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ΣΧΕΔΙΑΣΜΟΣ ΚΑΙ ΠΡΟΚΑΤΑΡΚΤΙΚΗ ΑΞΙΟΛΟΓΗΣΗ ΥΒΡΙΔΙΚΟΥ ΦΩΤΟΒΟΛΤΑΪΚΟΥ/ΘΕΡΜΙΚΟΥ ΣΥΣΤΗΜΑΤΟΣ ΜΕ ΑΞΙΟΠΟΙΗΣΗ ΥΛΙΚΩΝ ΑΛΛΑΓΗΣ ΦΑΣΗΣ (PVPCM-T)

DESIGN AND PRELIMINARY EVALUATION OF A HYBRID PHOTOVOLTAIC/THERMAL SYSTEM USING PHASE CHANGE MATERIALS (PVPCM-T)

ΜΑΡΙΑ ΡΙΚΑ ΠΑΠΠΑ

ΤΡΙΜΕΛΗΣ ΕΠΙΤΡΟΠΗ

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Ευχαριστίες

Στην παρούσα διπλωματική εργασία, θα ήθελα να εκφράσω τις θερμές μου ευχαριστίες στον επιβλέποντα καθηγητή μου, κ. Γεώργιο Αραμπατζή, για την αμέριστη υποστήριξη, τις πολύτιμες συμβουλές και την καθοδήγησή του καθ' όλη τη διάρκεια της έρευνας μου.

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CONTENTS

ABSTRACT

Investigations demonstrate that excessive operating temperatures of photovoltaic (PV) modules diminish their efficiency and operational lifespan. To counter this, embedding Phase Change Materials (PCM) into PV systems can help in reducing the operating temperatures and elevating overall performance. This study examines a combination of Photovoltaic/Thermal technology with p hase Change Materials system meticulously designed with copper pipes arranged in a serpentine configuration, submerged in RT42 paraffin wax, and utilizing circulating water to optimize heat dissipation. The system was meticulously modeled and simulated within the ANSYS Fluent environment, employing data gathered under the elevated thermal conditions characteristic of Chania, Crete. The investigation included three instances: the PCM at 50°C did not achieve complete melting, with water temperatures settling at 40°C; at 55°C, it melted after 6.22 hours, producing water at 45°C; and at 64.5°C, the PCM melted in 3.3 hours, maintaining low PV temperatures for more than 3.3 hours and generating water at 50°C. The findings indicate that the integration of PCM within the system significantly enhances both electrical and thermal efficiency, effectively postponing the escalation of PV module temperatures during peak solar irradiance periods. The system's capability to simultaneously generate electricity and produce hot water exemplifies its versatility, particularly in regions characterized by high solar exposure. Prospective enhancements may encompass real-time electrical monitoring, comprehensive life cycle assessments, and the incorporation of environmentally sustainable materials. In summary, the PV-PCM-T system presents a pragmatic approach Created to enhance the efficiency and electricity production of PV modules in areas with strong sunlight, by optimizing their performance a nd energy generation.

ΠΕΡΙΛΗΨΗ

Η ερευνητική δραστηριότητα στον τομέα των ΑΠΕ έχει ότι οι υπερβολικές θερμοκρασίες λειτουργίας των φωτοβολταϊκών (PV) πλαισίων μειώνουν την αποδοτικότητά τους και τη διάρκεια ζωής τους. Για να αντιμετωπιστεί αυτό, η ενσωμάτωση Υλικών Αλλαγής Φάσης (PCM) στα φωτοβολταϊκά συστήματα μπορεί να βοηθήσει στη μείωση των θερμοκρασιών λειτουργίας και στην αύξηση της συνολικής απόδοσης. Αυτή η διατριβή μελετά ένα υβριδικό σύστημα Φωτοβολταϊκού/Θερμικού (PV-PCM-T), το οποίο έχει σχεδιαστεί προσεκτικά με σωλήνες χαλκού διαμορφωμένους σε σχήμα σερπαντίνας, βυθισμένους σε παραφίνη RT42, και χρησιμοποιεί κυκλοφορούν νερό για τη βέλτιστη απομάκρυνση θερμότητας. Το σύστημα μοντελοποιήθηκε και προσομοιώθηκε λεπτομερώς στο περιβάλλον ANSYS Fluent, χρησιμοποιώντας δεδομένα που συλλέχθηκαν υπό τις αυξημένες θερμικές συνθήκες που χαρακτηρίζουν τα Χανιά της Κρήτης. Η μελέτη περιλάμβανε τρεις περιπτώσεις: στην πρώτη, το PCM στους 50°C δεν έλιωσε πλήρως, με τη θερμοκρασία του νερού να σταθεροποιείται στους 40°C· στη δεύτερη, στους 55°C, το PCM έλιωσε μετά από 6,22 ώρες, παράγοντας νερό στους 45°C· και στην τρίτη, στους 64,5°C, το PCM έλιωσε σε 3,3 ώρες, διατηρώντας χαμηλές θερμοκρασίες στα PV για περισσότερες από 3,3 ώρες και παράγοντας νερό στους 50°C. Τα ευρήματα δείχνουν ότι η ενσωμάτωση του PCM στο σύστημα βελτιώνει σημαντικά τόσο την ηλεκτρική όσο και τη θερμική απόδοση, καθυστερώντας αποτελεσματικά την αύξηση της θερμοκρασίας των φωτοβολταϊκών πλαισίων κατά τις περιόδους μέγιστης ηλιακής ακτινοβολίας. Η ικανότητα του συστήματος να παράγει ταυτόχρονα ηλεκτρισμό και ζεστό νερό υποδεικνύει την ευελιξία του, ιδιαίτερα σε περιοχές με υψηλή ηλιακή έκθεση. Οι μελλοντικές βελτιώσεις θα μπορούσαν να περιλαμβάνουν παρακολούθηση ηλεκτρικών μετρήσεων σε πραγματικό χρόνο, ολοκληρωμένες αξιολογήσεις κύκλου ζωής και την ενσωμάτωση περιβαλλοντικά βιώσιμων υλικών. Συμπερασματικά, το σύστημα PV-PCM-T προσφέρει μια πρακτική προσέγγιση για τη βελτιστοποίηση της απόδοσης των φωτοβολταϊκών πλαισίων και της ενεργειακής απόδοσης σε περιοχές με αυξημένη ηλιακή ένταση.

Table of Abbreviations

Abbreviation	*Full Term*
C_M	The heat storage capacity of the solar panel (J/K)
E_c	Thermal energy transferred to the PCM during a selected period (KWh)
G_t	Solar Irradiance
G_{STC}	Solar radiation under standard test conditions (STC) [W/m^2]
HNMS	Hellenic National Meteorological Service
ε	Emissivity
h	Heat Transfer Coefficient
K	Heat transfer ability (W/m·K)
ΔT	Temperature gradient
P_{STC}	Nominal power of the PV under typical test conditions (STC) [W/ m2]
P_{sol}	Solar power absorbed as heat(W)
P_{rad}	Electrical energy generation from the photovoltaic module (W)
P_M	Energy flow through convection from the photovoltaic panel to the environment (W)
P_{conv}	Power exchange through radiation between the surfaces of the photovoltaic panel and the sky/ground (W)
P_C	thermal energy conveyed to the phase change material (W)
PCM	Phase Change Material
PV	Photovoltaic
PVT	Photovoltaic Thermal
RES	Renewable Energy Sources
STC	Standard Test Conditions
T_a	Ambient Temperature
T_{PV}	Operating Temperature of PV
$T_{PV,front}$	Heat of the posterior face of the PV panel (°C)
$T_{PV,back}$	Temperature of the posterior aspect of the photovoltaic module (°C)
$T_{PCM,melt}$	Melting temperature of PCM
T_{sky}	Temperature of the sky (°C)
T_{ground}	Surface temperature of the terrestrial environment (°C)
t	Time (s) (m/s)
v_w	Wind velocity

α	the attenuation coefficient of the incident solar irradiance
β	The inclination angle of the photovoltaic module (°)
γ_{PM}	Thermal power coefficient [%/℃]
ε	Emissivity
ε_{mFront}	The capacity of the solar panel's front surface to emit radiation.
ε_{mBack}	The radiation emission capability of the rear surface of the photovoltaic panel
σ	Stefan-Boltzmann constant ($W/K^4 \cdot m^2$)
n_{elec}	Electrical Efficiency

Table 1: Table of Abbreviations

CHAPTER 1- Introduction

1.1 Photovoltaic Technology growth and its significance.

As technology rapidly advances, coupled with a growing demand for comfort, improved mobility, and an ever-increasing global population, energy consumption has surged at an unprecedented pace. The heavy dependence on fossil fuels has greatly contributed to environmental damage, especially through rising pollution levels, which remains a major issue. In response to this, renewable energy technologies hold significant promise for meeting global energy needs while minimizing environmental harm. Solar energy is acknowledged as an exceptionally practical and consistent renewable energy option, driving numerous government agencies to kickstart incentive programs focusedon promoting the development of solar energy infrastructure, including solar panels used for generating electricity. The photovoltaic method permits the instant changeover of solar radiation into electric power. PV systems consist of solar cells that capture solar radiation and convert it into electricity. These cellular structures are composed of strata of semiconducting substances, and upon exposure to solar radiation, an electric powered field is produced throughout the strata, culminating in the motion of electrical current. The quantity of electrical energy produced by each photovoltaic cell is intrinsically correlated to the intensity of solar radiation, indicating that the efficacy of energy conversion predominantly hinges upon the prevailing illumination conditions. (Tyagi *et al.*, 2013)

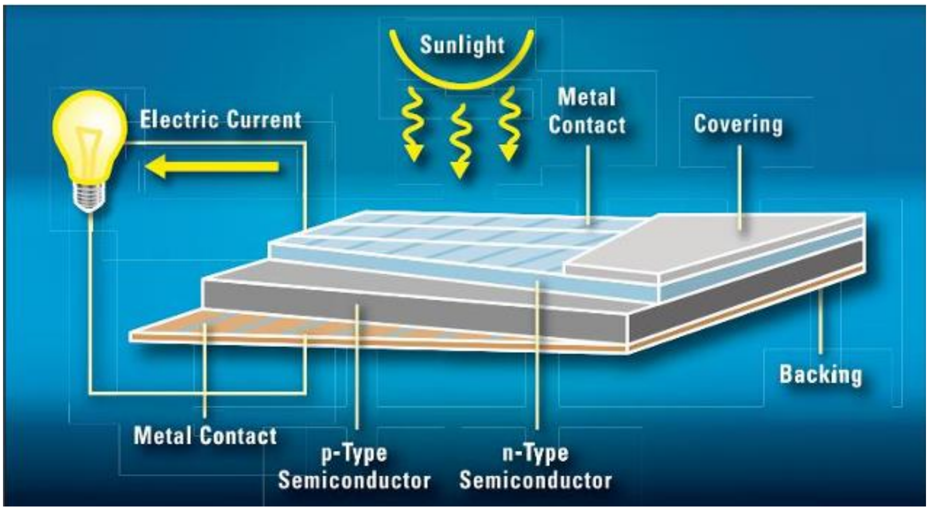

Figure 1: A basic solar cell

Lately, the area of solar power technology has witnessed remarkable progress, motivated by technological discoveries, encouraging legislative frameworks, and a heightened understanding of the critical need for renewable energy options. The developments recognized in photovoltaic technology have been sparked by a multitude of inventive concepts that have essentially revamped the industry (Singh, 2013). However, the existing photovoltaic (PV) arrangements continue to be somewhat confined, responsible for only 0.1% of the complete worldwide energy output. Despite this limitation, market analysts posit that the growth rate of photovoltaic installations averages 40% annually. Throughout the preceding five years, PV technology has successfully diminished its cost per unit by approximately one-third. With persistent technological advancements and continuous research endeavors aimed at enhancing efficiency, photovoltaic technology is anticipated to sustain its accelerated growth trajectory and ultimately establish itself as a prominent global energy source. By 2022, estimates estimate the worldwide cumulative capacity of solar PV systems to a whopping 1177 gigawatts (GW), highlighting a significant accomplishment in the adoption of sustainable energy alternatives. The year 2022 alone witnessed the assembly of around 237 GW of new PV capacity, emphasizing the swift proliferation of this sector. The notable escalation in photovoltaic installations has resulted in a 25.2% augmentation in energy output relative to the preceding year, thereby illustrating the enhanced efficacy and potential of contemporary photovoltaic technologies. Worldwide trends in solar energy indicate a substantial increase in photovoltaic installations, mirroring the swift proliferation of this renewable energy source.(Syahirah *et al.*, 2022)

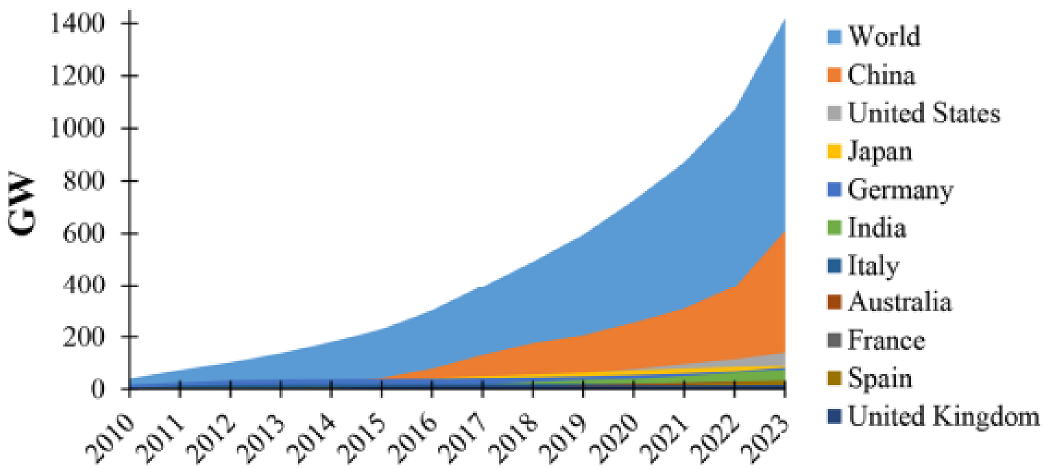

Figure 2 : Assessment of the yearly photovoltaic installations (GW) (Hossain *et al.*, 2024)

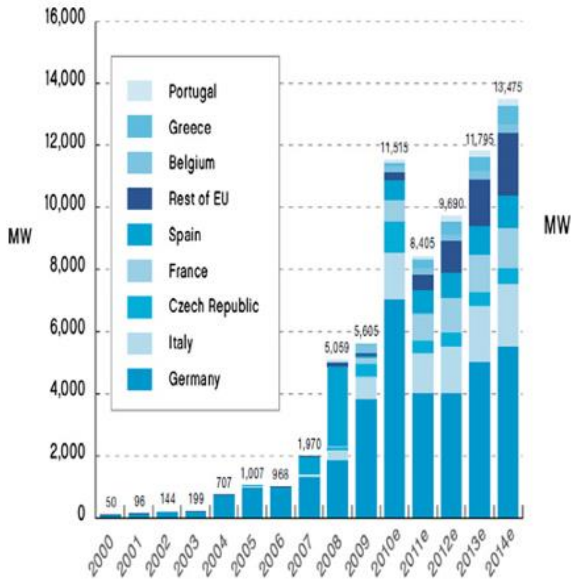

Figure 3: Photovoltaic division in European Continent

(Tyagi *et al.*, 2013)

It is anticipated that solar photovoltaic (PV) technology, along with wind energy, will play a key role in changing the structure of the worldwide power network. In the coming decades, Solar PV is anticipated to provide 25% of the total global electricity requirements , representing an over tenfold growth in its portion of the energy mix compared to 2016 levels. Reaching this objective will necessitate a significant expansion of solar PV capacity, reaching 8,519 gigawatts (GW) by 2050. *(Hossain* et al.*, 2024)*.

1.2 Factors Influencing the Effectiveness of a Photovoltaic Module

The operational effectiveness of photovoltaic systems is contingent upon various determinants, which can generally be grouped into environmental conditions, material properties, and the components of the system. The thermal performance conditions of photovoltaic cells will play a crucial rol e in the environment. This happens because only a small portion of the sunlight—usually less than 20%—is turned into electricity. This occurs because only a limited amount of sunlight is involved. The rise in cell temperature leads to a drop in their open circuit voltage, leading to a slight decrease in efficiency for every degree Celsius increase in temperature.

Dust accumulation on solar panels is another element that can impact how we ll they operate. Particulate matter, such as dust, has the potential to obstruct solar radiation from penetrating the cellular structures, thereby diminishing the quantum of energy they are capable of producing. The impact on efficiency depends on how much dust there is and the size of the particles.

