Outdoor testing of PV module temperature and performance under different mounting and operational conditions. *Solar Energy Materials and Solar Cells*, *95*(1), 373-376.
124. Mattei, M.; Notton, G.; Cristofari, C.; Muselli, M.; Poggi, P. Calculation of the polycrystalline PV module temperature using a simple method of energy balance. *Renew. Energy* 2006, *31*, 553–567.
125. Notton, G.; Cristofari, C.; Mattei, M.; Poggi, P. Modelling of a double-glass photovoltaic module using finite differences. *Appl. Therm. Eng.* 2005, *25*, 2854–2877.
126. Rao, A.; Mani, M. Evaluating the nature and significance of ambient wind regimes on solar photovoltaic system performance. In *Proceedings of the Building Simulation Applications Conference*, Bozen-Bolzano, Italy, January 2013.
127. Mattei, M.; Notton, G.; Cristofari, C.; Muselli, M.; Poggi, P. Calculation of the Polycrystalline PV Module Temperature Using a Simple Method of Energy Balance. *Renewable Energy* 2006, *31*, 553–567.
128. Tina, G.M.; Abate, R. Experimental Verification of Thermal Behaviour of Photovoltaic Modules. In Proceedings of the 14th IEEE Mediterranean Electrotechnical Conference (MELECON 2008), Ajaccio, France, 5–7 May 2008; pp. 579–584.
129. Trillo-Montero, D.; Santiago, I.; Luna-Rodriguez, J.J.; Real-Calvo, R. Development of a Software Application to Evaluate the Performance and Energy Losses of Grid-Connected Photovoltaic Systems. *Energy Convers. Manag.* 2014, *81*, 144–159.
130. Drif, M.; Pérez, P.J.; Aguilera, J.; Almonacid, G.; Gomez, P.; De la Casa, J.; Aguilar, J.D. Univer Project: A Grid-Connected Photovoltaic System of 200 kWp at Jaén University—Overview and Performance Analysis. *Sol. Energy Mater. Sol. Cells* 2007, *91*, 670–683.
131. Nolay, P. Development of a General Method for Analyzing Photovoltaic Systems. Ph.D. Thesis, École Nationale Supérieure des Mines de Paris (ENMP), Paris, France, 1987.
132. García, M. A., & Balenzategui, J. L. (2004). Estimation of photovoltaic module yearly temperature and performance based on nominal operation cell temperature calculations. *Renewable energy*, *29*(12), 1997-2010.
133. Fuentes, M.K. A Simplified Thermal Model for Flat-Plate Photovoltaic Arrays; Sandia National Labs., Albuquerque, NM, USA, 1987; No. SAND-85-0330.
134. Chatzipanagi, A.; Frontini, F.; Dittmann, S. Investigation of the Influence of Module Working Temperatures on the Performance of BiPV Modules. In *Proceedings of the 27th European Photovoltaic Solar Energy Conference and Exhibition*, Frankfurt, Germany, 24–28 September 2012; pp. 24–28.
135. Koka, K. Photovoltaic Module Performance and Thermal Characterizations: Data Collection and Automation of Data Processing. Master's Thesis, Arizona State University, 2011.
136. Tang, Y.; TamizhMani, G.; Ji, L.; Osterwald, C. Outdoor Energy Rating Measurements of Photovoltaic Modules. Ph.D. Thesis, Arizona State University, 2005.
137. Kratochvil, J.A.; Boyson, W.E.; King, D.L. *Photovoltaic Array Performance Model*; SAND2004-3535; Sandia National Laboratories: Albuquerque, NM, USA; Livermore, CA, USA, 2004.
138. Lasnier, F. Photovoltaic Engineering Handbook; Routledge: 2017.
139. Koteswararao, B.; Radha, K.; Vijay, P.; Raja, N. Experimental Analysis of Solar Panel Efficiency with Different Modes of Cooling. *Energies* 2016, *8*(3), 1451–1456.
140. Dorobanțu, L.; Popescu, M.O.; Popescu, C.L.; Crăciunescu, A. Experimental Assessment of PV Panels, Front Water Cooling Strategy. *Energies* 2013, *1*(11), 1–4.
141. Dwivedi, P.; Sudhakar, K.; Soni, A.; Solomin, E.; Kirpichnikova, I. Advanced Cooling Techniques of PV Modules: A State of Art. *Case Stud. Therm. Eng.* 2020, *21*, 100674.
142. Bayrak, F.; Oztop, H.F.; Selimefendigil, F. Effects of Different Fin Parameters on Temperature and Efficiency for Cooling of Photovoltaic Panels under Natural Convection. *Sol. Energy* 2019, *188*, 484–494.
143. H.A. Kazem, A.H.A. Al-Waeli, M.T. Chaichan, K. Sopian, "Numerical and experimental evaluation of nanofluid-based photovoltaic/thermal systems in Oman:

Using silicone-carbide nanoparticles with water-ethylene glycol mixture," *Case Studies in Thermal Engineering*, vol. 26, April 2021, Article 101009.
144. Teo, H.G.; Lee, P.S.; Hawlader, M.N.A. An active cooling system for photovoltaic modules. *Appl. Energy* 2012, *90*, 309–315.
145. Salih, S.M.; Abd, O.I.; Abid, K.W. Performance enhancement of PV array based on water spraying technique. *Int. J. Sustain. Green Energy* 2015, *4*, 8–13.
146. Tonui, J. K., & Tripanagnostopoulos, Y. (2007). Air-cooled PV/T solar collectors with low cost performance improvements. *Solar energy*, *81*(4), 498-511.
147. Sajjad, U.; Amer, M.; Ali, H.M.; Dahiya, A.; Abbas, N. Cost-effective cooling of photovoltaic modules to improve efficiency. *Case Stud. Therm. Eng.* 2019, *14*, 100420.
148. Kasaeian, A.; Pourfayaz, F.; Khodabandeh, E.; Yan, W.M. Experimental studies on the applications of PCMs and nano-PCMs in buildings: A critical review. *Energy Build.* 2017, *154*, 96–112.