Finer particles are in a position to block a lot more light, which has a bigger effect on the functional efficiency of the module. A photovoltaics' (PV) module effectiveness, can depend heavily on the amount of sunlight it receives, making solar radiation a key factor. The level of sunlight fluctuates throughout the day, reaching its peak energy production when the module is directly positioned in the sunlight. Seasonal changes and weather conditions, like cloud cover, could be the reason for low radiation reception. Additionally, shadows from nearby objects can partially block the panels, leading to a big drop in energy production since solar panels do not respond well to shading in an easy manner.(Jathar *et al.*, 2023)

The type of semiconductor material used in photovoltaic (PV) cells is a key factor in their overall efficiency. For example, silicon-based cells vary in performance depending on whether they are monocrystalline, polycrystalline, or amorphous. Monocrystalline silicon cells typically provide better efficiency than polycrystalline or amorphous cells because of their uniform crystal structure and higher purity.(Venkateswari and Sreejith, 2019)

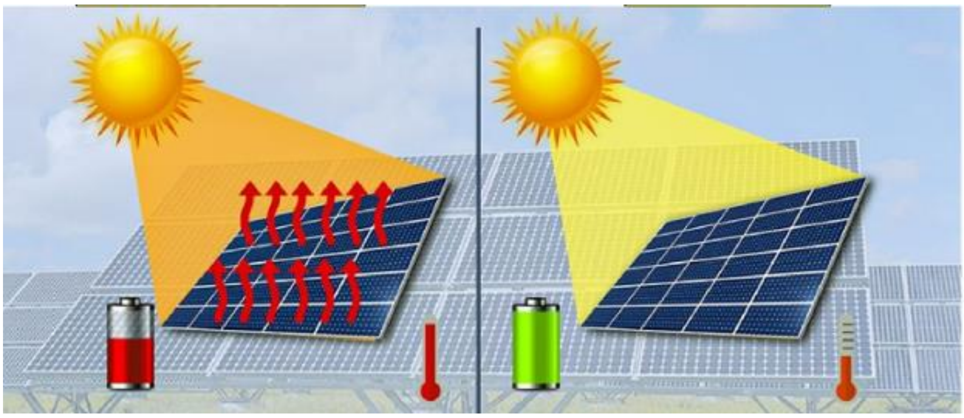

Figure 4: Solar panels do not respond well to shading in an easy manner.

In conclusion, the factors that affect the operational efficiency of a photovoltaic system are outlined as follows:

- Material of the Solar Cells
- Temperature
- Material of the Solar Cells
- Irradiance (Sunlight Intensity)
- Angle and Orientation of the Solar Panels
- Shading
- Dust, Dirt, and Debris
- Age and Degradation of Panels
- Reflection Losses
- Wiring and Connections
- Inverter Efficiency

- Spectral Content of Sunlight
- System Design (including MPPT)

1.3 Photovoltaic Thermal Panels

PVT solar collectors are designed to generate both thermal and electrical energy at the same time. Ongoing explorations are centered on establishing innovative cooling solutions for these configurations, which typically feature solar photovoltaic panels, a collector for thermal energy, and a medium to facilitate heat transfer. The solar energy panels are key in changing sunlight into electrical power, in contrast, the thermal collector is designated to gather the extra thermal energy created in this transformation process. In an effort to boost operational efficiency, fluids like water or nanofluids are employed. A key part of making PVT systems more efficient is the use of a solar absorber with built-in fluid channels to help manage the heat. (Emmanuel *et al.*, 2021)

Setup allows for effective heat transfer, which is essential for keeping the module's temperature at an optimal level.
The collector's construction and design are also significant factors.
Additionally, the shape of the thermal collector matters; designs with an arched cross-section tend to perform better than those with a rectangular shape. Modifying the size and spacing of the flow channels within the collector can further improve thermal regulation, leading to an overall increase in energy efficiency. (Pang *et al.*, 2020)

When comparing PVT modules to traditional photovoltaic systems, the clear advantage of PVT technology lies in its ability to serve dual purposes. The primary function of traditional photovoltaic systems is to convert sunlight to electric power with typical efficiencies ranging between 6% and 20%. In contrast, PVT modules not just produce electrical energy but additionally shoot winter energy, using the heat created from solar radiation to increase total power output. The integration of each thermal and electrical energy production facilitates their application for heating purposes within commercial or residential settings. In turn, photovoltaic-thermal (PVT) systems exhibit a greater energy production per unit area versus independent photovoltaic panels. Moreover, PVT systems have the added benefit of managing excess heat that can reduce the efficiency of traditional photovoltaic modules. By converting this excess heat into useful thermal energy, PVT modules help prevent overheating, which in turn can maintain or even improve electrical efficiency. This methodology not only enhances the overall energy output but also advances sustainability objectives by optimizing the utilization of accessible solar energy resources. As a result, the integration of photovoltaic thermal (PVT) systems straight into energy networks can result in more efficient and adaptable energy generation, thereby fostering sustainable energy solutions for the future. (Dubey and Tay, 2013) , (Ma, Li and Kazemian, 2020)

1.4 Phase-Change-Materials

PCMs have garnered significant academic interest in contemporary research due to their unique properties and broad applicability within diverse industrial domains. A PCM is a substance that transitions between different states of matter by absorbing and releasing energy through a phase change process, which occurs at a specific temperature *(Figure 6).* The phase change heat storage consists of three fundamental mechanisms: solid sensible heat storage, liquid latent heat storage, and sensible heat storage. When the PCM reaches its melting point, it absorbs latent heat, causing it to melt further. Notably, latent heat storage in PCM holds three times more energy than sensible heat storage.

PCMs are systematically classified into various categories, encompassing organic compounds, inorganic substances, and eutectic mixtures, each yielding distinct benefits that are specifically aligned with a multitude of applications. The thermal properties of phase change materials (PCMs), such as their significant heat absorption during melting and large capacity to store heat, equip them with enhanced capabilities for efficiently storing and releasing thermal energy.

PCMs can be systematically categorized into accordance with their operational temperature ranges, chemical compositions, and the phase transition phenomena they undergo. Phase change materials are for starters split into 4 main thermal categories: the low temperature range , the medium low range, the moderate range and the high temperature range.

The corresponding temperatures in each range are:

-20°C to 5°C

5°C to 40°C

40°C to 80°C

80°C to 200°C.

This categorization is important when choosing the right PCMs for different purposes, such as using low temperature PCMs in refrigerated items and high temperature PCMs in solar power systems.(Du *et al.*, 2018).

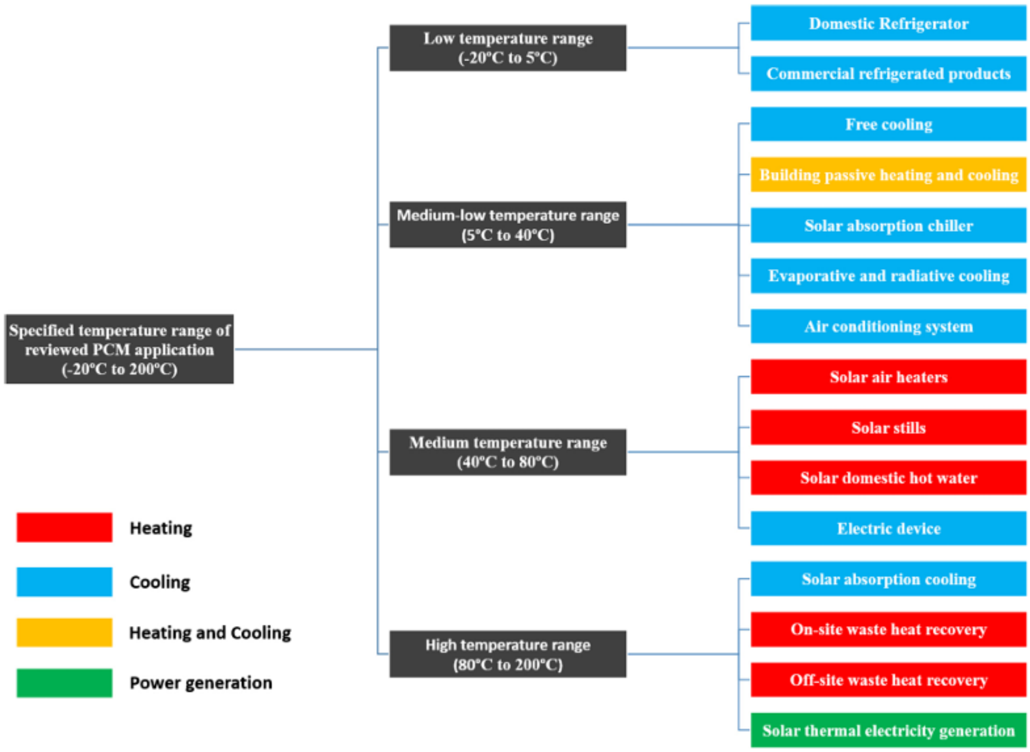

Figure 5: Categorization of examined utilizations of PCMs within specified temperature intervals.

Phase change materials are also categorized into three types, according to their chemical composition:

- organic,
- inorganic, and
- eutectic

Organic materials that phase-change, exemplified by paraffin and fatty acids, are recognized for their superior thermal stability throughout multiple phase transition cycles, rendering them particularly suitable for a variety of engineering applications. Inorganic PCMs, which encompass salt hydrates and metallic substances, typically provide enhanced latent heat storage capacities; however, they may encounter challenges such as phase segregation.

Eutectic PCMs consist of uniform mixtures that demonstrate congruent melting and freezing behaviors, and they may be formulated from

- organic-organic,
- inorganic-organic, or
- inorganic-inorganic compounds.

Finally, PCMs may also be categorized according to the nature of the phase transition process:

- solid-liquid,
- liquid-gas, and
- solid-solid transitions.

Solid-liquid phase change materials, primarily employed due to their comparatively straightforward encapsulation methodologies and their versatility in various thermal management applications. A comprehensive understanding of these classifications facilitates the judicious selection and implementation of PCMs across various domains, underscoring the critical need for focused research and development aimed at optimizing their efficacy in specific contexts .(Leong, Abdul Rahman and Gurunathan, 2019)

The thermal traits of phase change materials (PCMs) are significant factors that deeply affect their performance and role in multiple domains. The thermal characteristics of phase change materials (PCMs) represent critical determinants that profoundly influence their efficacy and function across various disciplines. The limited ability of PCMs to conduct heat is a significant barrier, as it restricts their effectiveness in absorbing and releasing thermal energy during phase transitions.(Singh, Sadeghi and Shabani, 2019)

Choosing the right PCMs is crucial for assessing the efficiency of thermal po wer storing systems, particularly in situations needing high-temperature functions. High-temperature PCMs, including molten salts and metallic alloys, are the focus of extensive research endeavors owing to their significant potential in the storage and release of considerable quantities of thermal energy across multiple cycles. The naturally high heat capacity displayed during the phase change process allows these materials to store significantly more energy compared to sensible heat storage systems, thus promoting a more isothermal operation throughout the charging and discharging processes. Advances in material selection, alongside the thorough examination of thermophysical properties, are essential for the advancement of more efficient PCMs that can endure elevated temperatures without succumbing to degradation. (Wei *et al.*, 2018) (Huang *et al.*, 2017).

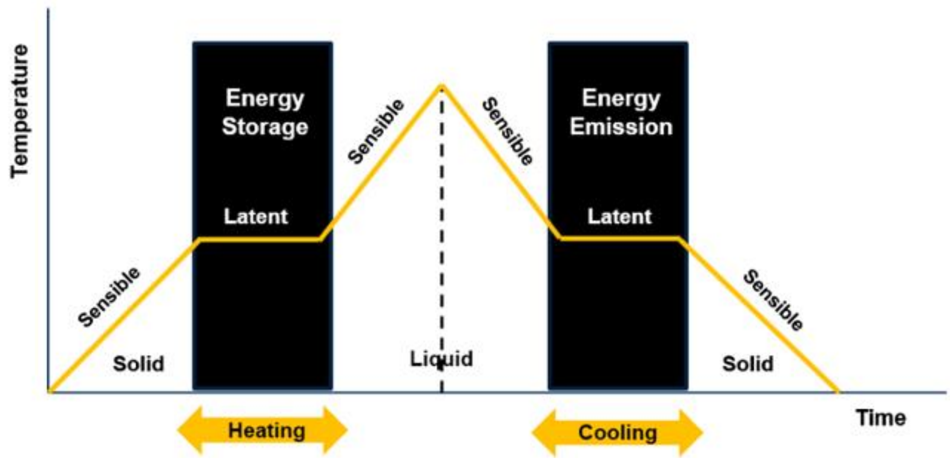

Figure 6: Representation illustrating the transition of phases within Phase Change Materials (PCM).

1.5 Subject of the Study

Addressing climate change has made renewable energy sources (RES) absolutely necessary. Within this category, photovoltaic technology is particularly distinguished by its numerous advantageous attributes. The sphere of solar panel technology has undergone quick evolution and expansion lately. Despite this progress, certain factors significantly influence the efficiency of photovoltaic systems. These factors, as discussed in paragraph 1.2, are subject to ongoing research aimed at minimizing their effects. The temperature at which solar panels function significantly influences their energy efficiency and overall lifespan. Consequently, developing effective techniques to mitigate these impacts remains a critical challenge for advancing photovoltaic technology.

This diploma thesis explores the design and implementation of systems aimed at controlling the operating temperatures of photovoltaic/thermal setups through the use of phase change materials. (PCM) and water as cooling mechanisms to aid in the release of heat from photovoltaic cells. The system, commonly designated as "PV-PCM-Thermal," not only produces electrical energy but also captures the thermal energy emitted from photovoltaic panels to elevate the temperature of water or alternative fluids. The incorporation of this dual function remarkably improves the total effectiveness of PV-T systems, permitting them to harness a larger variety of sun power.

The performance of the system is assessed in comparison to a non-PCM system under the real-world conditions of the Mediterranean in Chania, Crete.to assess the advantages of the proposed method and identify potential improvements. Additionally, the research prioritizes developing operational temperature estimation models for PV-PCM-T systems based on experimental data and formulating a universal design methodology for such systems. The design is based on an existing theoretical energy balance model for a photovoltaic system.

In a nutshell, the aims of this diploma thesis include:

- Establishing a detailed methodological framework for assessing PV-PCM-T systems.
- Creating a design methodology for PV-PCM-T systems, substantiated largely through the accuracy of the theoretical energy balance model.
- Defining criteria for constructing proposed temperature management setups for photovoltaic modules.
- Construction of a PV-PCM-T system
- Performing an adequate number of experimental tests to thoroughly examine the operating temperatures of PCM-equipped thermophotovoltaic and conventional photovoltaic systems.
- Assessing the energy performance (output power, energy generation, efficiency) of both photovoltaic configurations and comparing them using

experimental findings. The study aims to compare the PV-PCM-T system with similar international research efforts.

- Concluding with insights.

These findings are expected to offer valuable information on enhancements necessary for incorporating cooling systems into current or future photovoltaic installations, with a primary focus on boosting energy efficiency and a secondary aim of generating usable hot water.

CHAPTER 2 – State of the art

2.1 Utilization of PCMS as a Cooling Technique for Photovoltaic Components.

In looking at the primary subject of this particular dissertation, several pertinent research emerges within the global academic community. These studies mostly focus on improving methods which employ PCMs to control the heat of photovoltaic (PV) panels. Particularly, this passive cooling technique combines a photovoltaic board with a specific kind of PCM, developing a bundled structure which improves energy efficiency and improves the transformation of solar power into electrical energy. Usually, a PV + PCM method is composed of a separate storage compartment for the PCM, connected to the rear of the solar panel. The PCM captures extra heating through the solar energy panel as latent heat, keeping the panel 's heat within the PCM's phase change range for extended periods. This course of action happens as heat transfers in the board to the PCM, initiating a solid-to-liquid phase change without the demand for extra power input. So, this strategy effectively cools the solar panel, protects the units from winter stress and damage, and also boosts the entire effectiveness of power transformation.(Sheik *et al.*, 2022)

2.1.1 Simulation and numerical modeling of the performance of PV-PCM systems

In 2004, there was a notable shift in the development of PV+PCM systems with the first thorough study of photovoltaic setups using phase change materials, as documented by Huang eta al. Huang and his group conducted a comprehensive study, which investigated the roles of PCMs in facilitating thermal management of photovoltaic (PV) systems embedded in structures. Their research amalgamated both empirical methodologies and computational simulations to assess the efficacy of PCMs in maintaining photovoltaic panel temperatures within optimal limits. This factor is crucial, as higher temperatures can significantly reduce both the efficiency and lifespan of photovoltaic panels.

Throughout the testing period, the scientists created a solar panel setup that included phase change materials and evaluated its performance in different weather conditions. They made use of a finite volume heat transfer model in two dimensions to predict the temperature distribution and heat transfer properties. Experimental evidence proved the model was valid and proved that by incorporating phase change materials the photovoltaic panel maximum temperature could be decreased by almost 10' C during extreme solar conditions.(Huang, Eames and Norton, 2004)

The study revealed that, in the absence of PCM, panel temperatures could surpass 55°C on sunny days, which is well above the ideal operating range of 25°C to 35°C for PV panels. However, with the use of PCM, temperatures were kept below 45°C, ensuring a more stable and efficient operation. The numerical analysis included a parametric study that examined different configurations of Photovoltaic with PCM systems. The simulation results demonstrated that the placement and amount of PCM played a crucial role in the system's ability to manage heat. For instance, increasing the thickness of the PCM by 2 cm caused a further 4% drop in temperature under the same conditions.

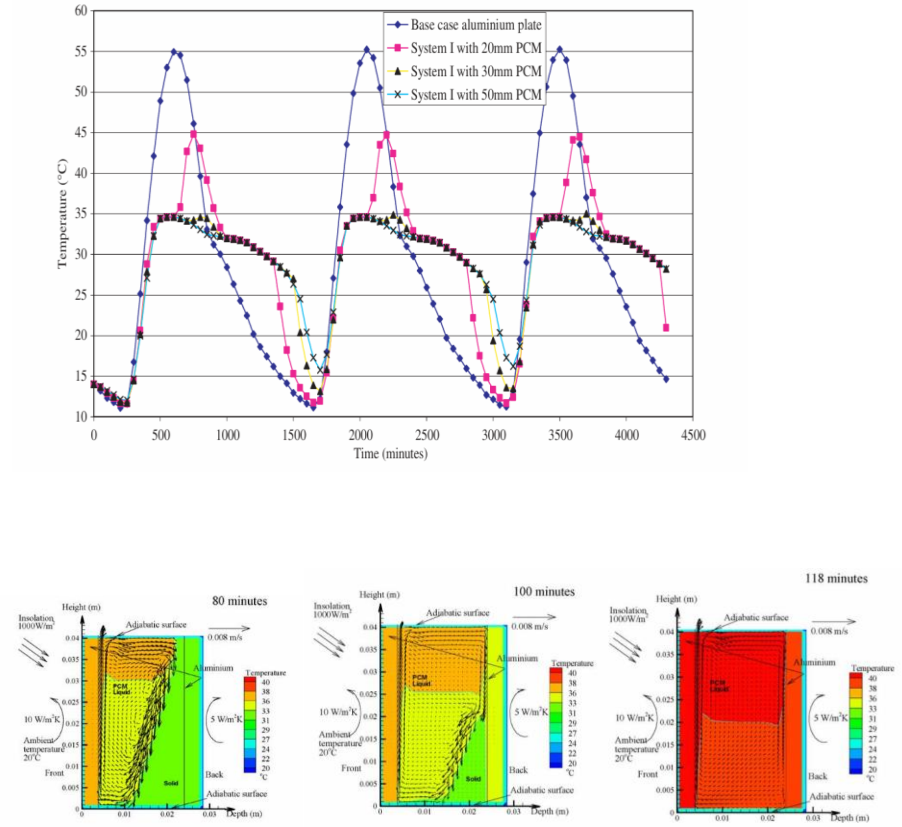

Figure 7: Schematic illustration and initial results of Huang's research

(Huang, Eames and Norton, 2004).

Two years later, the same research team conducted a follow-up study on PV+PCM systems. Huang and his colleagues demonstrated that incorporating PCMs into PV systems can significantly reduce operating temperatures, thereby improving electrical conversion efficiency. They tested two specific types of PCMs, RT25 and GR40, to assess how they affect the way in which PV panels manage heat under various operational conditions.

A crucial finding from their trials was that adding internal fins to the PCM containers significantly enhanced heat dissipation. By setting the amount and plan of these fins, the analysis provided useful insights into optimizing PV/PCM system designs for optimum thermal efficiency. For example, using RT25 with strategically placed aluminum fins led to a temperature reduction of more than 30°C set alongside a system with no PCM.

Additionally, the numerical analysis, supported by experimental validation, enabled Huang and his team to provide predictive insights into how these systems behave under various operating conditions. They concluded that PCMs, especially when used alongside well-designed internal fins, present an effective solution for controlling temperature increases in PV panels, leading to improved performance and longevity. This research not only broadens our understanding of thermal management in solar energy systems but also paves the way for future studies on integrating advanced materials and designs to further enhance of solar panels integrated into building structures.

(Huang, Eames and Norton, 2006)

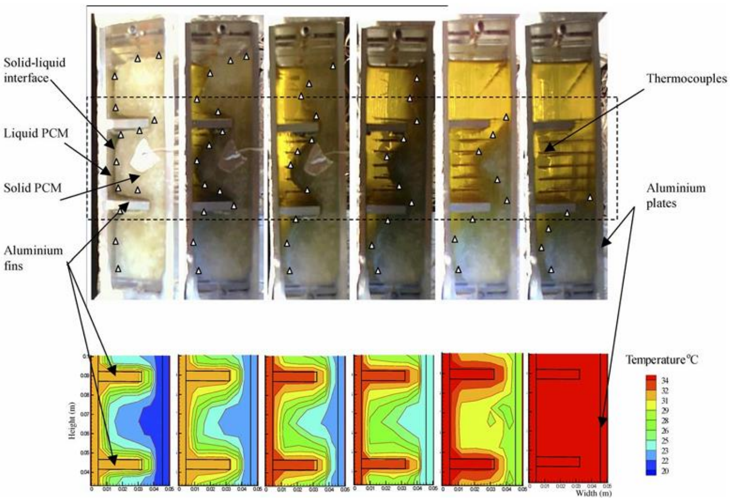

Figure 8: Photographs as well as temperature profiles , to document the melting process of the pcm

(Huang, Eames and Norton, 2006)

Several years after the initial research, Sourav Khanna and his team (Khanna, Reddy and Mallick, 2018) conducted a study focused on optimizing solar photovoltaic systems that incorporate fins and phase change materials (PCMs). This research highlights the significant role that combining PCMs with fins plays in improving the thermal regulation of photovoltaic systems, thereby enhancing their overall efficiency. The research determined the best setups for the PCM container by modifying its depth, which significantly influenced the thermal efficiency of the system. For solar irradiance amounts of three kWh / m2 / day, researchers found that a container depth of 2.8 cm was optimal, but rose to 4.6 cm below 5 kWh / m2 / day irradiance. The ideal temperature conditions for PV cells were maintained at these depths, leading to decreased temperatures and an extended duration.

Additionally, the study explored how fin spacing, thickness, and length affected the system's thermal performance. The findings indicated that a fin spacing of 25 cm was most effective for efficient heat transfer. Furthermore, fin thickness proved to be a key factor, with 2 mm identified as the optimal thickness, balancing thermal conductivity and material efficiency.

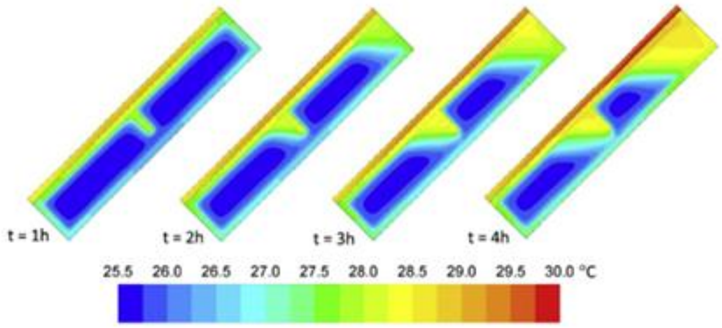

Figure 9: Thermal conditions of the Finned-PV-PCM configuration

(Khanna, Reddy and Mallick, 2018)

In 2019, Grabo and his colleagues created a mathematical model to analyze just how heat is distributed in a photovoltaic module with phase change material. This model successfully accounted for important heat transfer mechanisms such as conduction, convection, and radiation, as well as the melting and solidification characteristics of the PCM. The computational technique used a repeated and indirect process in MATLAB to make accurate alterations based on elements like shape, substance characteristics, and fluctuating surroundings like sunlight exposure, surrounding temperature, and air movement. Simulation outcomes were compared with experimental data, showing an average deviation of just ±1.7 K, providing strong validation of the model's ability to predict thermal behavior in PCM-enhanced PV modules. Notably, the research showed that using PCM could extend the lifespan of PV modules by up to 10 years. However, the study also observed a roughly 12% decrease in energy production compared to PV systems without PCM, illustrating a balance between increased durability and reduced energy output. (Grabo *et al.*, 2019)

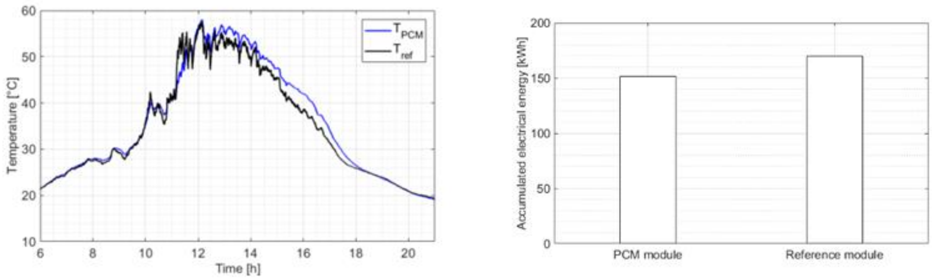

Figure 10: Comparison of temperatures for two modules.

In the year 2020, Mahmoud B. Elsheniti along with his research team discovered a novel one dimensional enhanced conduction model (ECM) meant to raise the simulation capabilities of photovoltaic (PV) panels by leveraging phase change materials (PCMs) for thermal regulation. This model modifies the effective thermal conductivity to integrate the influences of convection within the PCM throughout both melting & solidification processes, thereby significantly increasing the computational process. The analysis demonstrated that this particular product may substantially lower computation time by 2 to 3 orders of magnitude than normal computational fluid dynamics (CFD) versions, all while upholding a good degree of accuracy.

The ECM underwent rigorous validation against empirical data, demonstrating substantial correspondence, which signifies its applicability for real-world scenarios. The research team performed simulations under a variety of conditions, encompassing differing panel inclinations and aspect ratios, which yielded critical insights for optimizing PV/PCM systems to enhance energy production and thermal management. A pivotal finding indicated that the adjustment of the inclination angle of the PV panels exerts a considerable influence on the cooling progress of the PCMs. The study elaborated on how alterations in angles affect heat transfer within the PCMs, offering strategic recommendations for optimizing PV panel configurations to maximize energy efficiency and prolong system longevity in practical applications.(Elsheniti *et al.*, 2020)

In a subsequent scholarly inquiry, Stefano Amelia, Roberta Arena, and Antonio Gagliano focused on enhancing the operational efficiency PV modules through the application of PCMs. The research undertook comprehensive numerical simulations to juxtapose a conventional PV module with a modified variant that integrates PCMs, with the objective of augmenting its thermal and electrical performance. The numerical findings derived from their simulations indicate that the PV-PCM configuration can significantly alleviate the increase in temperature within PV cells during periods of peak solar irradiation. The study revealed a decrease in maximum cell temperature ranging from 5 °C to 12 °C, which is likely to be influenced by PCM properties and environmental conditions. This thermal regulation directly contributed to an enhancement in electrical efficiency by 3.5% on an annual basis and a peak power output increase of 10% during the warmest months. Furthermore, the dynamic behavior of the PCM throughout the thermal cycles revealed critical insights regarding their effectiveness. PCMs with lower melting points failed to achieve complete solidification overnight, thus storing a lesser quantity of thermal energy than initially projected. In contrast, PCMs with higher melting points exhibited superior thermal management by attaining complete solidification at night and effectively storing and releasing heat throughout the day. (Aneli, Arena and Gagliano, 2021)

(Ahmad *et al.*, 2021)

In the same year, a study led by Abdalqader Ahmad and his team employed computational fluid dynamics (CFD) to analyze various PCM configurations under different environmental conditions. The research explored multiple PCMs with varying phase change temperatures, specifically RT42, RT31, and RT25, evaluating their effectiveness in systems both with and without insulation. The CFD simulations demonstrated that trapezoidal PCM containers significantly outperformed traditional rectangular ones in cooling the PV modules. This design enabled a more consistent distribution of temperature throughout the module, and that is crucial for ensuring optimal efficiency. The study quantitatively showed that the optimal configuration could increase system efficiency by 17% and boost power output by 14.6% during peak solar exposure. These setups not only kept the PV module temperatures up to 5°C lower than the ambient temperature but also proved effective under a range of thermal conditions. Furthermore, adding insulation to the PCM design enhanced the thermal performance but required a larger volume of PCM to achieve optimal results. For instance, the comparative analysis between insulated and non-insulated systems revealed that the volume of PCM needed increased depending on the specific PCM used, highlighting a trade-off between thermal management efficiency and material usage

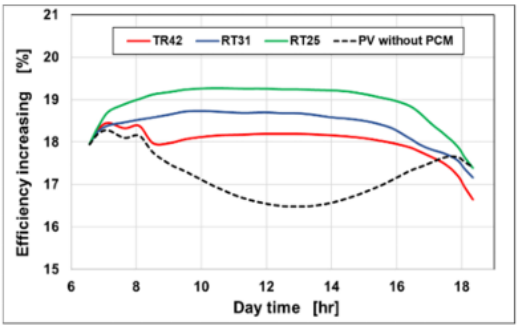

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Figure 11: PV module efficiency at the operation temperature

(Ahmad *et al.*, 2021)

Deepak Kumar Sharma and colleagues conducted an empirical investigation into the effect of phase change materials (PCMs) over the winter performance of photovoltaic (PV) systems. This research offers a quantitative analysis of how PCMs is able to better PV efficiency by controlling temperature under real world environmental conditions. Sharma, Rathod, and also Bhale developed an one dimensional transient mathematical model to mimic the cold weather actions of each regular PV panels and all those incorporated with PCMs. The assessment revealed significant benefits in temperature regulation when PCMs have been used. For example, the PV PCM device demonstrated a maximum solar cell temperature which was aproximatelly 24.87°C smaller than that associated with a standard PV system, reflecting a 35.08 % reduction in temperature as a result of the PCM's capacity to control heat build up through latent heat storage. Furthermore, the study highlighted a particular period - about ten hours into the observation period - if the temperature difference was most significant, showcasing the usefulness of PCMs in maintaining great conditions for PV panels during peak sunshine.

These findings are crucial in illustrating the practical application of PCMs to boost energy efficiency and improve the operational stability of PV systems. Additionally, complementary numerical studies by other research groups have been conducted to evaluate the effects of PCM integration on managing operational temperatures and optimizing photovoltaic panel performance. (Sharma, Rathod and Bhale, 2023)

2.1.2. Performance analysis of PV - PCM systems through experimentation.

Building on the insights gained from the simulation the PV PCM system, an in-depth study was conducted to highlight the crucial role that PCM play improving the efficiency of solar panels. This part of the research delves into the core operational characteristics of the PV-PCM system, specifically examining its behavior under real-world environmental conditions. The objective of this study is providing a better comprehension of how PCM plays a role in enhancing the efficiency and thermal regulation of PV systems in everyday scenarios, where outside things like weather and solar intensity constantly fluctuate

In 2015, Hasan and his team developed the following PV-PCM system:

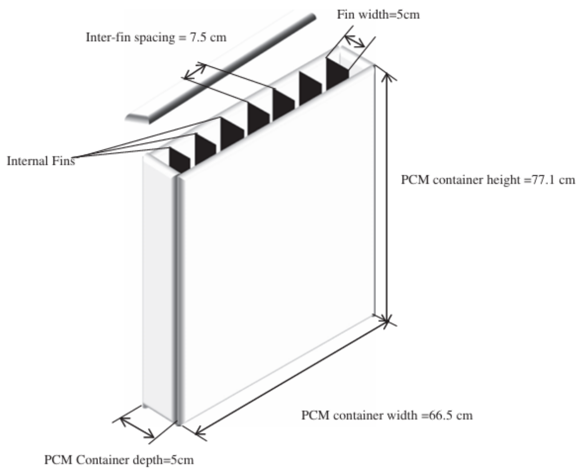


Figure 12: PV PCM system by Hasan and his team

Back in 2015, Hasan along with his research group showcased a photovoltaic-thermal energy storage system that explored the effectiveness of two unique PCMs: the salt hydrate calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$) and a eutectic blend of cupric acid and palmitic acid. The salt hydrate PCM exhibited remarkable efficiency in maintaining the temperatures of photovoltaic (PV) panels at significantly lower levels in comparison to those lacking PCM integration. The quantitative findings of the study indicated that, under the persistent and extreme solar conditions characteristic of Vehari, the salt hydrate

The PV panels operating at a lower temperature than the control panels were reduced by up to 13' C by PCM. This considerable reduction in temperature resulted in an enhancement of the electrical output of the panels, thereby demonstrating a significant increase in photovoltaic conversion efficiency.

Conversely, in cooler and more variable climatic conditions of Ireland, the influence of PCMs was less pronounced yet remained advantageous. Within this geographic context, the salt hydrate PCM decreased the temperatures of the Photovoltaic modules by up to 5°C when compared to panels devoid of PCM. Although the enhancement in efficiency was comparatively modest, the outcomes underscored the adaptability of PCMs across various environmental settings. The significance of these discoveries is considerable, as they demonstrate not just the tangible benefits of using PCMs in photovoltaic arrays but also emphasize the vital necessity of picking a fitting PCM that matches distinct weather conditions. Hasan and his team furnished compelling numerical evidence advocating for the implementation of thermal management strategies in solar panel systems, particularly in regions characterized by elevated temperatures. This comprehensive study enriches our comprehension of how advanced materials science can facilitate the optimization of renewable energy technologies, permitting the development of customized solutions that effectively address the diverse geographical and climatic challenges encountered.(Hasan *et al.*, 2015)

In the experimental study conducted by Z.Li and his research group, (Tao, Zhenpeng and Jiaxin, 2019) a traditional photovoltaic (PV) panel was compared with a Photovoltaic panel integrated with PCM, referred to as the PV-PCM system. Temperature sensors strategically placed across both panels allowed for detailed monitoring of thermal variations. The PV-PCM panel experienced a substantial temperature drop in this setup. In particular, the application of PCMs resulted in a temperature reduction of as much as 10 °C within a span of 6 hours, showcasing the efficiency of PCMs in sustaining cooler operational temperatures. Additionally, information on electric performance, such as voltage, current, and power output, were collected, displaying a marked improvement in the effectiveness on the PV panel. The findings suggest that the incorporation of PCMs, particularly beeswax and paraffin, can elevate PV efficiency from the typical 6.1%-6.5% range to a more optimal 7.0%-7.8% range. This enhancement is directly linked to the reduced operational temperatures achieved through PCM use. The study's experimental findings were further supported by simulation models, which helped reinforce the empirical results. For example, (Arıcı *et al.*, 2018) developed an one dimensional model that simulated system performance, displaying a temperature reduction of 0.31 to 10.26°C for the PV panels and an average yearly efficiency increase of 1.59 % in 2 Turkish cities. The study also emphasized innovative system design strategies, proposing new configurations to improve thermal conductivity and heat dissipation. These advancements included partitioning the PCM container into parallel sections and adding a water jacket for nighttime heat extraction, which enhanced system efficiency.