149. Shahsavar, A.; Ameri, M. Experimental investigation and modeling of a direct-coupled PV/T air collector. *Sol. Energy* 2010, *84*, 1938–1958.
150. Prudhvi, P.; Sai, P.C. Efficiency Improvement of Solar PV Panels Using Active Cooling. *Proceedings of the 11th International Conference on Environment and Electrical Engineering*, Venice, Italy, 18–25 May 2012; IEEE: Piscataway, NJ, USA, pp. 1093–1097.
151. Kabeel, A.E.; Abdelgaied, M.; Sathyamurthy, R. A Comprehensive Investigation of the Optimization Cooling Technique for Improving the Performance of PV Module with Reflectors under Egyptian Conditions. *Solar Energy* 2019, *186*, 257–263.
152. Bahaidarah, H.; Subhan, A.; Gandhidasan, P.; Rehman, S. Performance Evaluation of a PV (Photovoltaic) Module by Back Surface Water Cooling for Hot Climatic Conditions. *Energy* 2013, *59*, 445–453.
153. Al-Housani, M.; Bicer, Y.; Koç, M. Experimental Investigations on PV Cleaning of Large-Scale Solar Power Plants in Desert Climates: Comparison of Cleaning Techniques for Drone Retrofitting. *Energy Convers. Manag.* 2019, *185*, 800-815.
154. Nižetić, S.; Čoko, D.; Yadav, A.; Grubišić-Čabo, F. Water Spray Cooling Technique Applied on a Photovoltaic Panel: The Performance Response. *Energy Convers. Manag.* 2016, *108*, 287-296.
155. Moharram, K.A.; Abd-Elhady, M.S.; Kandil, H.A.; El-Sherif, H. Enhancing the Performance of Photovoltaic Panels by Water Cooling. *Ain Shams Eng. J.* **2013**, *4*(4), 869-877.
156. Rostami, Z.; Rahimi, M.; Azimi, N. Using high-frequency ultrasound waves and nanofluid for increasing the efficiency and cooling performance of a PV module. *Energy Convers. Manag.* 2018, *160*, 141–149.
157. Najafi, H.; Woodbury, K. A. Optimization of a cooling system based on Peltier effect for photovoltaic cells. *Solar Energy* 2013, *91*, 152-160.
158. Hasan, A., Sarwar, J., Alnoman, H., Abdelbaqi, S., 2017. Yearly energy performance of a photovoltaic-phase change material (PV-PCM) system in hot climate. Sol. Energy 146, 417–429.
159. Zhao, Y.H. A Sort of Micro Heat Pipe Array and Processing Technics. *Chinese Patent*: 200810225649, 2008.
160. Tang, X.; Quan, Z.; Zhao, Y. Experimental Investigation of Solar Panel Cooling by a Novel Micro Heat Pipe Array. *Energy Power Eng.* 2010, *2*, 171–174.
161. Chandrasekar, M.; Suresh, S.; Senthilkumar, T. Passive Cooling of Standalone Flat PV Module with Cotton Wick Structures. *Energy Convers. Manag.* 2013, *71*, 43–50.
162. Zhu, L., Raman, A., Wang, K. X., Anoma, M. A., & Fan, S. (2014). Radiative cooling of solar cells. *Optica*, *1*(1), 32-38.

163. Rodrigyuez, G.D. A utility perspective of the role of energy storage in the smart grid. In Proceedings of the Power and Energy Society General Meeting (IEEE), Minneapolis, MN, USA, 25–29 July 2010.
164. Dolara, A.; Leva, S.; Manzolini, G. Comparison of different physical models for PV power output prediction. *Sol Energy* 2015, 119, 83–99.
165. Huld, T.; Amillo, A.M.G. Estimating PV module performance over large geographical regions: The role of irradiance, air temperature, wind speed and solar spectrum. *Energies* 2015, *8*, 5159–5181.
166. Liou, H.M. Overview of the PV technology status and perspective in Taiwan. *Renew. Sustain. Energy* 2010, *14*, 1202–1215.
167. Katsumata, N.; Nakada, Y.; Minemoto, T.; Takakura, H. Estimation of irradiance and outdoor performance of PV modules by meteorological data. *Sol. Energy Mater. Sol. Cells* 2011, *95*, 199–202.
168. Fudholi, A.; Sopian, K.; Yazdi, M.H.; Ruslan, M.H.; Ibrahim, A.; Kazem, H.A. Performance analysis of photovoltaic thermal (PVT) water collectors. *Energy Convers. Manag.* 2014, *78*, 641–651.
169. Naves, A.X.; Barreneche, C.; Fernández, A.I.; Cabeza, L.F.; Haddad, A.N.; Boer, D.; Life cycle costing as a bottom line for the life cycle sustainability assessment in the solar energy sector: A review. *Sol. Energy* 2019, *192*, 238–262.
170. Molaei, M.J. The optical properties and solar energy conversion applications of carbon quantum dots: A review. *Sol. Energy* 2020, *196*, 549–566.
171. Yang, K.Y.; Lee, W.; Jeon, J.Y.; Ha, T.J.; Kim, Y.H.; Controlling the visibility of embedded silicon solar cells in building-integrated photovoltaic windows using surface structure modification and metal-oxide back coating. *Sol. Energy* 2020, *197*, 99–104.
172. Trindade, A.; Cordeiro, L. Automated formal verification of stand-alone solar photovoltaic systems. *Sol. Energy* 2019, *193*, 684–691.
173. Joshi, S.; Dhoble, A.S. Photovoltaic—Thermal systems (PVT): Technology review and future trends. *Renew. Sustain. Energy Rev.* 2018, *92*, 848–882.
174. Wolf, M. Performance analyses of combined heating and photovoltaic power systems for residences. *Energy Convers.* 1976, *16*, 79–90.
175. Ahmed, M.T.; Rashel, M.R.; Ahmed, M.T. Tlemçani. A Study of Thermal Regulations and Efficiency Analysis in Hybrid PVT Panel. In Proceedings of the 6th International Conference on Numerical and Symbolic Computation Developments and Applications, Evora, Portugal, 30–31 March 2023.