Additionally, the study investigated the combination of concentrating photovoltaic (CPV) systems with phase change materials (PCMs). Lu et al. (2018) found that integrating PCMs into CPV systems might reduce the average temperature of PV modules by 20 to 25 'C, leading to a 10 to 12 % increase in electrical conversion efficiency. (Lu *et al.*, 2018)

In their continued investigation, Sun et al, demonstrated a considerable improvement in each electrical and thermal performance of photovoltaic systems integrated into structures through the utilization of PCMs. Incorporating PCMs at a volumetric ratio of 5.2% led to a reduction in peak energy demand by up to 47% during summer months. This study highlighted how PCMs can absorb excess thermal energy during periods of high solar irradiation, effectively lowering the heat load and reducing the need for cooling. As a result, this not only enhances indoor comfort but also reduces energy consumption by easing the strain on air conditioning systems.

Additionally, the research revealed that the same volume of PCMs caused a one-hour shift in peak demand, distributing energy use more evenly throughout the day. This shift is especially advantageous for lowering energy use during peak pricing periods, bringing about financial savings. The study also noted a slight 1.3% increase in daytime demand during the winter, suggesting that the interaction between PCM performance and seasonal changes is more complex.

Sun et al.'s analysis offers a detailed quantitative analysis, indicating that PCMs may efficiently reduce temperature variations and also improve the entire efficiency and sustainability of building with integrated photovoltaic systems. This study underscores the possibility of pairing PCMs with PV systems like a practical method of strengthening building energy efficiency and also promoting sustainability.(Sun *et al.*, 2022)

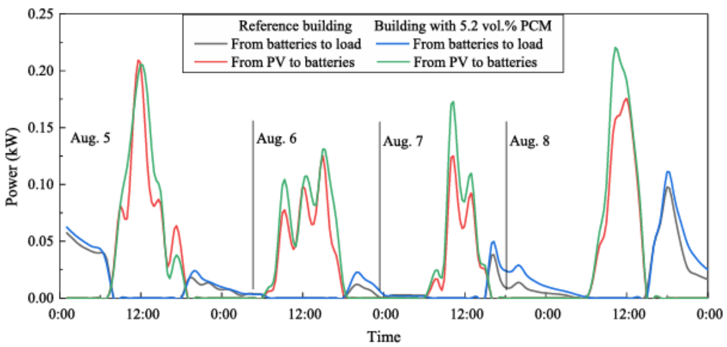


Figure 13: Daily electric energy consumption patterns for structures incorporating phase change materials (PCMs) versus those devoid of such materials during the summer season..

In 2023, Hussein M. Maghrabie and his team conducted an experiment to explore how a PV module's thermal regulation could be improved making use of a paraffin wax RT-42 PCM applied on the back of the panel. The carefully designed outdoor setup aimed to mimic real environmental conditions and also included 2 identical polycrystalline silicon solar panels, each one capable of producing up to 40 W of power. The main goal of the research was to compare the electrical and thermal performance of a standard PV panel with one that had been enhanced with phase change material technology.

The experiment demanded modification of the PCM thickness to three distinct measurements—1 cm, 2 cm, and 3 cm—along with the adjustment of the panel angles to 15°, 20°, 25°, and 30°. This arrangement sought to elucidate the manner in which diverse configurations influenced the thermal regulation of the panel, particularly during periods of peak solar irradiance. The research team employed an infrared thermal imaging camera to capture intricate temperature distributions on the frontal surfaces of both panels, thereby enabling the observation of the real-time thermal implications of PCM integration.

Extensive data acquisition encompassed the quantification of solar irradiance utilizing a pyranometer, alongside the electrical outputs (voltage and current) documented via digital multimeters. These instruments facilitated precise evaluations of the panels' electrical efficiency across varied experimental scenarios. For instance, when the panel was inclined at 30° with a 3 cm PCM layer, the PV-PCM panel exhibited a 15.8% enhancement in power output in relation to the reference panel. Also, the PV-PCM panel showed a 14.4% rise in electrical efficiency under comparable conditions, which points to the substantial capabilities of PCMs in refining the efficiency of PV modules .(Maghrabie *et al.*, 2023)

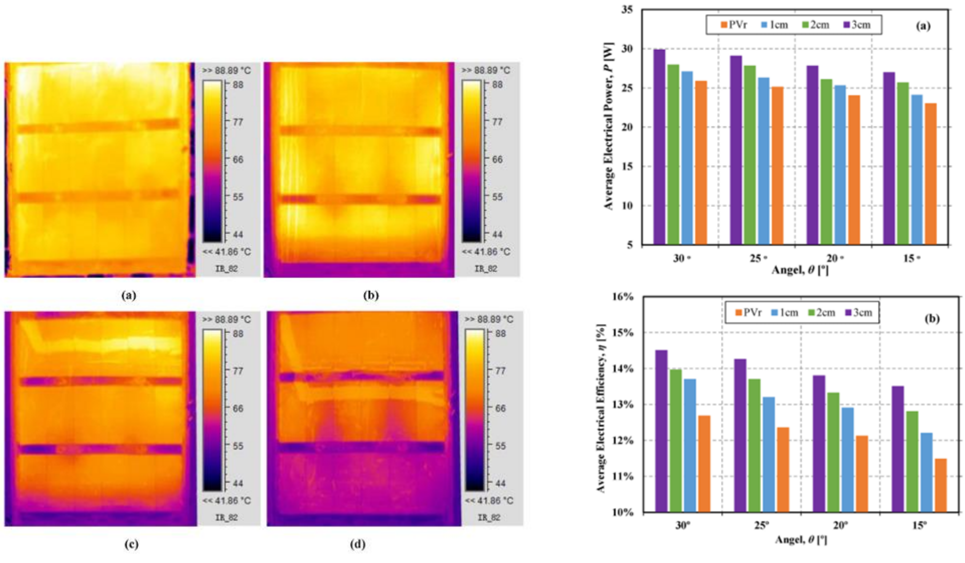


Figure 14 : Experimental results of the .(Maghrabie et al., 2023) study

Despite the encouraging outcomes exhibited by PV-PCM systems in augmenting the efficiency and thermal management of PV panels, there exists considerable potential for enhancement. The efficacy of phase change materials in maintaining panel temperatures and boosting energy output indicates a formidable approach for refining solar panel performance. Nonetheless, to further elevate the energy efficiency and functional capabilities of these systems across diverse environmental conditions, researchers have initiated investigations into more sophisticated configurations. This inquiry has culminated in the examination of photovoltaic systems that incorporate both PCMs and thermal collectors. These systems are designed not only to optimize the management of thermal loads but also to capitalize on the surplus heat extracted by phase change materials for supplementary energy generation, thereby establishing a more comprehensive energy solution. This advancement highlights a persistent dedication to improving and broadening the functionalities of solar energy technologies.

2.2 Thermophotovoltaic systems with application of phase change materials

In 2011, a research team at the University of Leeds, led by C.S. Malvi, conducted a study focused on developing an energy balance model to assess a hybrid system. The aim of this study was to investigate the way in which PCMs could improve thermal management and boost the electrical efficiency of solar systems. Malvi's team designed a complex system that included a glass cover, highly conductive adhesive layers, PV cells, copper plates with integrated water channels, PCM layers, and insulation. This setup was meticulously simulated to mimic the interactions between these components under solar exposure. The primary objective was to enhance the system's performance through the optimization of thermal regulation using PCMs.

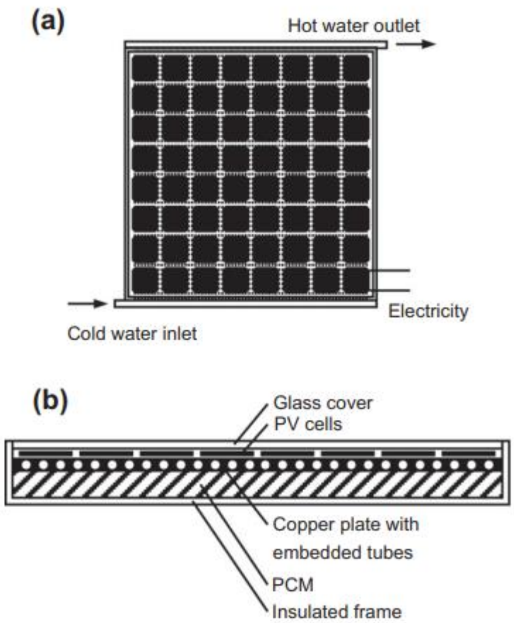


Figure 15: Set up by Malvi end the research group.

The study 's simulations revealed important findings about system performance. Particularly, the usage of PCMs resulted in a considerable decrease in the optimum temperatures of the PV cells, dropping to close to 12°C during peak solar radiation. This decrease in temperature directly resulted in a roughly nine % improvement in electric-powered efficiency. The PCMs properly absorbed extra heat, stopping the common efficiency losses observed in PV cells at higher temperatures. Furthermore, the method was in a position to boost the typical water temperature within the winter circuit by as much as 20°C. This was achieved by effectively transferring the heating from the overheated PV cells on the water moving through the copper heat exchanger, showcasing the system 's ability to create both thermal and electrical energy concurrently, rendering it perfect for home consumption wherein all power types are needed.

The study also assessed various PCM properties. Strong emphasis was placed on choosing a PCM with a melting point aligned with the PV cells' operating temperature range. Properly selected PCMs not only optimized heat absorption during peak sunlight but also allowed for a slow release of heat, maintaining PV cell efficiency over longer periods. The research proposed that a practical implementation of this system would involve several panels arranged in an active closed-loop configuration, well-suited for residential rooftops with limited space. This setup would maximize both electricity generation and thermal energy collection, making it a highly efficient solution for homes.(Malvi, Dixon-Hardy and Crook, 2011)

Sajan Preet and Brij Bhushan carried out an extensive experimental study in 2017 that aimed to improve the functionality of a water based photovoltaic / thermal system by incorporating PCM. The main goal of this research was to evaluate the thermal and electrical effectiveness of different types of photovoltaic systems, including a standard system, a PV/T system with two absorber plates, in addition to a PV/T system with PCM, particularly paraffin wax RT-30, which had ideal phase change properties at normal solar panel temperatures. The experimental setup was very carefully created to test these 3 configurations with water flows of 0.013 kg / s, 0.023 kg / s and 0.031 kg / s. The researchers thoroughly checked out the effects of varying flow rates on the performance of PV/T systems. (Preet, Bhushan and Mahajan, 2017a)

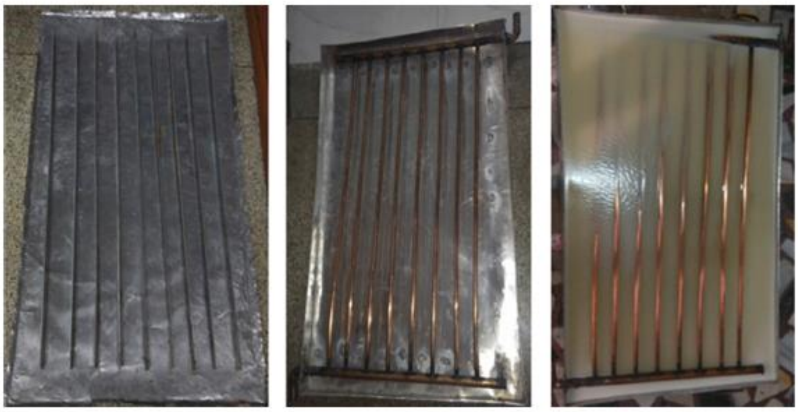


Figure 16: Experimental set up by (Preet, Bhushan and Mahajan, 2017a)

In 2019, Zhenpeng Li and his team conducted an in-depth investigation to evaluate the performance enhancements of solar photovoltaic (PV) systems by integrating PCMs and a thermal collector, as detailed below:

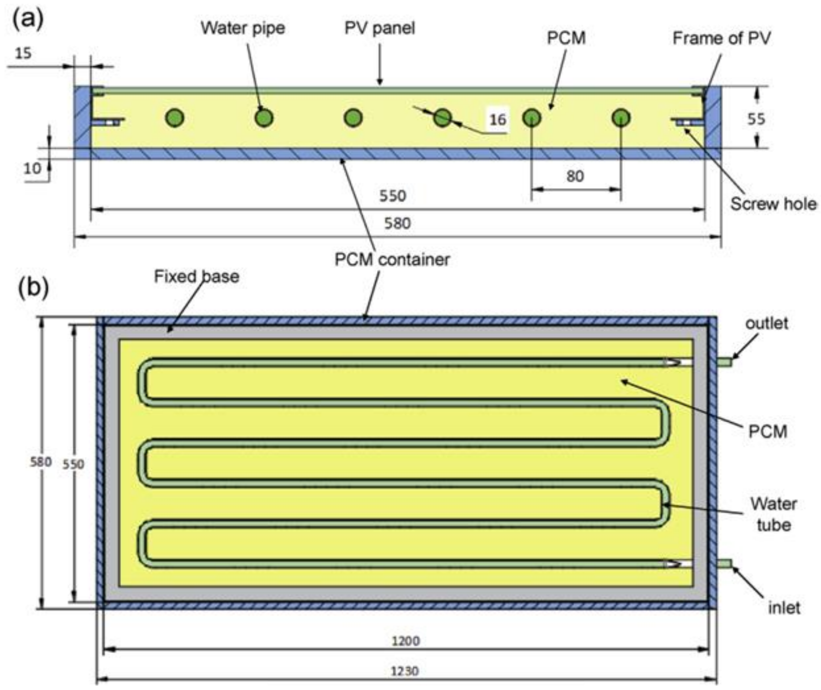


Figure 17: PV-PCM-T module by Zhenpeng Li et al

The study introduced three distinct configurations for testing: a standard solar energy (SE) setup, a solar energy system enhanced with phase change compounds (PCC) (SE-PCC), and a solar energy system incorporating both PCC and a thermal collector (SE-PCC-T). Each of these configurations was equipped with a variety of sensors to measure important operational parameters, such as the temperatures of the PV panels and PCM, and for the Photovoltaic-Thermal-PCM setup, the water temperature within the thermal collector. In addition, the electrical outputs, including voltage, current, and power, were carefully monitored to determine system performance under real-world conditions.

During the experiment, the PV-PCM-T configuration showcased significant benefits in both thermal management and energy efficiency. By incorporating a thermal collector in the PCM-enhanced PV system, the researchers successfully captured the heat absorbed by the PCM, increasing the water temperature by nearly 15°C. This approach not only helped maintain optimal operating temperatures for the PV panels but also significantly boosted the total amount of energy generated by the system. The integrated setup demonstrated an increase in energy yield by 74.3%, exergy yield by 8.32%, and electrical output by 30.4%, underscoring the effectiveness of combining PCMs and thermal collectors in solar energy systems.(Li *et al.*, 2019).

His research created a brand new strategy where water was distributed straight across the surface area of the PV panels, functioning as a coolant to decrease the panel temperature and thereby improve entire performance. Arefin's experimental setup was meticulously developed to look at the effect of changing water flow rates, from 0.5 L/min to two L/min, on the system 's effectiveness. This PV/T process provided a regular PV module attached to a flat plate collector, whereby the water flowed. As the water passed over the PV panels, it absorbed excess heat produced by the panels during sun exposure, providing cooling while at the same time heating the water, that may subsequently be utilized for different winter applications. The use of water-based cooling led to a significant decrease in the operational temperature of the PV panels, reducing it by up to 12°C. This drop in temperature resulted in a notable increase in the electrical efficiency of the panels, estimated at 1.5%. The combined solar and thermal system achieved an overall efficiency of approximately 80%, with the thermal collector efficiency reaching 64% and the solar panel efficiency at 16%. (Arefin, 2019)

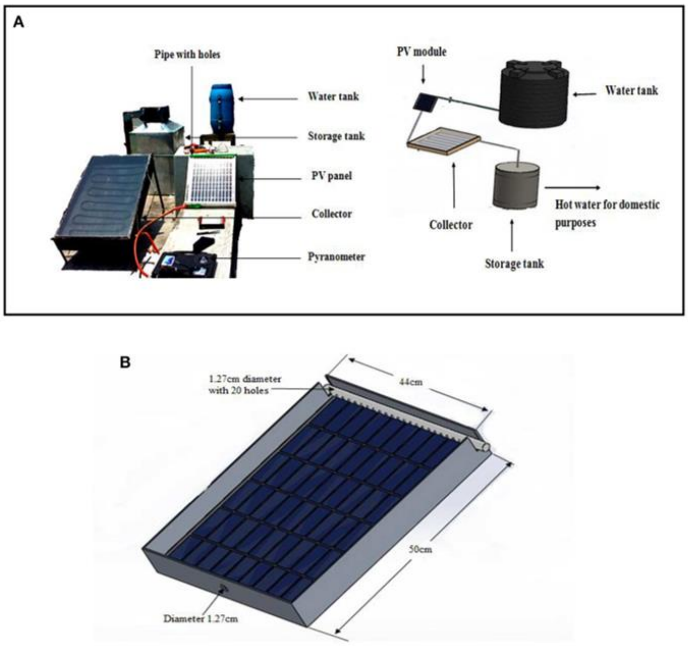


Figure 18: Experimental setup by Md. Arman Arefin

Ali Naghdbishi along with his colleagues (Naghdbishi, Akbari, and Yazdi, 2020) carried out an experiment in Iran aimed at improving the efficiency of PVT systems through the incorporation of PCMs and nanofluids. Paraffin wax was used as a PCM for passive temperature control, while a water-glycol blend enhanced with multi-wall carbon nanotubes (MWCNTs) served as the active cooling agent. MWCNTs were chosen for their excellent thermal conductivity, allowing lower nanoparticle concentrations to be used, minimizing pressure drops and reducing energy consumption from pumping.

The study compared the functionality of a regular PV module having a hybrid PVT/PCM system under different operational conditions and also direct sunlight to simulate real world environments. The results showed that adding MWCNTs on the cooling fluid greatly boosted both electrical and thermal efficiency, with changes of 23.58 % and 4.21 %, respectively, when compared with water by itself. Furthermore, both thermal and electrical efficiencies observed obvious gains, demonstrating the usefulness of this particular cool method. The PCM likewise had a crucial part in keeping the PV panel 's temperature close to the melting point of the paraffin wax, advertising even heat distribution and also making sure constant efficiency over time. (Naghdbishi, Yazdi and Akbari, 2020)

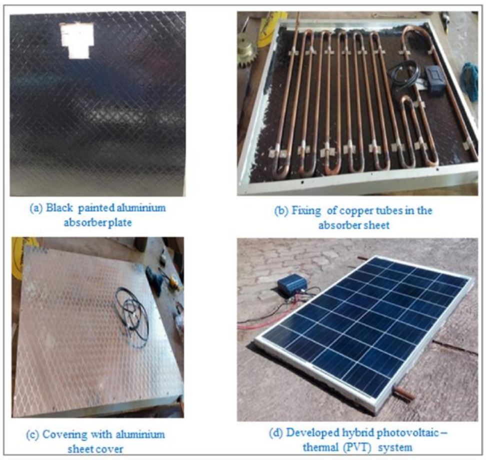


Figure 19: Experimental setup by Govind S. Menon et al.

In 2020, Govind S. Menon along with his colleagues conducted a thorough investigation into the effectiveness of a PVT system that used water and copper oxide based nanofluid for cooling. The study in India examined the effects of various cooling techniques on the thermal and electrical efficiency of PVT systems. The experimental configuration was comprised of a PVT system with a winding pipe layout and a thermal absorber made of sheets and tubes, aimed at enhancing heat transfer from the photovoltaic panels. The system underwent testing in different settings to assess how effectively it reduced temperature, utilized electricity, and also performed thermally when using water and nanofluid as cooling agents.

For the PVT system cooled with water, a temperature reduction of around 15°C at midday led to a higher level of electrical efficiency from 12.98% (uncooled) to 14.58%. When nanofluid was used, the temperature drop was significantly higher at 23.7°C, boosting the electrical efficiency to 17.61%. This improvement highlights the superior thermal conductivity and heat dissipation characteristics of nanofluids compared to water. The thermal efficiency also showed significant differences, with the nanofluid-cooled system achieving 71.17%, well above the 58.77% efficiency observed in the water-cooled system. (Menon *et al.*, 2022)

In the year 2021, Hongtao Xu and his research cohort executed an experimental investigation, conducted under the ambient conditions of Shanghai. The experimental setup formulated by the research team included a solar collector featuring metallic fins and a serpentine copper conduit, meticulously engineered to effectively manage the thermal load during periods of peak solar irradiance. The choice of conduits shaped like serpents in the PV/T-PCM system was crucial for improving thermal management. Serpentine conduits are favored due to their capacity to provide an extensive surface interface, thereby facilitating enhanced heat absorption from the photovoltaic panels. The shaping of the pipes (serpentine shape) minimizes the pressure drop and maximizes the effectiveness of the cooling system.

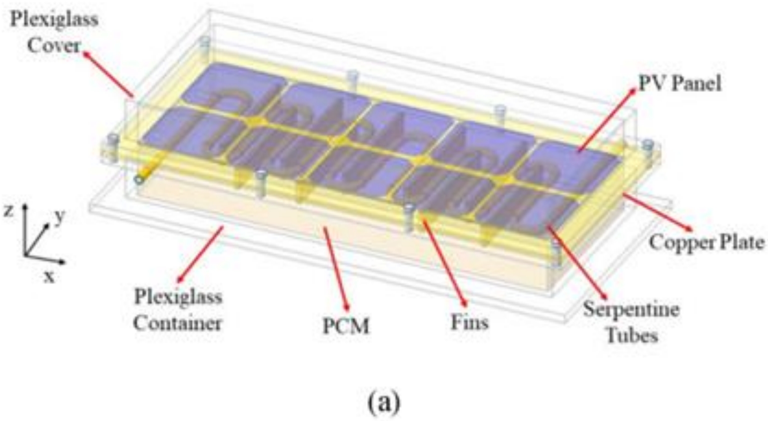


Figure 20 The solar collector

During the study, five different thermal regulation strategies were analyzed in detail to find the most effective method. Results showed that while PCM successfully controlled the Photovoltaic's temperature, there was a risk of overheating after extended exposure to high solar radiation. Continuous thermal regulation demonstrated significant efficiency improvements, increasing energy output by 5.4% and 22.2% compared to systems without thermal control. The most efficient approach, however, was intermittent regulation set at 45°C, which achieved the best energy and exergy efficiencies at 86.3% and 15.5%, respectively, optimizing performance while avoiding the risk of PCM overheating .(Xu *et al.*, 2021)

In 2023, Manfeng Li and his research team at North China University conducted a study using a new flat-and-pipe PVT-PCM collector to explore how PCM can manage excess heat from solar panels. The PCM was chosen based on its melting temperature, aligning with typical photovoltaic (PV) cell operations, improving thermal absorption and release. The team also tested different water flow rates to measure their effect on thermal and electrical performance. By integrating PCM into the PVT system, they lower the peak temperature of the solar cells by 12.54°C compared to the PVT-only setup and by 42.28°C versus traditional PV systems. This cooling led to better electrical efficiency, with the PVT-PCM system generating 1.13 watts more power than the PVT setup and 4.59 watts more than standard PV systems. Additionally, the system showed a 3.06% enhance in power output density and a 16.15% improvement in efficiency over both PVT and conventional PV systems. (Li *et al.*, 2023)

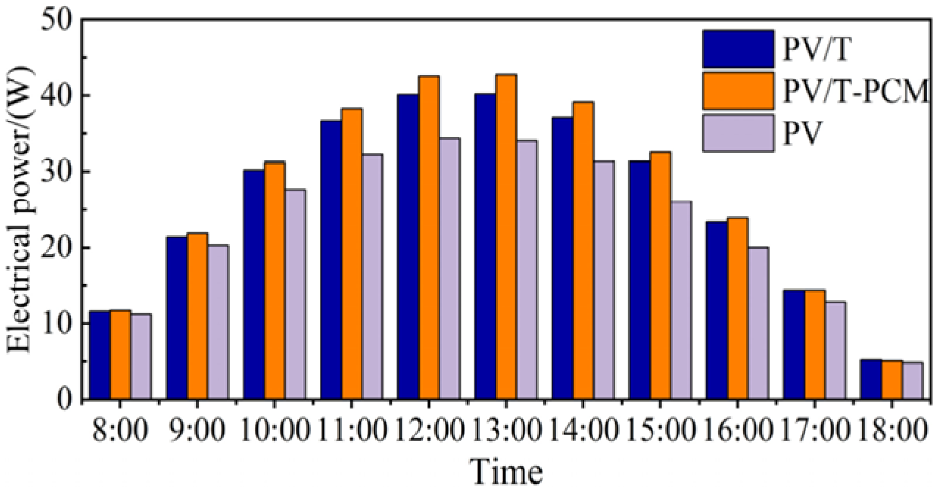
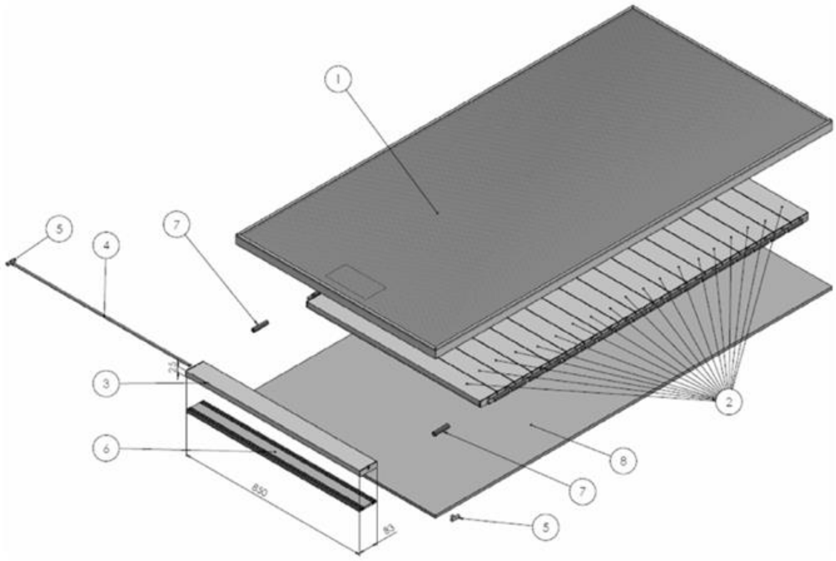


Figure 21: Hourly variation of electrical power

In 2021, a research team led by Mauricio Carmona at Universidad Del Norte in Colombia conducted a comparative study between a PVT-PCM system and a standard PV module. The study included testing a PVT-PCM hybrid module as well as a standard PV module with the same specifications in order to easily compare their performance. The experiment began with a comparison of the electrical outputs of the 2 modules, prior to adding PCM to the hybrid system. The addition of PCM to the hybrid PVT module resulted in a 7.43 % increased daily electrical efficiency when compared with the traditional PV system. Additionally, the hybrid system achieved a remarkable overall daily efficiency of 31.35%, far surpassing the PV module's 13.12%. This outcome highlights the PVT-PCM module’s effectiveness in maximizing energy extraction from sunlight, resulting in an overall 20.45% increase in energy efficiency .(Carmona, Palacio Bastos and García, 2021)



1	Traditional PV module
2	Thermal module (PCM Container)
3	Finned absorber plate (Aluminum 3000 Series)
4	Copper tubing (ASTM B280 type M 3/8")
5	Copper TEE
6	Individual PCM container thermal insulation (12 mm polystyrene foam)
7	Neoprene tubing 10 mm ID
8	General thermal insulation (12 mm polystyrene foam)

Figure 21: Schematic of PVT PCM system by Carmona et.al

In 2021, Miqdam T. Chaichan conducted an in-depth study on how different phase change materials (PCMs) with varying melting and solidification points affect the efficiency of photovoltaic-thermal (PVT) systems cooled by water. The analysis focused on two types of PCMs: paraffin wax, which melts at 45°C, and petroleum jelly (Vaseline), which melts at 25°C. The study also evaluated a hybrid PCM mixture combining these materials in various ratios to determine the best configuration for maximizing performance during Iraq's intense summer heat.

The experiment aimed to examine the impact of thermal properties of PCMs on the performance of PVT systems under indoor conditions akin to the harsh summer in Iraq. The combination of paraffin and Vaseline yielded the most favorable outcomes, leading to a reduction in the surface temperature of photovoltaic cells and an improvement in the overall performance of the system. Vaseline was added to paraffin to bring down its melting point, leading to considerably lower operating temperatures and improved thermal and electrical efficiency. Using phase change materials with reduced melting points resulted in positive outcomes, enhancing electrical efficiency by 13.7 % and reaching a maximum thermal efficiency of 39.0 %. This research emphasizes the significance of choosing the appropriate PCM melting temperatures to enhance the performance of PVT systems, providing a promising approach to enhance the cost efficiency and operational effectiveness of solar power systems.(Chaichan *et al.*, 2021)

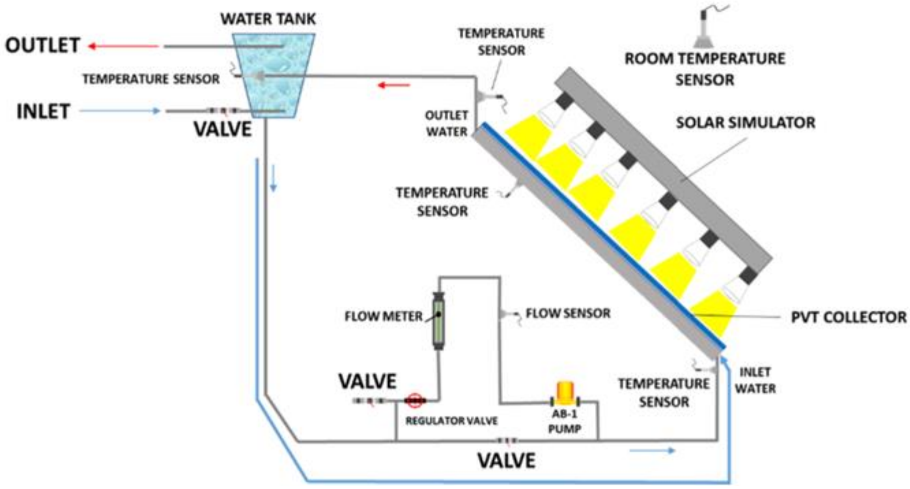


Figure 22: A detailed diagram of a solar simulator outlines the primary elements of the PVT system

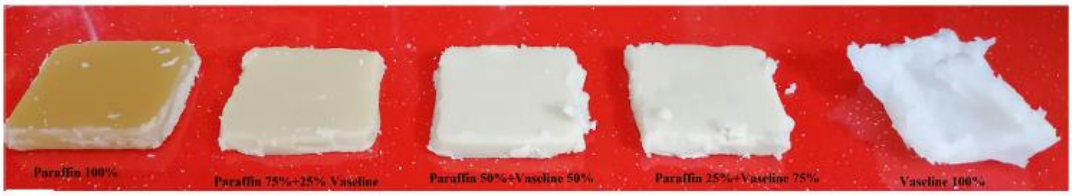


Figure 23: Combinations of paraffin, Vaseline, and other blended materials.

In 2022, Afzanizam Mohd Rosli and his team at Universiti Teknikal Malaysia Melaka used CFD to explore the benefits of adding PCMs to photovoltaic thermal (PVT) systems. Their setup included a standard PV module with a PCM layer beneath it, designed to absorb heat that would typically be lost. The PCM was chosen for its optimal thermal properties, such as thermal conductivity and a melting point suited to local conditions. During peak sunlight, the PCM absorbed excess heat, reducing panel temperatures and preventing efficiency drops. As temperatures fell, the stored heat was released, helping maintain steady panel performance. Simulations showed that the PCM lowered peak cell temperatures by about 12°C, lowering the typical temperature from 45°C in regular systems to 33°C in the PCM-enhanced setup. This thermal control improved electrical efficiency by 6.5%, raising it from 15% to 21.5%. The system's thermal efficiency also increased, from 40% to 50%, thanks to the PCM's ability to store and release heat. These results demonstrated the effectiveness of PCMs in improving both temperature regulation and energy efficiency in PVT systems.(Rosli *et al.*, 2022)

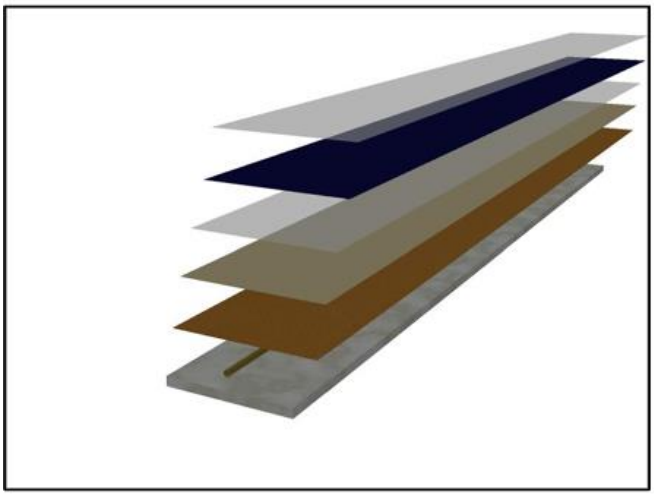


Figure: 24 PVT-PCM

Raquel Simón-Allué and her team conducted a research that carried out over nine months in Zaragoza, Spain, involving a comparative analysis between 20 standard PVT panels and 20 PVT panels enhanced with PCMs. The study revealed significant data on efficiency improvements. The PCM-enhanced PVT panels demonstrated a notable increase in thermal efficiency, with measurements showing an average improvement of 26% over standard panels. This boost in thermal efficiency was particularly marked during peak summer months, a period during which the PCM's heat management capabilities were most effective due to higher ambient temperatures and increased solar irradiance. Electrical efficiency also benefited from the PCM integration, albeit to a lesser extent, with an average increase of 3% observed across the testing period. Additional in-depth measurements from the field tests revealed that the panels with PCM integration kept a more stable operating temperature, lowering the peak temperature by as much as 11°C in comparison to panels without PCM. This temperature regulation contributed to the increased electrical efficiency by reducing thermal losses commonly associated with higher PV panel temperatures. Despite these promising results, the study also highlighted challenges in the practical deployment of PCM in PVT systems. Issues such as the cost-effectiveness of integrating PCM, its long-term reliability, and the potential for increased system weight were identified as barriers to widespread adoption.(Simón-Allué *et al.*, 2022)

Figure 25: PVT-PCM design

Xiangfei Kong along with his group conducted a thorough experiment that aimed to test the effectiveness of a PV / T - CPCM along with phase change material (PCM) in the same year. The use of serpentine copper tubes in the PCM improved heat transfer and prevented the system from overheating, leading to increased efficiency. The use of serpentine tubes improved the exchange of heat transfer fluid with the PCM, resulting in superior heat absorption and dissipation. The phase change material trapped additional heat from the sun's strongest rays, keeping the photovoltaic cells from getting too hot.