176. Florschuetz, L.W. Extension of the hottel-whillier model to the analysis of combined photovoltaic / thermal flat plate collectors. *Sol. Energy* 1979, *22*, 361–366.
177. Fine, J.P.; Dworkin, S.B.; Friedman, J. A methodology for predicting hybrid solar panel performance in different operating modes. *Renew. Energy* 2019, *130*, 1198–1206.
178. Khelifa, A.; Touafek, K.; Moussa, H.B.; Ismail, T. Analysis of a hybrid solar collector photovoltaic thermal (PVT). *Energy Procedia* 2015, *74*, 835–843.
179. Magrassi, F.; Rocco, E.; Barberis, S.; Gallo, M.; Del, B.A. Hybrid solar power system versus photovoltaic plant: A comparative analysis through a life cycle approach. *Renew. Energy* 2019, *130*, 290–304.
180. Abdelrazik, A.S.; Al-Sulaiman, F.A.; Saidur, R.; Ben-Mansour, R. A review on recent development for the design and packaging of hybrid photovoltaic/thermal (PVT) solar systems Renew. *Sustain. Energy Rev.* 2018, *95*, 110–129.
181. Al-Sabounchi, A.M.; Yalyali, S.A.; Al-Thani, H.A. Design and performance evaluation of a PV grid-connected system in hot weather conditions. *Renew. Energy* 2013, *53*, 71–78.
182. Gasparin, F.P.; Buhler, A.J.; Rampinelli, G.A.; Krenzinger, A. Statistical analysis of I–V curve parameters from PV modules. *Sol. Energy* 2016, *131*, 30–38.

183. Chow, T.T.; He, W.; Chan, A.L.S.; Fong, K.F.; Lin, Z.; Ji, J. Computer modeling and experimental validation of a building-integrated PV and water heating system. *Appl. Therm. Eng.* 2008, *28*, 1356–1364.
184. Bazilian, M.D.; Leerders, F.; Van Der Ree, B.G.C.; Prasad, D.P.V. Cogeneration in the built environment. *Sol. Energy* 2001, *71*, 57–69.
185. Ahmed, M.T.; Rashel, M.R.; Tlemçani, M. Parametric Study and Efficiency Analysis Hybrid PVT System. In proceedings of the AMPSECA, Marrakech, Morocco, 25–26 May 2023.
186. Samykano, M. Hybrid Photovoltaic Thermal Systems: Present and Future Feasibilities for Industrial and Building Applications. *Buildings* 2023, *13*, 1950.
187. Herrando, M.; Wang, K.; Huang, G.; Otanicar, T.; Mousa, O.B.; Agathokleous, R.A.; Ding, Y.; Kalogirou, S.; Ekins-Daukes, N.; Taylor, R.A.; Markides, C.N. A Review of Solar Hybrid Photovoltaic-Thermal (PV-T) Collectors and Systems. *Prog. Energy Combust. Sci.* 2023, *97*, 101072.
188. Va, T.; Sekhar, R. Hybrid Photovoltaic/Thermal (PVT) Collector Systems with Different Absorber Configurations for Thermal Management—A Review. *Energy Environ*. 2021, 34.
189. Dewangan, D.; Ekka, J.P.; Arjunan, T.V. Solar photovoltaic thermal system: A comprehensive review on recent design and development, applications and future prospects in research. *Int. J. Ambient Energy* 2022, *43*, 7247–7271.
190. Abdin, Z.U. Modeling and Control of Hybrid PV Thermal Panels. Modeling and Simulation. Ph.D. Thesis, Université de Picardie Jules Verne, Amiens, France, 2022. NNT: 2022AMIE0057.
191. Zhou, B.; Pei, J.; Nasir, D. M.; Zhang, J. A review on solar pavement and photovoltaic/thermal (PV/ T) system. *Transportation Research Part D: Transport and Environment* 2021, 93.
192. Bandaru, S.H.; Becerra, V.; Khanna, S.; Radulovic, J.; Hutchinson, D.; Khusainov, R. A Review of Photovoltaic Thermal (PVT) Technology for Residential Applications: Performance Indicators, Progress, and Opportunities. *Energies* 2021, *14*, 3853.
193. Rajoria, C.S.; Kumar, R.; Sharma, A.; Singh, D.; Suhag, S. Development of flat-plate building integrated photovoltaic/thermal (BIPV/T) system: A review. *Mater. Today Proc.* 2020, *46*, 5342–5352.
194. Noxpanco, M.G.; Wilkins, J.; Riffat, S. A Review of the Recent Development of Photovoltaic/Thermal (PV/T) Systems and Their Applications. *Future Cities Environ.* **2020**, *6*, 9.
195. Sredendek, K.; Seme, S. A review of hybrid photovoltaic/thermal systems. *J. Energy Technol.* 2019, *12*, 39–49.
196. Yuting, J.; Guruprasad, A.; Guiyin, F. Development and applications of photovoltaic–thermal systems: A review. Renew. Sustain. *Energy Rev.* 2019, 102, 249–265.
197. Abdullah, A.L.; Misha, S.; Tamaldin, N.; Rosli MA, M.; Sachit, F.A. Technology Progress on Photovoltaic Thermal (PVT) Systems with Flat-Plate Water Collector Designs: A Review. *J. Adv. Res. Fluid Mech. Therm. Sci.* 2019, 59, 107–141.
198. Sachit, F.A.; Tamaldin, N.; Rosli, M.A.M.; Misha, S.; Abdullah, A.L. Current progress on flat-plate water collector design in photovoltaic thermal (PV/T) systems: A review. *J. Adv. Res. Dyn. Control Syst.* 2018, *10*, 680–689.
199. Keizer, C.D.; Bottse, J.; Jong, M.D.; Folkerts, W. An Overview of PVT modules on the European Market and the Barriers and Opportunities for the Dutch Market. In Proceedings of the ISES EuroSun 2018 Conference, Rapperswil, Switzerland, 10–13 September 2018.