The pump' s operation, which circulated fluid through tubes to transfer heat from PV cells to PCM, was a crucial design element. This resulted in a decrease in PV panel temperature from 33.2'C to 28.5'C, improving overall system efficiency. The system reached a thermal efficiency of 19.6 % and showed a total energy efficiency improvement of 7.9 % and 10.7 % when compared with PV - CPC and PT-CPC systems operating on their own. The PV cells became more efficient when operating at cooler temperatures, which helped to maintain optimal performance. (Kong *et al.*, 2022)

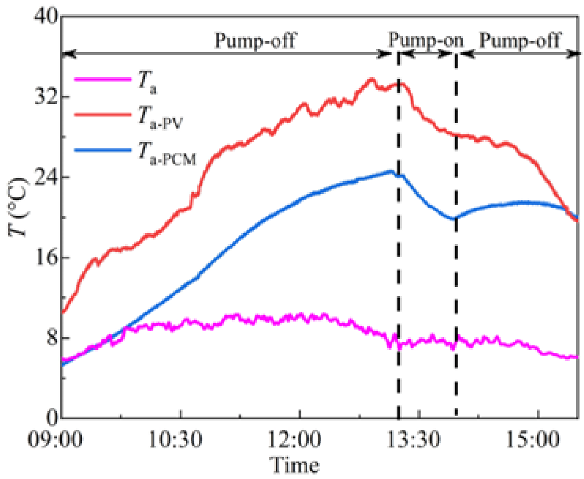


Figure 26: Temperature of ambience, PCM and PV modules.(Kong et al., 2022)

In 2023, Abdulsahib M. Bassam and his team at Universiti Kebangsaan Malaysia conducted an in-depth study to improve the efficiency PVT systems by utilizing nano-enhanced PCMs and advanced flow manipulation techniques. The focus of the research was to integrate nano-enhanced PCMs into PVT systems to help regulate the temperature of photovoltaic cells, which directly impacts their electrical efficiency. To further improve heat transfer, the team introduced micro-fin tubes and counterclockwise twisted tapes, designed to increase coolant flow turbulence and boost thermal extraction from the PV cells.

The combination of nano-enhanced PCMs and innovative flow designs leading to substantial enhancements in the stability and efficiency of the system. The innovative PVT systems demonstrated a peak temperature reduction of 15°C than standard methods with no PCMs. This temperature drop helped maintain the photovoltaic cells' electrical efficiency, which increased by about 5% over standard systems. Additionally, the thermal efficiency saw a notable improvement of up to 10%, thanks to the enhanced heat dissipation provided by the micro-fin tubes and twisted tapes, which maximized heat transfer and fluid dynamics. (Bassam *et al.*, 2023)

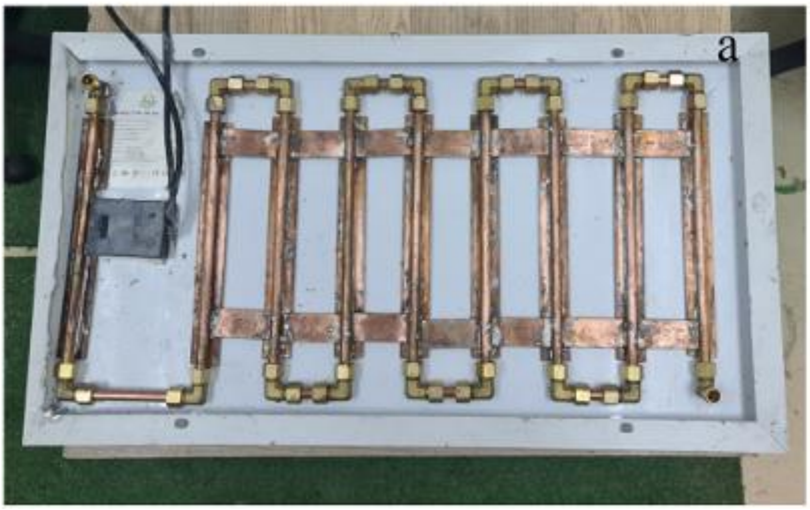


Figure 27: PVT-PCM by Bassam et al

Alaa Hamada and his staff completed a comprehensive research on the functionality of a PVT based on water system improved with encapsulated PCM spheres. The goal of this research was to improve both power output and efficiency in photovoltaic panels by integrating cooling systems, a promising approach that has not yet been fully utilized in commercial applications. Hamada's PVT-PCM system stood out for its ability to function in both active and passive cooling modes. Unlike previous PVT designs, this system was carefully engineered to achieve higher energy generation and thermal retention while minimizing frictional power losses, making it more suitable for practical use.

The study took place in Egypt, in actual outdoor settings, where the effectiveness of the PVT PCM panel was evaluated against a standard PV panel that relies on natural air cooling. The results were important: The actively cooled PVT PCM panel with 3 L / min flow of water produced a spectacular top overall efficiency of 74.1 %, exceeding the 34.6 % efficiency of the passively cooled PVT PCM panel and well beyond the 12 % efficiency of the standard panel. These findings demonstrate how PCM capsules can improve the electrical and thermal capabilities of PV panels by preventing temperature rises that can lower efficiency..(Hamada *et al.*, 2023)

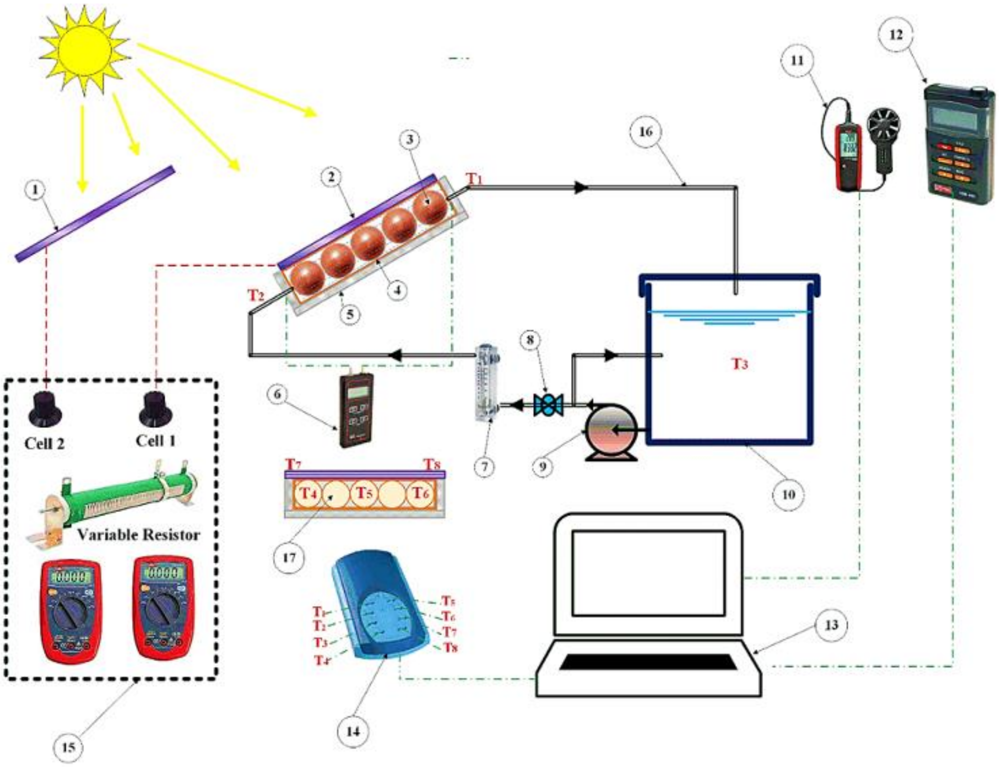


Figure 28: experimental test rig conducted by Hamada et al.

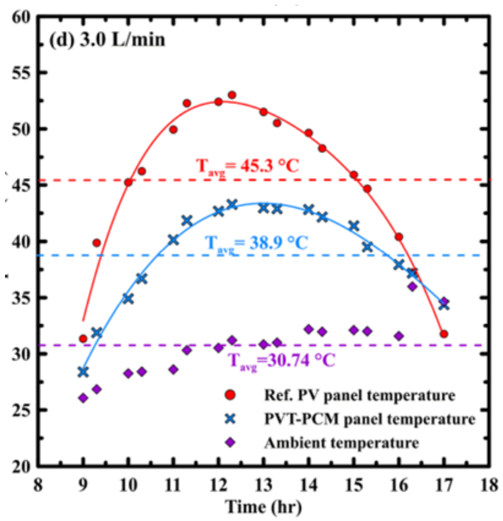


Figure 29: Results of PV temperature at water flow of 3 L/min

In 2023, MD Shouquat Hossain and his team researched methods to enhance the effectiveness of a 250 Watt photovoltaic module consisting of 60 polycrystalline silicon cells, combined with a water based thermal collector. They adapted the PV panels by including aluminum - encased phase change materials to more effectively regulate the heat they absorb. Serpentine copper tubes were included in the design of the panels, and this was one of the most impressive features. These tubes, with a diameter of 1.27 cm, thickness of 1 mm, and length of 14 meters, were created to enhance the surface area that is available in contact with the heat transfer fluid, resulting in improved efficiency in heat exchange.

The addition of PCMs helped lower the maximum temperature of the PV cells by up to 12°C compared to panels without them, keeping the cells in their optimal temperature range. This cooling effect boosted the electrical efficiency by about 5%, as it reduced the thermal stress that usually hampers PV performance at high temperatures. The system also saw a nearly 10% improvement in thermal efficiency, thanks to the PCMs' ability to absorb and release heat, preventing overheating and ensuring smoother energy conversion.

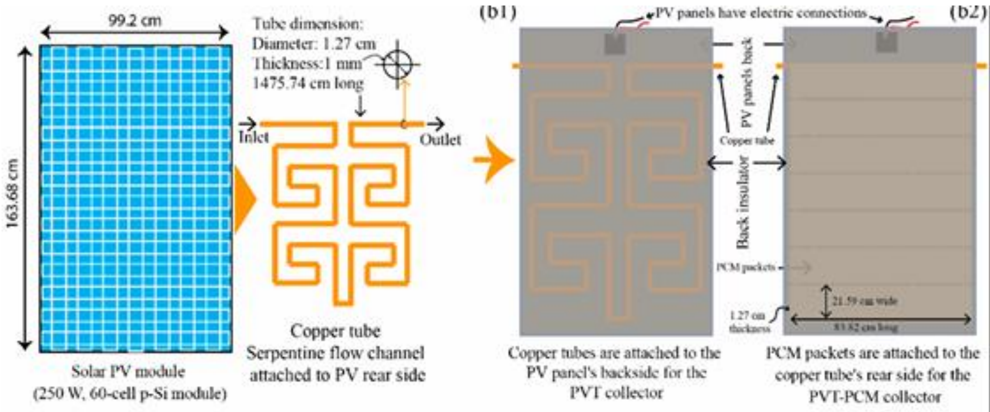


Figure 30: Double serpentine flow channel

Incorporating PCMs helped lower the peak temperatures of the PV cells by as much as 12°C compared to systems without them. This cooling effect was crucial for keeping the cells within their ideal operating temperature, which is key for maintaining high efficiency. As a result, the electrical efficiency improved by around 5%, directly due to the reduced heat stress on the PV cells, which normally lose efficiency when exposed to higher temperatures. Moreover, the thermal efficiency of the systems also saw substantial improvements, with an increase of nearly 10% in overall thermal output. This enhancement was attributed to the effective heat retention and management capabilities of the PCMs, which not only prevented overheating but also ensured a more stable and efficient energy conversion process.(Hossain *et al.*, 2023)

In 2023, Mahmoud B. Elsheniti and his team conducted a study to improve solar panel performance in Riyadh's harsh climate by integrating PCMs with a photovoltaic thermal (PVT) system. The style featured U shaped copper tubes connected to the rear of the panels to optimize heat transfer. The PCM, with a high melting point suited for Riyadh's heat, activated only when needed to prevent overheating. This setup reduced peak panel temperatures by as much as 10°C and much better electric efficiency by aproximatelly five %. Overall, the system 's thermal efficiency increased by around eight % when compared with systems with no PCM.

Figure 31 : Schematic of PVT PCM system by Mahmoud B. Elsheniti

(Elsheniti *et al.*, 2023)

Someshwar S. Bhakre and his team conducted a detailed numerical study, using a setup with two separate containers attached to the back of a photovoltaic (PV) panel—one filled with PCM and the other with water. Different water container thicknesses (20 mm, 30 mm, and 40 mm) were tested to improve the cooling effect provided by the PCM, with the system positioned at a 90-degree angle. Their findings showed that the 30 mm water container was the most effective. Using ANSYS FLUENT software, they created a two-dimensional model to simulate system behavior at various angles. The results revealed that adjusting the angle to 90 degrees lowered the average temperature of the PV panel and PCM, which improved the system's electrical efficiency. Incorporating PCM reduced the PV panel temperature by 5.88% at a 30-degree angle and 1.36% at 90 degrees, leading to corresponding increases in electrical efficiency of 14.93% and 1.35%. (Bhakre, Sawarkar and Kalamkar, 2023)

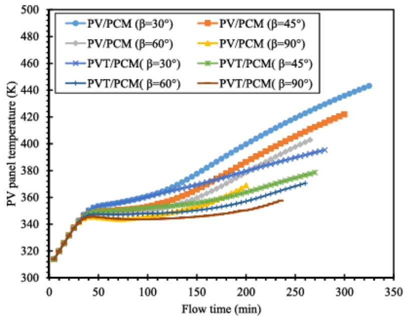


Figure 32: Fluctuations in the mean temperature of photovoltaic panels in relation to flow duration across various system orientations .(Bhakre, Sawarkar and Kalamkar, 2023)

In the year 2024, Reji Kumar Rajamony and his research team undertook a thorough examination of the advancements and obstacles associated with the incorporation of PCMs into PVT systems. The scholars underscored critical technical challenges, including the increase in weight, complexities related to installation, and issues regarding long-term reliability and thermal conductivity. For example, while PCMs are capable of decreasing the temperatures of solar panels by nearly 5°C in times of high solar exposure, managing the added weight and space is vital for system stability. Furthermore, they investigated novel methodologies such as the micro-encapsulation of PCMs to enhance thermal conductivity and facilitate integration. From an economic standpoint, the review provided a cost-benefit analysis indicating that, although the integration of PCMs raises initial expenditures by 10-15%, the resultant increase in efficiency could yield energy savings of up to 20% throughout the operational lifespan of the system, thereby presenting a favorable return on investment, particularly in regions characterized by elevated solar exposure.