200. Babu, C. The role of thermoelectric generators in the hybrid PV/T systems: A review. *Energy Convers. Manag.* 2017, *151*, 368–385.
201. Sathe, T.M.; Dhoble, A.S. A review on recent advancements in photovoltaic thermal techniques, *Renew. Sustain. Energy Rev.* 2017, *76*, 645–672.

202. Al-waeli, A.H.; Sopian, K.B.; Kazem, H.A.; Chaichan, M.T. Photovoltaic Solar Thermal (PV/T) Collectors Past, Present and Future: A Review. *Int. J. Appl. Eng. Res.* 2016, *11*, 10757–10765.
203. Tyagi, V.V.; Kaushik, S.C.; Tyagi, S.K. Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology. *Renew. Sustain. Energy Rev.* 2012, *16*, 1383–1398.
204. Avezov, R.R.; Akhatov, J.; Avezova, N.R. A Review on Photovoltaic-Thermal (PV–T) Air and Water Collectors. *Appl. Sol. Energy* 2011, *47*, 169–183.
205. Hasan, M.A.; Sumathy, K. Photovoltaic thermal module concepts and their performance analysis: A review. *Renew. Sustain. Energy Rev.* 2010, *14*, 1845–1859.
206. Ahliouati, M.; Rabie, E.O.; Kandoussi, K.; Boutaous, M.; Amal, L.; Louzazni, M.; Daya, A. Energetic and parametric studies of a basic hybrid collector (PV/T-Air) and a photovoltaic (PV) module for building applications: Performance analysis under El Jadida weather conditions. *Mater. Sci. Energy Technol.* 2023, *6*, 267–281.
207. Pathak, P.K.; Ghoshroy, D.; Yadav, A.K.; Padmanaban, S.; Blaabjerg, F.; Khan, B. A State-of-the-Art Review on Heat Extraction Methodologies of Photovoltaic/Thermal System. *IEEE Access* 2023, *11*, 49738–49759.
208. Azad, A.K.; Parvin, S. Photovoltaic thermal (PV/T) performance analysis for different flow regimes: A comparative numerical study. *Int. J. Thermofluids* 2023, *18*, 1000319.
209. Barbu, M.; Siroux, M.; Darie, G. Performance Analysis and Comparison of an Experimental Hybrid PV, PVT and Solar Thermal System Installed in a Preschool in Bucharest, Romania. *Energies* 2023, *16*, 5321.
210. Herez, A.; Jabe, H.; El-hage, H.H.; Lemenand, T.; Chahine, K.; Ramadan, M.; Khaled, M. Parabolic trough photovoltaic thermoelectric hybrid system: Simulation model, parametric analysis, and practical recommendations. *Int. J. Thermofluids* 2023, *17*, 100309.
211. Ajel, M.G.; Gedik, E.; Wahhab, H.A.A.; Shallal, B.A. Performance Analysis of an Open-Flow Photovoltaic/Thermal (PV/T) Solar Collector with Using a Different Fins Shapes. *Sustainability* 2023, *15*, 3877.
212. Farjad, M.; Soloveva, T. A. Performance analysis of solar water heating (swh) and photovoltaic-thermal (pvt) systems in vladivostok, russia. *jp j. Heat Mass Transf.* 2023, *32*, 15–29.
213. Madas, S.R.; Narayanan, R.; Gudimetla, P. A systematic review on furtherance of photovoltaic thermal panel technology. In Proceedings of the 3rd International Conference on Energy and Power (ICEP2021), Chiang Mai, Thailand, 18–20 November 2021.
214. Nascimento, V.F.; Yahyaoui, I.; Fiorotti, R.; Amorim, A.E.A.; Belisario, I.C.; Abreu, C.E.S.; Rocha, H.R.O.; Tadeo, F. Dimensioning and efficiency evaluation of a hybrid photovoltaic thermal system in a tropical climate region. *Sustain. Energy Grids Netw.* 2022, *32*, 100954.
215. Yousif, J.H. Prediction and evaluation of photovoltaic-thermal energy systems production using artificial neural network and experimental dataset. *Therm. Eng.* 2021, *27*, 101297.
216. Amal, H.; Hicham, E.H.; Hierry, L.; Mohamad, R.; Mahmoud, K. Parabolic trough photovoltaic/thermal hybrid system: Thermal modeling and parametric analysis. *Renew. Energy Elsevier* 2021, *165*, 224–236.
217. Ventura, C.; Tina, G.M.; Gagliano, A.; Aneli, S. Enhanced models for the evaluation of electrical efficiency of PV/T modules. *Sol. Energy* 2021, *224*, 531–544.
218. Hossain, R.; Ahmed, A.J.; Islam, S.M.K.N.; Saha, N.; Debnath, P.; Kouzani, A.Z.; Mahmud, M.A.P. New Design of Solar Photovoltaic and Thermal Hybrid System for Performance Improvement of Solar Photovoltaic. *Int. J. Photoenergy* 2020, *2020*, 8825489.
219. Al-Waeli, A.H.A.; Kazem, H.A.; Chaichan, M.T.; Sopian, K. A review of photovoltaic thermal systems: Achievements and applications. *Int. J. Energy Res.* 2020, *45*, 1269–1308.
220. Khordehgah, N.; Zabnienska-Gora, A.; Jouhara, H. Energy Performance Analysis of a PV/T System Coupled with Domestic Hot Water System. *ChemEngineering* 2020, *4*, 22.
221. Abdul-Ganiyu, S.; Quansah, D.A.; Ramde, W.W.; Seidu, R.; Adaramola, M.S. Investigation of Solar Photovoltaic-Thermal (PVT) and Solar Photovoltaic (PV) Performance: A Case Study in Ghana. *Energies* 2020, *13*, 2701.
222. Barbu, M.; Darie, G.; Siroux, M. Analysis of a Residential Photovoltaic-Thermal (PVT) System in Two Similar Climate Conditions. *Energies* 2019, *12*, 3595.

223. Antony, A.; Wang, Y.D.; Roskilly, A.P. A detailed optimisation of solar photovoltaic/thermal systems and its application. *Energy Procedia* 2019, *158*, 1141–1148.
224. Abdullah, A.L.; Misha, S.; Tamaldin, N.; Rosli, M.A.M.; Sachit, F.A. Hybrid Photovoltaic Thermal PVT Solar Systems Simulation via Simulink/Matlab. *CFD Lett.* 2019, *4*, 64–78.
225. Fuentes, M.; Vivar, M.; Casa, J.D.L.; Aguilera, J. An experimental comparison between commercial hybrid PV-T and simple PV systems intended for BIPV. *Renew. Sustain. Energy Rev.* 2018, *93*, 110–120.
226. Nasir, F.H.M.; Husaini, Y. MATLAB Simulation of Photovoltaic and Photovoltaic/Thermal Systems Performance. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *341*, 012019.
227. Al-Waeli, A.H.A.; Sopian, K. Photovoltaic/Thermal (PV/T) systems: Status and future prospects. *Renew. Sustain. Energy Rev.* 2017, *77*, 109–130.
228. Ahmed, M.T.; Rashel, M.R.; Ahmed, M.T. Tlemçani. A Study of Thermal Regulations and Efficiency Analysis in Hybrid PVT Panel. In Proceedings of the 6th International Conference on Numerical and Symbolic Computation Developments and Applications, Evora, Portugal, 30–31 March.
229. Hasanuzzaman, M.; Malek, A.B.M.A.; Islam, M.M.; Pandey, A.K.; Rahim, N.A. Global advancement of cooling technologies for PV systems: A review. *Sol. Energy* 2016, *137*, 25–45.
230. Sargunanathan, S.; Elango, A.; Mohideen, S.T. Performance enhancement of solar photovoltaic cells using effective cooling methods: A review. *Renew. Sustain. Energy Rev.* 2016, *64*, 382–393.
231. Oussama, R.; Houcine, D.; Abdelmajid, J. A numerical investigation of a photovoltaic thermal (PV/T) collector. *Renew. Energy* 2015, *77*, 43–50.
232. Khelifa, A.; Touafek, K.; Moussa, H.B.; Tabet, I. A numerical modeling of hybrid photovoltaic/thermal (PV/T) collector. *Sol. Energy* 2016, *135*, 169–176.
233. Moradia, M.; Ebadian, M.A.; Lin, C.-X.. A review of PV/T technologies: Effects of control parameters. *Int. J. Heat Mass Tran* 2013, *64*, 483–500.
234. Chow, T.T.; A review on photovoltaic/thermal hybrid solar technology. *Appl. Energy* 2010, *87*, 365–379.
235. Tiwari, A.; Sodha, M.S. Performance evaluation of hybrid PV/thermal water/air heating system: A parametric study. *Renew. Energy* 2006, *31*, 2460–2474.
236. IRENA. *Climate Change and Renewable Energy: National Policies and the Role of Communities, Cities and Regions; A Report to the G20 Climate and Sustainability Working Group (CSWG)*; International Renewable Energy Agency: Abu Dhabi, UAE, 2019.
237. Mostakim, K.; Hasanuzzaman, M. Global Prospects, Challenges, and Progress of Photovoltaic Thermal System. *Sustain. Energy Technol. Assess.* 2022, *53*, 102426.
238. Ngunzi, V.; Njoka, F.; Kinyua, R. Modeling, Simulation, and Performance Evaluation of a PVT System for the Kenyan Manufacturing Sector. *Heliyon* 2023, *9*(8), e18632.
239. Cabral, D.O. Photovoltaic-Thermal Solar Collectors–A Rising Solar Technology for an Urban Sustainable Development. *IntechOpen* 2022.
240. Kalogirou, S.A.; Tripanagnostopoulos, Y. Industrial Application of PV/T Solar Energy Systems. *Appl. Therm. Eng.* 2007, *27*(8–9), 1259–1270.
241. I.C. Change, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014, 1454, 147.
242. IRENA, I.E. Solar Heat for Industrial Processes. *Technol. Briefs* 2015, 37, 1–36.
243. Olsson, O.; Schipfer, F. Decarbonizing Industrial Process Heat: The Role of Biomass. *Research Report* 978-1-910154-96-0.
244. Byrne, J.; Taminiau, J.; Kurdgelashvili, L.; Kim, K.N. A Review of the Solar City Concept and Methods to Assess Rooftop Solar Electric Potential, with an Illustrative Application to the City of Seoul. *Renew. Sustain. Energy Rev.* 2015, *41*, 830–844.
245. Ahmed, M.T.; Rashel, M.R.; Abdullah-Al-Wadud, M.; Hoque, T.T.; Janeiro, F.M.; Tlemcani, M. Mathematical Modeling, Parameters Effect, and Sensitivity Analysis of a Hybrid PVT System. *Energies* 2024, *17*(12), 2887.
246. Qiu, Z.; Zhao, X.; Li, P.; Zhang, X.; Ali, S.; Tan, J. Theoretical Investigation of the Energy Performance of a Novel MPCM (Microencapsulated Phase Change Material) Slurry-Based PV/T Module. *Energy* 2015, *87*, 686–698.

247. Lamnatou, C.; Vaillon, R.; Parola, S.; Chemisana, D. Photovoltaic/Thermal Systems Based on Concentrating and Non-Concentrating Technologies: Working Fluids at Low, Medium and High Temperatures. *Renew. Sustain. Energy Rev.* 2021, *137*, 110625.
248. Alkhwaji, A.; Elbahloul, S.; Abdullah, M.Z.; Bakar, K.F.B.A. Selected Water Thermal Properties from Molecular Dynamics for Engineering Purposes. *J. Mol. Liq.* 2021, *324*, 114703.
249. Dupeyrat, P.; Ménézo, C.; Wirth, H.; Rommel, M. Improvement of PV Module Optical Properties for PV-Thermal Hybrid Collector Application. *Sol. Energy Mater. Sol. Cells* 2011, *95*(8), 2028–2036.