The environmental benefits of employing PCMs in PVT systems were also emphasized, particularly their role in reducing the carbon footprint by optimizing the energy conversion process. Enhanced thermal management through PCMs not only leads to more efficient solar panel operations but also reduces reliance on traditional energy sources, thereby decreasing overall greenhouse gas emissions. The review concluded with suggestions for future research directions, including the development of bio-based or hybrid PCMs, which could offer greater sustainability and efficiency. It called for more extensive field testing and long-term performance monitoring to fully understand the practical viability and durability of PCM-integrated PVT systems.(Rajamony *et al.*, 2024)

In 2019, H. Fayaz et al. investigated the implications of incorporating Phase Change Materials (PCMs) into photovoltaic thermal (PV/T) systems, with an emphasis on diminishing the operational temperatures of photovoltaic cells to enhance electrical efficiency. Utilizing both computational simulations and empirical experimentation, the authors illustrate that PV/T systems augmented with PCMs are capable of reducing cell temperatures by as much as 9°C, which translates to a maximum enhancement in electrical efficiency of 7.6% when contrasted with non-PCM systems. By decreasing temperature, we not only improve efficiency but also may extend the service life of the solar cells by minimizing heat-related deterioration. Moreover, the role of phase change materials in absorbing and releasing heat is vital for regulating cell temperatures during peak sunlight hours, leading to better overall system functionality.(Fayaz *et al.*, 2019)

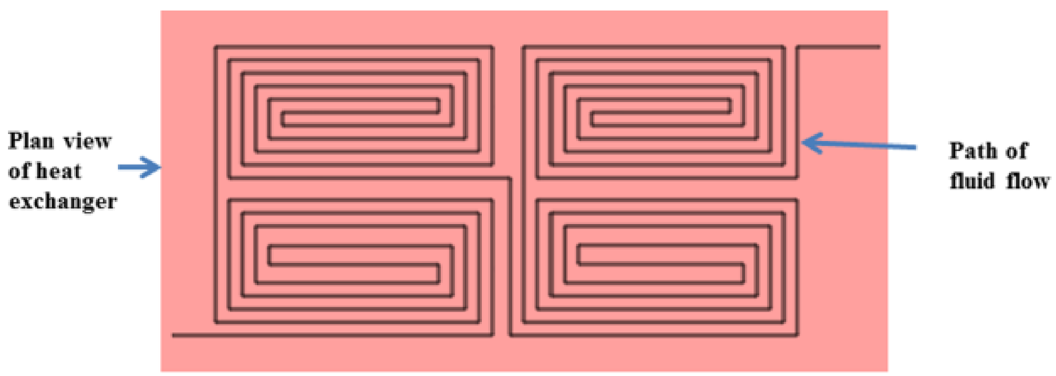


Figure 33 :Thermal Collector used in the study

Researcher	**PVT-PCM Temp reduction compared to the traditional PV (°C)**	**PV Efficiency without PCM**	PV Efficiency with PCM	Main conclusion
(Arefin, 2019)	**reduced by up to 12°C**	11.23%	12.78%	The study concludes that using a top surface water cooling method in integrated photovoltaic thermal systems significantly enhances system efficiency
(Carmona, Palacio Bastos and García, 2021)	**reduced by between 10 and 17°C**	13.12%	20.55%	-
(Simón-Allué *et al.*, 2022)	**10°C**	Not specified	PV efficiency increased by 13%	Despite these promising results, the study acknowledges significant challenges in implementing PCM in real-world installations, such as cost-effectiveness and system reliability.
(Bassam *et al.*, 2023)	**decreased by about 46°C**	5.8%	10.59%	Incorporation of nano PCM and micro-fins tubes with counterclockwise twisted tape in a PVT system significantly enhance efficiency
(Hamada *et al.*, 2023)	**3.6 °C**	12%	actively cooled panel, with water flow rate of 3 L/min : efficiency of 74.1%	using encapsulated PCM balls enhances both the electrical and thermal system performance
(Hossain *et al.*, 2023)	**8.97°C**	14.57%	15.32%	This study indicates that PCMs effectively lower cell temperatures and enhance overall system performance under varying weather conditions
(Elsheniti *et al.*, 2023)	**10.6 °C**	At midday, the efficiency reached up to **12.94%**	At midday, reaching as high as **14.38%**	-

(Bhakre, Sawarkar and Kalamkar, 2023)	**23°C** at a 30° system orientation	the highest at around **9.33%**	**10.43%**	The research indicates that a water container thickness (WCT) of 30 mm yields optimal outcomes, facilitating the cooling of photovoltaic (PV) panels, lowering their thermal temperature, and augmenting their electrical efficiency. Also, the PVT/PCM framework produced better thermal energy results compared to typical PV/PCM systems.
(Menon *et al.*, 2022)	**15°C**	**12.98%**	**14.58%**	The use of nanofluid cooling and a serpentine coil thermal absorber is a key innovation, offering superior cooling and performance**.**
(Fayaz *et al.*, 2019)	**9°C**	Not specified	**7.6% increase**	**-**

Table 2: Comparative analysis of different research results

CHAPTER 3 - Methodology and Calculations

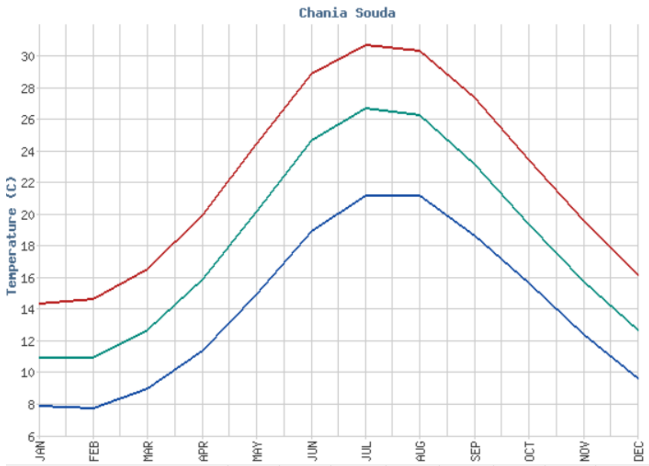
The initial phase of the research involved an extensive review of global academic literature to identify key design factors relevant to a PVT-PCM system. Due to the complex combinations required when selecting both general and specific parameters for such a system, defining and organizing the research goals became critical steps to ensure smooth progress. In the next phase, the system will be thoroughly modeled to determine its ideal design features. This process will include a detailed analysis of factors such as material properties, heat transfer, and structural components to ensure the system's performance meets the set criteria. The goal of this thorough modeling method is to improve the design to be able to make a strong structure that improves the overall performance and effectiveness of the PVT PCM system.

Following the design phase, ANSYS simulation software will be employed to conduct an in-depth evaluation of the system's thermal behavior. This simulation will allow for a detailed evaluation of how well the system is functioning under various conditions. Additionally, ANSYS will provide valuable insights into the thermal exchange and phase transition processes within the PCM, ensuring that the proposed design is both validated and optimized for real-world applications. By leveraging this advanced simulation tool, the precision and effectiveness of the design strategy will be confirmed, laying a solid foundation for future experimental studies and system improvements.

3.1 General Information on the Study System and Study Area

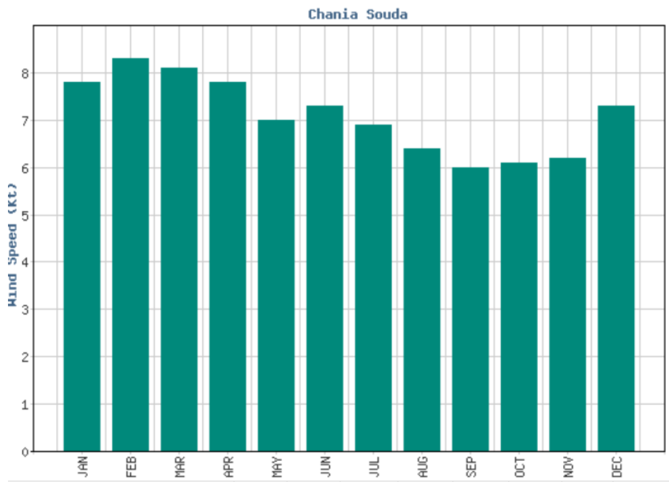
For the design and modeling of the system, data obtained from the same location in May 2021 by (Savvakis and Tsoutsos, 2021) was utilized. Given that Crete experiences warm climatic conditions for the majority of the year, it provides an optimal environment for the study of the cooling system in thermophotovoltaic applications. Specifically, the landscape and Crete's position, roughly at the center of the Mediterranean, give it a climate that ranges between a continental Mediterranean and a desert-like Mediterranean. Most of Crete is classified within a semi-arid bioclimatic zone with warm or mild winters. However, its mountainous and semi-mountainous regions are mostly in the sub-humid and humid bioclimatic zones, experiencing mild or cold winters. Based on data provided by the Hellenic National Meteorological Service (HNMS) from Chania's main weather station (located at longitude: 24°7'0'', latitude: 35°29'0'', elevation: 150 meters), the coldest months of the year are January and February, with average monthly ambient temperatures ($T_{a,m}$) hovering around 11°C. In contrast, July and August are the hottest months, with temperatures reaching 26.7°C and 26.3°C, respectively. Specifically, from the data collected, it is found that for an average ambient temperature of 23.3°C, the average surface temperature of the photovoltaic panel is approximately 53°C. This fact highlights the necessity of our research in this particular area.

The predominant winds in the region are from the northwest, with the highest average wind speeds typically occurring in January, February, and March.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Minimum Monthly Temperature	7.9	7.8	9.0	11.4	15.0	19.0	21.2	21.2	18.7	15.7	12.4	9.7
Monthly Mean Temperature	11.0	11.0	12.7	15.9	20.2	24.7	26.7	26.3	23.2	19.4	15.8	12.7
Maximum Monthly Temperature	14.4	14.7	16.6	20.0	24.5	28.9	30.7	30.4	27.4	23.5	19.6	16.2

Figure 34: Temperature data, Chania



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Prevailing Wind Direction	W	W	W	W	W	W	NW	NW	W	N	W	W
Monthly Mean Wind Power	7.8	8.3	8.1	7.8	7.0	7.3	6.9	6.4	6.0	6.1	6.2	7.3

Figure 35: Wind data, Chania

3.2 Design and Fabrication of the PV-PCM-T System

The fundamental elements in the formulation of a cooling system encompass the choice of the heat transfer medium, the attributes of the apparatus employed for thermal dissipation, and the features of the principal energy source. Considering these factors, the PV-PCM-T system was conceptualized and subsequently constructed.

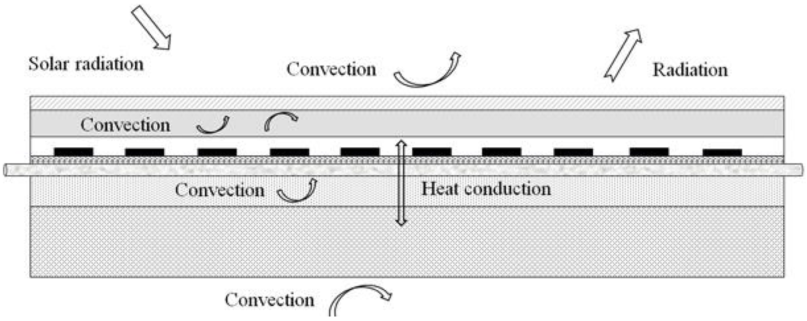


Figure 36: PVT-PCM system heat exchange.

(Li *et al.*, 2023)

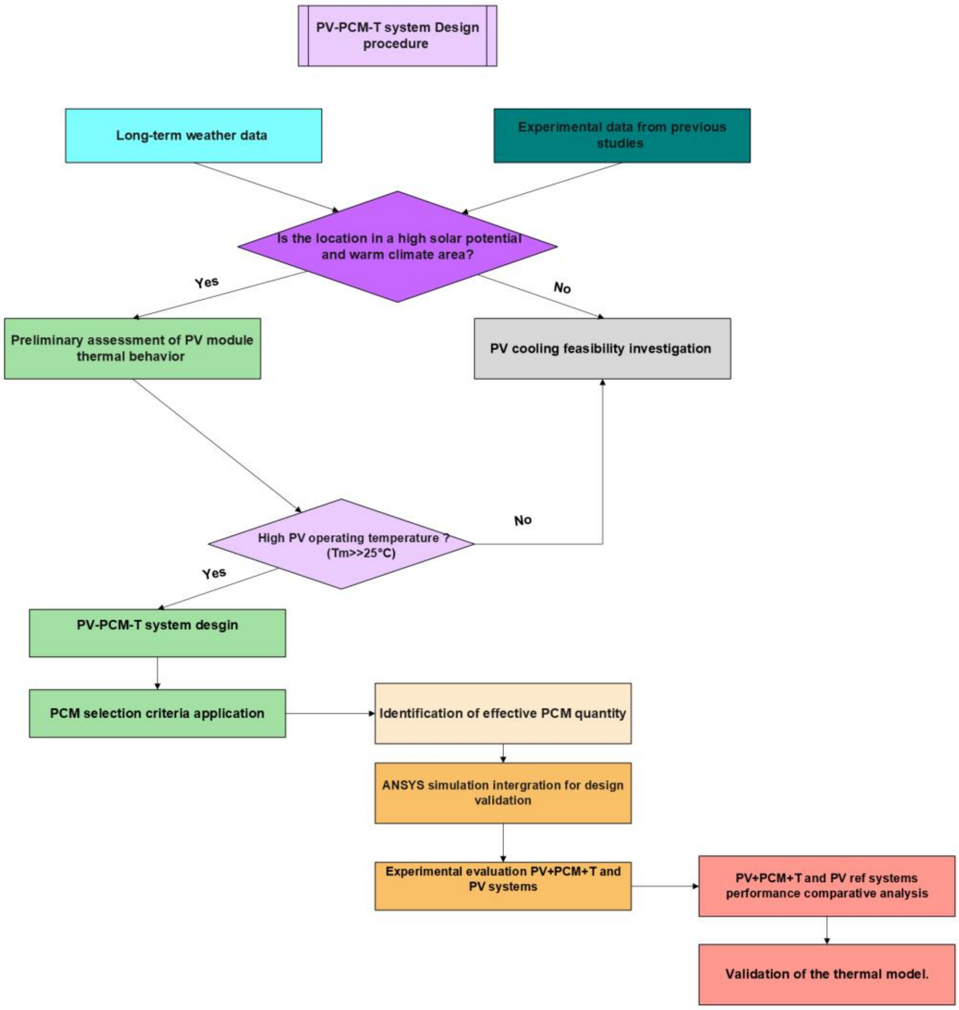


Diagram 1:Methodological Approaches Employed for the Design and Empirical Assessment of the System

3.2.1 Criteria for selecting PCM

Incorporating Phase Change Materials (PCMs) into photovoltaic (PV) systems is a highly effective method for improving both the performance and lifespan of solar panels by managing heat buildup, which often reduces their electrical efficiency. The selection of appropriate PCMs is guided by key factors that align technical requirements with practical use, ensuring efficient temperature control for PV systems. One of the most important considerations is the PCM's melting point, which is carefully chosen to match the typical operating temperature range of PV cells. This alignment ensures the PCM absorbs and stores excess heat as soon as the cells reach their optimal temperature, preventing overheating. Typically, PCMs with a melting point between 25°C and 30°C are ideal for areas where ambient temperatures frequently cause PV cells to exceed this range. (Ma *et al.*, 2015).

A significant element to take into account the absorbed heat required for the phase change of fusion associated with a phase change material (PCM), which measures how much thermal energy it can absorb during a phase change without significantly altering its temperature. A higher latent heat of fusion is beneficial, as it allows the PCM to store more heat, providing an extended cooling effect on photovoltaic (PV) cells during intense sunlight(Ar, Bilgin and Ni, 2018). Another crucial aspect is thermal conductivity, which plays a key role in the PCM's effectiveness in PV systems. According to (Khan, Khan and Ghafoor, 2016) a PCM with high thermal conductivity can quickly absorb and release heat, helping to maintain the efficiency and longevity of PV cells. Additives like graphite or metals are often used to enhance the thermal conductivity of PCMs, improving heat transfer. Additionally, the density and specific heat of a PCM contribute to its thermal mass, which influences its capacity to store heat. PCMs with higher density and specific heat help stabilize the PV system’s temperature during daily fluctuations. (Ni, 2021)

Economic considerations are also pivotal in the selection of PCMs. The integration of PCMs into PV systems must balance the initial cost against potential long-term energy savings. Affordable and readily available PCMs are preferred to ensure the economic viability of the system over its operational lifespan. The compatibility and chemical stability of the PCM with other system components are critical to avoid any detrimental chemical interactions that could degrade the system over time. It is essential that the PCM retains its physical and chemical properties consistently across numerous thermal cycles. Lastly, the environmental impact of the PCM is an important consideration. The ideal PCM should be environmentally friendly, non-toxic, and recyclable, aligning with the broader sustainability goals of solar energy systems. Utilizing environmentally benign PCMs not only supports the ecological benefits of solar energy but also promotes its adoption as a sustainable energy solution.

The characteristics of the ideal PCM are summarized in the next table:

Thermal Characteristics	Chemical Characteristics	Physical Characteristics	Economic Characteristics
Phase change matches application	Stable	Minimal density fluctuation	Affordable and widely available
High enthalpy change around the target temperature	Compatible with container materials	High density	
Good thermal conductivity in both solid and liquid states	Supercooling, safe , non-toxic, non-flammable	Little to no supercooling	

Table 3 : Characteristics of the ideal PCM (Chen and Wan, 2011)

To determine the optimal phase change material (PCM) for the development and implementation of the photovoltaic phase change material thermal (PV+PCM+T) system, practical data from monitoring a photovoltaic installation in the selected study area between May and July 2021 was utilized. The research revealed that the average operating temperature of the photovoltaic panel (Tm) during its active hours was 51°C, which aligns with the requirements of the proposed application. Moreover, the suitability of the PCM for the suggested application is intrinsically linked to its thermophysical and chemical characteristics. Taking into account these aspects, paraffin wax stands out as a leading option for energy storage owing to its chemical stability, non-corrosive properties, neutral color, resilience, cost efficiency, broad availability, ecological benefits, and safe nature. In conclusion, the choice of paraffin wax (RT42), with its first melting temperature (TPCM,melt1) at 38°C and a final melting temperature (TPCM,melt2) of 43°C, was made for the planned system because it adheres to the essential standards needed for the application and is compatible with the climate of the research locality.

Melting area	Congealing area	Heat storage capacity ± 7,5%	Specific heat capacity	Density solid at 15°C	Density liquid at 80°C	Heat conductivity (both phases)	Max operating temperature
38-43 Main peak:41 [°C]	43-37 [°C]	165 [kj/kg]	2 [kj/kg*k]	0.88 [kg/l]	0.76 [kg/l]	0.2 [W/(M*k)]	72 [°C]

Table 4: Datasheet of RT42 paraffin wax

3.2.2 Thermal modeling of the Photovoltaic -PCM-T System Design

The System's configuration features a variety of unique layers, specifically the photovoltaic layer, the phase change material layer, the collector tube, PCM, and a steel containment assembly. Consequently, an energy equilibrium can be formulated for each of these distinct layers. Recognizing that the phase change material layer includes elaborate mathematical representations, and that crucial data involves the thermal settings of the photovoltaic system and the operational fluid, extensive work has been focused on improving these equations. This optimization facilitates the establishment of a relationship between the thermal states of the PV and PCM, as well as that of the working fluid, and vice versa. The following section articulates the energy balance equations pertinent to the PV, PCM, and working fluid.