250. Touafek, K.; Haddadi, M.; Malek, A. Experimental Study on a New Hybrid Photovoltaic Thermal Collector. *Appl. Sol. Energy* 2009, *45*, 181–186.
251. Kidegho, G.; Njoka, F.; Muriithi, C.; Kinyua, R. Evaluation of Thermal Interface Materials in Mediating PV Cell Temperature Mismatch in PV–TEG Power Generation. *Energy Rep.* 2021, *7*, 1636–1650.
252. Zhang, X.; Zhao, X.; Smith, S.; Xu, J.; Yu, X. Review of R&D Progress and Practical Application of the Solar Photovoltaic/Thermal (PV/T) Technologies. *Renewable and Sustainable Energy Reviews* 2012, *16*(1), 599–617.
253. Singh, S.; Agrawal, S.; Avasthi, D. V. Optimization of Design Parameters of Glazed Hybrid Photovoltaic Thermal Module Using Genetic Algorithm. In *2014 Innovative Applications of Computational Intelligence on Power, Energy and Controls with Their Impact on Humanity (CIPECH)*; IEEE, 2014; pp. 405–410.
254. Agrawal, S.; Tiwari, G. N. Energy and Exergy Analysis of Hybrid Micro-Channel Photovoltaic Thermal Module. *Solar Energy* 2011, *85*(2), 356–370.
255. Kalogirou, S. A.; Sotirios, K.; Konstantinos, B.; Camelia, S.; Badescu, V. Exergy Energy of Solar Thermal Collectors and Processes. *Progress in Energy and Combustion Science* **2016**, *56*, 106–137.
256. Daghigh, R.; Ruslan, M.H.; Sopian, K. Advances in Liquid-Based Photovoltaic/Thermal (PV/T) Collectors. *Renew. Sustain. Energy Rev.* 2011, *15*, 4156–4170.
257. Tripanagnostopoulos, Y.; Souliotis, M.; Battisti, R.; Corrado, A. Application Aspects of Hybrid PV/T Solar Systems. *Phys. Dep. Univ. Patras* 2003, *26500*, 1–15.
258. Michael, J.J.; Iniyan, S.; Goic, R. Flat Plate Solar Photovoltaic-Thermal (PV/T) Systems: A Reference Guide. *Renew. Sustain. Energy Rev.* 2015, *51*, 62–88.
259. Zondag, H.A.; De Vries, D.W.; Van Helden, W.G.J.; Van Zolingen, R.J.C.; Van Steenhoven, A.A. The Yield of Different Combined PV-Thermal Collector Designs. *Sol. Energy* 2003, *74*, 253–269.
260. Makki, A.; Omer, S.; Sabir, H. Advancements in Hybrid Photovoltaic Systems for Enhanced Solar Cells Performance. *Renew. Sustain. Energy Rev.* 2015, *41*, 658–684.
261. Ibrahim, A.; Othman, M.Y.; Ruslan, M.H.; Alghoul, M.A.; Yahya, M.; Zaharim, A.; et al. Performance of Photovoltaic Thermal Collector (PVT) with Different Absorbers Design. *WSEAS Trans. Environ. Dev.* 2009, *5*, 321–330.
262. Faghri, A. Review and Advances in Heat Pipe Science and Technology. *J. Heat Transf.* 2012, *134*, 123001.
263. Long, H.; Chow, T.T.; Ji, J. Building-Integrated Heat Pipe Photovoltaic/Thermal System for Use in Hong Kong. *Sol. Energy* 2017, *155*, 1084–1091.
264. Chen, H.; Zhang, H.; Li, M.; Liu, H.; Huang, J. Experimental Investigation of a Novel LCPV/T System with Micro-Channel Heat Pipe Array. *Renew. Energy* 2018, *115*, 773–782.
265. Hou, L.; Quan, Z.; Zhao, Y.; Wang, L.; Wang, G. An Experimental and Simulative Study on a Novel Photovoltaic-Thermal Collector with Micro Heat Pipe Array (MHPA-PV/T). *Energy Build.* 2016, *124*, 60–69.
266. Zhang, T.; Yan, Z.W.; Xiao, L.; Fu, H.D.; Pei, G.; Ji, J. Experimental Study and Design Sensitivity Analysis of a Heat Pipe Photovoltaic/Thermal System. *Appl. Therm. Eng.* 2019, *162*, 114318.
267. Pei, G.; Huide, F.; Huijuan, Z.; Ji, J. Performance Study and Parametric Analysis of a Novel Heat Pipe PV/T System. *Energy* 2012, *37*, 384–395.
268. Pei, G.; Huide, F.; Tao, Z.; Ji, J. A Numerical and Experimental Study on a Heat Pipe PV/T System. *Sol. Energy* 2011, *85*, 911–921.

269. Nazir, H.; Batool, M.; Osorio, F.J.B.; Isaza-Ruiz, M.; Xu, X.; Vignarooban, K.; Phelan, P.; Inamuddin; Kannan, A.M. Recent Developments in Phase Change Materials for Energy Storage Applications: A Review. *Int. J. Heat Mass Transf.* 2019, *129*, 491–523.
270. Asefi, G.; Ma, T.; Wang, R. Techno-Economic Evaluation of Photovoltaic Thermal System Integrated with Porous Phase Change Materials: Case Studies in China. *Energy Convers. Manag.* 2022, *290*, 117227.
271. Hasan, A.; McCormack, S.J.; Huang, M.J.; Norton, B. Evaluation of Phase Change Materials for Thermal Regulation Enhancement of Building Integrated Photovoltaics. *Sol. Energy* **2010**, *84*, 1601–1612.
272. Huang, J.M. The Effect of Using Two PCMs on the Thermal Regulation Performance of BIPV Systems. *Sol. Energy Mater. Sol. Cells* 2011, *95*, 957–963.
273. Kern, J.; Russell, M.C. Combined Photovoltaic and Thermal Hybrid Collector Systems. In *Proceedings of the IEEE Photovoltaic Specialists Conference*; Washington, DC, USA, 1978; pp. 1153–1157.
274. Xu, G.; Deng, S.; Zhang, X.; Yang, L.; Zhang, Y. Simulation of a Photovoltaic/Thermal Heat Pump System Having a Modified Collector/Evaporator. *Sol. Energy* 2009, 83, 1967–1976.
275. Lämmle, M.; Herrando, M.; Ryan, G. (2020). Basic concepts of PVT collector technologies, applications, and markets. International Energy Agency. Available online: https://task60.iea-shc.org/Data/Sites/1/publications/D5_Basic_concepts_of_PVT_technologies_200501.pdf (accessed on 2 January 2025).
276. Kumar, R.; Rosen, M.A. A Critical Review of Photovoltaic–Thermal Solar Collectors for Air Heating. *Appl. Energy* 2011, *88*, 3603–3614.
277. Kamthania, D.; Nayak, S.; Tiwari, G.N. Performance Evaluation of a Hybrid Photovoltaic Thermal Double Pass Facade for Space Heating. *Energy Build.* 2011, *43*, 2274–2281.
278. Tiwari, S.; Tiwari, G.N.; Al-Helal, I.M. Performance Analysis of Photovoltaic Thermal (PVT) Mixed-Mode Greenhouse Solar Dryer. *Solar Energy* 2016, *133*, 421–428.
279. Koyuncu, T. An Investigation on the Performance Improvement of Greenhouse-Type Agricultural Dryers. *Renew. Energy* 2006, *31*, 1055–1071.
280. Tiwari, S.; Tiwari, G.N.; Al-Helal, I.M.; Mohan, M. Thermal Modelling of Photovoltaic Thermal (PVT) Integrated Greenhouse System for Biogas Heating. *Solar Energy* 2016, *136*, 639–649.
281. Kumar, S.; Tiwari, A. An Experimental Study of Hybrid Photovoltaic Thermal (PV/T)-Active Solar Still. *Int. J. Energy Res.* 2008, *32*, 847–858.
282. Allouhi, A.; Rehman, S.; Buker, M.S.; Said, Z. Recent Technical Approaches for Improving Energy Efficiency and Sustainability of PV and PV-T Systems: A Comprehensive Review. *Sustainable Energy Technologies and Assessments* 2023, *56*, 103026.
283. Joshi, A.S.; Dincer, I.; Reddy, B.V. Performance Analysis of Photovoltaic Systems: A Review. *Renew. Sustain. Energy Rev.* 2009, *13*, 1884–1897.
284. Darling, S.B.; You, F.; Veselka, T.; Velosa, A. Assumptions and the levelized cost of energy for photovoltaics. *Energy Environ. Sci.* 2011, *4*, 3133–3139.
285. Branker, K.; Pathak, M.J.M.; Pearce, J.M. A review of solar photovoltaic levelized cost of electricity. *Renew. Sustain. Energy Rev.* 2011, *15*, 4470–4482.
286. Sera, D.; Teodorescu, R.; Rodriguez, P. PV Panel Model Based on Datasheet Values. In Proceedings of the 2007 IEEE International Symposium on Industrial Electronics, Vigo, Spain, 4–7 June 2007; pp. 2392–2396. IEEE.
287. Abdulrazzaq, A.K.; Plesz, B.; Bognár, G. A Novel Method for Thermal Modelling of Photovoltaic Modules/Cells under Varying Environmental Conditions. *Energies* 2020, *13*(13), 3318.
288. Cengel, Y.A.; Ghajar, A.J. *Heat and Mass Transfer (in SI Units)*; McGraw-Hill Education: New York, NY, USA, 2014.
289. Najafi, H.; Najafi, B. Sensitivity analysis of a hybrid photovoltaic thermal solar collector. In Proceedings of the 2011 IEEE Electrical Power and Energy Conference, Winnipeg, MB, Canada, 2011, 3–5 October; pp. 62–67.
290. Pop, T.; Buzduga, C.; Ifrim, V. C.; Pentiuc, R.-D.; Bejenar, C. Modeling and Simulation of a Commercial PV/T in MATLAB/Simulink Software Environment. In *Proceedings of the 2022*

International Conference and Exposition on Electrical and Power Engineering, Iasi, Romania, 20–22 October 2022.
291. Al-Waeli, A.H.; Kazem, H.A.; Chaichan, M.T.; Sopian, K. *Photovoltaic/Thermal (PV/T) Systems: Principles, Design, and Applications*; Springer Nature: Cham, Switzerland, 2019.
292. Abdullah, A.L.; Misha, S.; Tamaldin, N.; Rosli, M.A.M.; Sachit, F.A. A Review: Parameters Affecting the PVT Collector Performance on the Thermal, Electrical, and Overall Efficiency of PVT System. *J. Adv. Res. Fluid Mech. Therm. Sci.* 2019, *60*(2), 191–232.
293. Gwandu, B.A.L.; Creasey, D.J. Humidity: A Factor in the Appropriate Positioning of a Photovoltaic Power Station. *Renew. Energy* 1995, *6*(3), 313–316.
294. Sarvi, M.; Azadian, A. A Comprehensive Review and Classified Comparison of MPPT Algorithms in PV Systems. *Energy Systems* 2022, *13*, 281–320.
295. Katche, M.L.; Makokha, A.B.; Zachary, S.O.; Adaramola, M.S. A Comprehensive Review of Maximum Power Point Tracking (MPPT) Techniques Used in Solar PV Systems. *Energies* 2023, *16*(5), 2206.
296. Ahmed, M.T.; Rashel, M.R.; Faisal, F.; Tlemçani, M. Non-Iterative MPPT Method: A Comparative Study. *Energies* 2020, *13*, 1234.
297. Vijayakumari, A. A Non-Iterative MPPT of PV Array with Online Measured Short Circuit and Open Circuit Quantities. *J. King Saud Univ.-Eng. Sci.* 2021, *33*, 176–185.
298. Rashel, M.R.; Albino, A.; Tlemcani, M.; Gonçalves, T.C.; Rifath, J. MATLAB Simulink Modeling of Photovoltaic Cells for Understanding Shadow Effect. *In Proceedings of the 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*, Birmingham, UK, 20–23 November 2016; pp. 747–750.
299. Rashel, M.R.; Albino, A.; Veiga, A.; Ahmed, M.T.; Tlemcani, M.; Goncalves, T.C. Comparison of Photovoltaic Panel's Standard and Simplified Models. *Proceedings of the 2016 International Conference for Students on Applied Engineering (ICSAE)*, Newcastle upon Tyne, UK, 20–21 October 2016; IEEE, pp. 133–136.
300. Jumaat, S.A.; Othman, M.H. Solar Energy Measurement Using Arduino. *MATEC Web of Conferences* 2018, *150*, 01007.
301. Islam, M.; Rashel, M.R.; Ahmed, M.T.; Islam, A.K.; Tlemçani, M. Artificial Intelligence in Photovoltaic Fault Identification and Diagnosis: A Systematic Review. *Energies* 2023, *16*(21), 7417.
302. Qin, L.; Shen, J.; Li, Q.; Shang, Z. Effects of convection patterns on freckle formation of directionally solidified Nickel-based superalloy casting with abruptly varying cross-sections. *J. Cryst. Growth* 2017, *466*, 45–55.
303. Farshchimonfared, M.; Bilbao, J.I.; Sproul, A.B. Full optimisation and sensitivity analysis of a photovoltaic–thermal (PV/T) air system linked to a typical residential building. *Sol. Energy* 2016, *136*, 15–22.
304. Wang, G.; Wang, B.; Yuan, X.; Lin, J.; Chen, Z. Novel design and analysis of a solar PVT system using LFR concentrator and nano-fluids optical filter. *Case Stud. Therm. Eng.* 2021, *27*, 101328.
305. Gu, W.; Ma, T.; Shen, L.; Li, M.; Zhang, Y.; Zhang, W. Coupled electrical-thermal modelling of photovoltaic modules under dynamic conditions. *Energy* 2019, *188*, 116043.
306. Zhe, L.W.; Irwan, Y.M.; Irwanto, M.; Amelia, A.R.; Safwati, I. Influence of wind speed on the performance of photovoltaic panel. *Indones. J. Electr. Eng. Comput. Sci.* 2019, *15*, 62.
307. Tripathi, A.K.; Ray, S.; Aruna, M.; Prasad, S. Evaluation of solar PV panel performance under humid atmosphere. *Mater. Today Proc.* 2021, *45*, 5916–5920.
308. Jiang, H.; Lu, L.; Sun, K. Experimental investigation of the impact of airborne dust deposition on the performance of solar photovoltaic (PV) modules. *Atmos. Environ.* 2011, *45*, 4299–4304.
309. Touati, F.A.; Al-Hitmi, M.A.; Bouchech, H.J. Study of the effects of dust, relative humidity, and temperature on solar PV performance in Doha: Comparison between monocrystalline and amorphous PVS. *Int. J. Green Energy* 2013, *10*, 680–689.
310. Kazem, H.A.; Chaichan, M.T.; Al-Waeli, A.H.; Al-Badi, R.; Fayad, M.A.; Gholami, A. Dust impact on photovoltaic/thermal system in harsh weather conditions. *Sol. Energy* 2022, *245*, 308–321.

311. MathWorks. Photovoltaic-Thermal (PVT) Hybrid Solar Panel. *MathWorks*. 2025. Available online: https://www.mathworks.com/help/sps/ug/photovoltaic-thermal-pvt-hybrid-solar-panel.html (accessed on 10 March 2023).
312. Abou Akrouch, M.; Faraj, J.; Hachem, F.; Castelain, C.; Khaled, M. A Comprehensive Review and Comparison of Cooling Techniques for Photovoltaic Panels: An Emphasis on Experimental Setup and Energy Efficiency Ratios. *Int. J. Thermofluids* 2024, *100774*.
313. Mowafy, A.G. Water-Based Photovoltaic-Thermal Hybrid System. Proceedings of the 2021 IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 2021, pp. 1–8. IEEE.
314. Senthil, R.; Elavarasan, R. M.; Pugazhendhi, R.; Premkumar, M.; Vengadesan, E.; Navakrishnan, S.; Natarajan, S. K. A Holistic Review on the Integration of Heat Pipes in Solar Thermal and Photovoltaic Systems. *Solar Energy* 2021, *227*, 577–605.
315. Shabgard, H.; Allen, M. J.; Sharifi, N.; Benn, S. P.; Faghri, A.; Bergman, T. L. Heat Pipe Heat Exchangers and Heat Sinks: Opportunities, Challenges, Applications, Analysis, and State of the Art. *Int. J. Heat Mass Transf.* 2015, *89*, 138–158.
316. Ismail, B.; Mohammed, B.; Abdelkhalek, O.; Elhadj, S. An Experimental Study of PV/T System Using Parabolic Reflectors and Heat Exchanger. *Indonesian J. Electr. Eng. Comput. Sci.* 2021, *24*(3), 1297–1306.
317. Majid, Z. A. A.; Razak, A. A.; Ruslan, M. H.; Sopian, K. Characteristics of Solar Thermal Absorber Materials for Cross Absorber Design in Solar Air Collector. *Int. J. Automot. Mech. Eng.* 2015, *11*, 2582.
318. Ahmed, M. T.; Rashel, M. R.; Islam, M.; Hoque, T. T.; Tlemçani, M.; Janeiro, F. M. Characterization, Performance, and Efficiency Analysis of Hybrid Photovoltaic Thermal (PVT) Systems. *Energies* 2025, *18*(5), 1050.
319. Ahmed, M. T.; Rashel, M. R.; Ali, M.S.; Ahmed, M. J.; Janeiro, F. M.; Tlemçani, M. Development of IoT-Based Monitoring and Fault Detection Technique of Hybrid PVT System. *Proceedings of the 2nd International Workshop on Mathematics and Physical Sciences*, 2024, p. 54.