The operational temperature of photovoltaic panels (Tphot) is a significant factor influencing their efficiency (nelec). This aspect has attracted considerable interest from the academic community, leading to the development of predictive analytical models through a meticulous investigation of the variables that affect this temperature. In contexts where precise and trustworthy data for modeling the escalation of photovoltaic panel operating temperature (Tm) is scarce, the simplified energy balance model is frequently the preferred methodology. This model facilitates a reasonably precise estimation of the controlled parameter (Tphot), evaluation of electrical power output, and calculation of the thermal energy retained within the various strata of the photovoltaic panel or expelled from its front and back surfaces into the surrounding environment. Understanding that these energy values are representative of the total capability of a photovoltaic panel throughout a designated timeframe, they guide the approximation of the thermal energy that could be extracted by a heat transfer medium like phase change materials (PCM).

In their 2001 research, Jones and Underwood introduced a model suggesting that the influence of environmental conditions and photovoltaic cell materials on the panel's operating temperature can be understood by analyzing the primary heat exchange processes with the surrounding environment. In the current study, this approach is used to determine the necessary amount of PCM, based on the principle that the PCM must absorb all the heat accumulated by the photovoltaic panel, which raises its operating temperature, along with the heat dissipated from the back of the panel into the environment. This principle sets an upper limit on the PCM's heat absorption capacity, simplifying the design of the PV+PCM system without the need for complex numerical modeling.

This section outlines the energy balance model as a key part of the overall theoretical design framework for standard PV+PCM+T systems. The main assumptions supporting the proposed model are as follows:

- Heat exchange occurring at the lateral edges of the photovoltaic panel is deemed negligible.

- The absorption (α) and emission (ε) coefficients of the photovoltaic panel are regarded as constants and independent of the wavelength (wl).

- It is assumed that the temperature remains consistent across both the front and back surfaces of the photovoltaic panel.

- The thermophysical characteristics of the materials utilized in the photovoltaic panel are treated as temperature-independent.

-At the primary time marker (t0), the thermal state of each layer in the photovoltaic panel is regarded as consistent with the surrounding temperature.

- Clear sky conditions are assumed to represent the prevailing meteorological circumstances.

In particular, the equation that outlines the energy balance among the sun energy, the generated electrical energy, the power exchanged between the photovoltaic panel and the environment, and the power lost through convection, is as follows:

$$\frac{dTm}{dt} = \frac{Psol - Prad - Pconv - P_M}{C_M} \qquad [1]$$

$Psol$: Sun energy captured in the form of thermal energy by the photovoltaic module. (W)

$Prad$: Electrical energy generation from the photovoltaic module (W)

$Pconv$: Power exchange through radiation between the surfaces of the photovoltaic panel and the sky/ground (W)

P_M: Energy flow through convection from the solar photovoltaic module to the surrounding ecosystem (W)

C_M: Thermal capacity of the photovoltaic panel (J/K)

t: Time (s)

(Jones and Underwood, 2002) , (Schiro *et al.*, 2017) , (Savvakis and Tsoutsos, 2021)

3.2.2.1 Radiative heat exchange

One can ascertain the thermal energy output from a photovoltaic panel by multiplying the attenuation coefficient for incoming solar irradiance (α), the panel's surface area (A) [m^2], and the solar radiation that impacts the front of the panel (Gt) [W/m^2].

$$Psol = a \cdot G_t \cdot A \qquad [2]$$

(Jones and Underwood, 2002) , (Ma, Zhao and Li, 2018), (Aneli, Arena and Gagliano, 2021) , (Savvakis and Tsoutsos, 2021)

The computation of heat transfer via radiation is performed employing the subsequent mathematical expression:

For the front surface of the PV module:

$$P_{rad,F} = \sigma \cdot A \cdot \{\left(\frac{1+cos\beta}{2}\right) \cdot \varepsilon_{mf} \cdot \left(T_{mF}^4 - T_{Sky}^4\right) + \left(\frac{1-cos\beta}{2}\right) \cdot \varepsilon_{mf} \cdot \left(T_{mF}^4 - T_{gF}^4\right)\} \qquad [3]$$

For the posterior face of the photovoltaic module:

$$P_{rad,B} = \sigma \cdot A \cdot \{\left(\frac{1-cos\beta}{2}\right) \cdot \varepsilon_{mB} \cdot \left(T_{mB}^4 - T_{Sky}^4\right) + \left(\frac{1\mp os\beta}{2}\right) \cdot \varepsilon_{mB} \cdot \left(T_{mB}^4 - T_{gF}^4\right)\} \qquad [4]$$

σ: Stefan-Boltzmann constant ($W/K^4 \cdot m^2$)

β: The inclination angle of the photovoltaic module (°)

ε_{mF} : The emissivity characteristic of the anterior surface of the photovoltaic module.

ε_{mB} : Emissivity of the back face of the photovoltaic module

$T_{PV,F}$: Temperature of the posterior face of the photovoltaic panel (K)

$T_{PV,B}$: Temperature of the back surface of the photovoltaic panel (K)

T_{Sky} : Sky temperature (K)

T_{gF} : Surface temperature of the terrestrial environment in proximity to the photovoltaic module. (K)

T_{gB} : Temperature of the terrestrial substrate posterior to the photovoltaic module (K)

The total heat exchange through radiation is calculated by summing up equations [3] and [4]:

$$P_{rad} = P_{rad,F} + P_{rad,B} \qquad [5]$$

(Armstrong and Hurley, 2010), (Hasan, Alnoman and Rashid, 2016), (Preet, Bhushan and Mahajan, 2017a)

The equation used in this thesis for calculating the sky temperature is as follows:

$T_{Sky} = Tamb - \delta T$, δT= 20K under clear sky conditions [6]

This equation was initially proposed by Schott (1985) and was later adopted by Jones and Underwood (2001).

Concerning ground temperature, several studies have suggested that it is commensurate with the surrounding thermal conditions. (Tamb). [(Notton *et al.*, 2005)(Armstrong and Hurley, 2010) (Usama Siddiqui *et al.*, 2012) (Sánchez Barroso *et al.*, 2016)]

In this thesis, the ground temperature is calculated using the following equations:

$T_{gF} = T\alpha mb + \delta T$, δT=5K under clear sky conditions [7]

$T_{gB} = Tamb$ [8]

(Savvakis and Tsoutsos, 2021)

3.2.2.2 Convective heat exchange

Concerning the phenomenon of heat transfer via convection occurring on the anterior and posterior surfaces of the photovoltaic module, it is estimated utilizing the subsequent mathematical expressions:

$P_{conv,F} = h_F \cdot A \cdot (T_{PV,F} - T_{amb,F})$ [9]

$P_{conv,B} = h_B \cdot A \cdot (T_{PV,B} - T_{amb,B})$ [10]

The total heat exchange through convection is calculated by summing up equations [9] and [10]:

$P_{conv} = P_{conv,F} + P_{conv,B}$ [11]

(Notton *et al.*, 2005) , (Schiro *et al.*, 2017) , (Preet, Bhushan and Mahajan, 2017b)

h : coefficient for convection [W/ m^2]

It is calculated using the empirical equation:

$\mathrm{h} = 1{,}31 \cdot (T_{PV} - T_{amb})^{1/3} + 2{,}8 + 3 \cdot v_w$ [12]

v_w: wind speed

(Duffie and Beckman , 1991) , (Notton *et al.*, 2005) , (Asefi, Ma and Wang, 2023)

3.2.2.3 Electrical power generated by the PV

Furthermore, the electrical energy produced by the photovoltaic module can be ascertained through the application of the relevant equations.

$P_{phot} = P_{STC} \cdot n_T \cdot \frac{G_t}{G_{STC}}$ [13]

where the coefficient n_T is identified as a correction factor that accounts for the effect of the operating temperature of the photovoltaic panel on its electrical power output.

It is determined through the subsequent mathematical expression:

$$n_T = 1 + \beta_{PMPP} \cdot (T_m - 25℃) \quad [14]$$

P_{STC} : Nominal power of the Photovolatic under STC conditions [W/ m^2]

G_{STC} Solar irradiance measured under standardized testing conditions (STC). [W/m^2]

β_{PMPP}: Thermal power coefficient [%/℃]

(Mavromatakis *et al.*, 2010),(Torres-Ramírez *et al.*, 2014),(Ehyaei and Farshin, 2017) (Mavromatakis *et al.*, 2010)

$n_{PV,STC}$	18.6%
G_T	997 W/m^2
A_a	0.6154 m^2
β_{PMPP}	-0.45%

Table 5: Values of the parameters used for calculating P_M

3.2.2.4 Heat transferred to the PCM

Based on the aforementioned analysis, the upper limit of thermal energy that may be conveyed from a photovoltaic panel to the designated phase change material (PCM) throughout its melting temperature spectrum, at any specific instance, can be ascertained through the subsequent equation. This computation facilitates a precise evaluation of the thermal exchange between the photovoltaic system and the phase change material, thereby enhancing the comprehension of the system's comprehensive energy management. By delineating the precise thermal transfer capacity, this methodology contributes to the optimization of the efficiency of the photovoltaic-phase change material thermal configuration and guarantees that the phase change material functions within its intended capacity for the absorption and storage of thermal energy.

$$P_c = P_{sol} - P_{rad,F} - P_{conv,F} - P_{phot} \quad [15]$$

The quantity of thermal energy assimilated by the phase change material (PCM) during a defined temporal interval can be precisely evaluated through the application of Simpson's rule. This method, applied through a simplified equation, provides a reliable approach to calculating the total heat transfer. By utilizing Simpson’s rule, which is effective in approximating the integral of a function, we can determine the cumulative heat absorbed by the PCM with greater precision. This methodology proves to be especially advantageous in the examination of non-linear fluctuations in temperature over temporal intervals, thereby facilitating a more comprehensive and precise assessment of the thermal efficacy of the system throughout the designated timeframe.

$$E_c = \Delta_t \cdot \sum_{i=1}^{N} P_c(t_i) \qquad [16]$$

P_c : Maximum heat energy conveyed to the phase change material (W)

E_c : Heat transferred to the Phase change material during a selected time (KWh)

Δ_t: Time duration separating consecutive measurements (h)

3.3 Calculation of the heat (E_C) transferred to the PCM and determination of the required quantity of PCM

The subsequent table delineates the values of the parameters employed in the computation of the thermal energy exchanged with the Phase Change Material (PCM).

Parameter	Value	Units
A	0.6154	m^2
α	0.88	-
β	30	°
ε_{mF}	0.9	-
ε_{mB}	0.9	-
G_{STC}	1000	W/m^2
σ	$5.67 \cdot 10^{-8}$	$W/K^4 \cdot m^2$

Table 6: Values of the parameters that serve as input variables in the energy balance model.

A comprehensive model was created in Excel using the previously mentioned equations to simulate the thermal behavior of the photovoltaic (PV) system. The equations were applied to data collected in June 2021 in Chania, Crete. The recorded data included photovoltaic panel temperature(T_{phot}), , solar radiation (G_t), ambient temperature (T_{am}), and wind speed (v_w), measured at 10-minute intervals from 8:00 AM to 6:00 PM. This research provided an exhaustive examination of the environmental parameters and operational efficacy throughout the diurnal cycle. This data compilation supported a detailed analysis regarding how external variables, including solar exposure and wind movement, influence the thermal dynamics of photovoltaic panels and how effectively heat is transferred to phase change materials. By employing this data, the model assists in elucidating the actual operational characteristics of the system, optimizing the design of the photovoltaic-phase change material interface, and enhancing predictions of energy efficiency across varied climatic contexts.

Thus, the values of P_{conv}, P_{rad}, P_{sol} , P_{Phot} and therefore ,using equation [15] , P_c were calculated for each time step, followed by the computation of the cumulative thermal energy transferred to the Phase Change Material (PCM) throughout the complete span of the designated timeframe.

The total heat transfer to the PCM, E_c, was calculated to be 0.88575.

In pursuit of enhancing the operational efficacy of the system, the quantity of phase change material (PCM) must be adequate to assimilate the thermal energy conveyed to the substance, as determined by prior calculations. In accordance with this principle, (Klugmann-Radziemska and Wcisło-Kucharek, 2017) formulated a pragmatic mathematical expression for the expeditious assessment of the necessary phase change material layer thickness. In the present study, a modified version from (Savvakis and Tsoutsos, 2021) of this equation has been applied to ensure accuracy and relevance to the specific conditions of the system.

$$d_{pcm} = \frac{E_c}{\rho_{pcm} \cdot A \cdot [c_{p,PCM} \cdot (T_{PCM,melt} - T_{PV,i}) + \lambda + c_{p,PCM} \cdot (T_{PV,f} - T_{PCM,melt})]} \quad [19]$$

$T_{PV,i}$: the initial operational temperature of the photovoltaic panel (assumed to correspond with the ambient temperature at the commencement of the day) [℃]

$T_{PV,f}$: the target final temperature of the photovoltaic panel [℃]

Parameter	Value	Units
ρ_{pcm}	880	kg/m^3
$c_{p,PCM}$	2	kj/kg·K
λ	165	kj/kg
$T_{PCM,melt}$	41	°C
$T_{PV,i}$	18.9	°C
$T_{PV,f}$	45	°C

Table 7: Information for determining the thickness of the PCM

Through the utilization of the equation [19] in conjunction with the data delineated in Table 5, the thickness of the phase change material (PCM) was ascertained to be 2.7 cm.

3.4 Configuration of the PV-PCM-T system

To achieve the goals of this thesis, a prototype PV-PCM-T system was created and developed to evaluate its thermal and energy efficiency under the Mediterranean climate of Chania, Crete. The system consists of a 100W polycrystalline solar panel, a stainless steel enclosure with a 3 cm depth, determined by the required PCM thickness, and a serpentine copper piping layout. Paraffin wax RT42 was chosen as the suitable PCM for this system. This setup was installed to thoroughly test its performance in real-world environmental conditions.

In greater detail, the photovoltaic panel utilized in the system possesses the following specifications:

Pmax [W]	100 W
Dimension [mm]	920x670x28x25 mm
Operating Temperature	-45~+80 °C
Cell Efficiency	18.6 %
Voc [V]	22.7 V
Vmp [V]	18.7 V
Isc [A]	5.67 A
Imp [A]	5.35 A

Table 8: PV panel characteristics

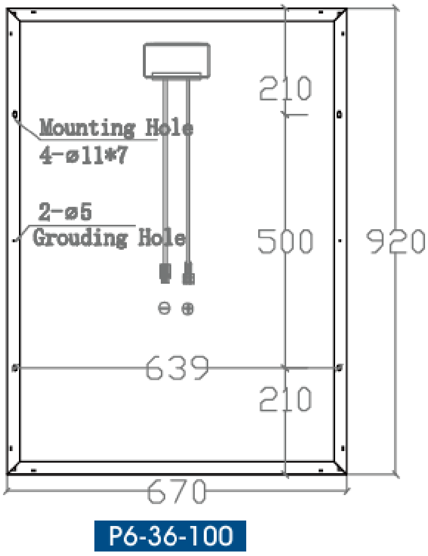


Figure 37: Engineering Drawing of the backside

The dimensions of the container holding the PCM were determined to be 900 x 650 x 30 mm to guarantee an appropriate alignment and cohesive incorporation with the posterior aspect of the photovoltaic module. The selected pipes are standard, readily available in the market, with a diameter of Φ22.

Regarding the selection of the pipe shape and the material used for the piping, the serpentine shape of the collector tubes in PV-PCM-T systems , according to previous research [(Sopian*, Alwaeli and Kazem, 2019) (Prasetyo *et al.*, 2023)] , significantly enhances the thermal management by ensuring a uniform distribution of heat across the system. Serpentine-shaped pipes are ideal for PV-PCM-T systems due to their ability to enhance heat transfer by maximizing surface area and promoting uniform heat distribution. Their long flow path ensures efficient cooling by providing more time for heat absorption, while their compact design optimizes space without compromising performance. The serpentine shape also improves system durability by reducing thermal stress, ensuring even melting and solidification of the PCM, and making installation simpler and cost-effective. Additionally, this layout is highly scalable, adaptable to both small and large PV systems, further enhancing the system's thermal regulation and efficiency.

This uniformity is crucial in maintaining the PV panels within their optimal temperature range, which enhances their electrical efficiency and extends their longevity.

Additionally, the use of copper for these serpentine pipes markedly improves heat conductivity, essential for efficient heat transfer. Copper pipes are ideal for PVT cooling systems because of copper's exceptional thermal conductivity, rated at 387.7 W/m·K. This property enables efficient heat transfer from the photovoltaic module, aiding in the cooling process. Copper rapidly conducts the thermal energy absorbed from the panels to the operational fluid, thereby facilitating the maintenance of ideal panel temperatures and enhancing overall efficiency. Furthermore, copper's strength and resistance to corrosion make it a dependable material for thermal systems that must withstand different environmental conditions over time (Shojaeefard *et al.*, 2023). When this configuration is combined with phase change materials (PCMs), it maximizes the surface area for heat exchange, enabling even more effective thermal management. The capability of the Phase Change Material (PCM) to retain surplus thermal energy and subsequently discharge it in accordance with demand contributes to the stabilization of the temperature of the Photovoltaic (PV) modules, thereby offering a responsive cooling mechanism that adjusts to fluctuations in solar irradiance, thus guaranteeing the persistent efficacy and dependability of the system. In conclusion, the key criteria for selecting this design include the structural simplicity and ease of fabrication, the proven efficiency of the pipe configuration as validated by previous research, and the high thermal conductivity of the materials, particularly the use of copper, which enhances overall system performance.

Using a stainless steel container in a PV-PCM thermal system combines durability, corrosion resistance, decent thermal conductivity, and high temperature resistance, making it ideal for outdoor, long-term use.

In light of the previously mentioned considerations, the final design configuration was established as follows.

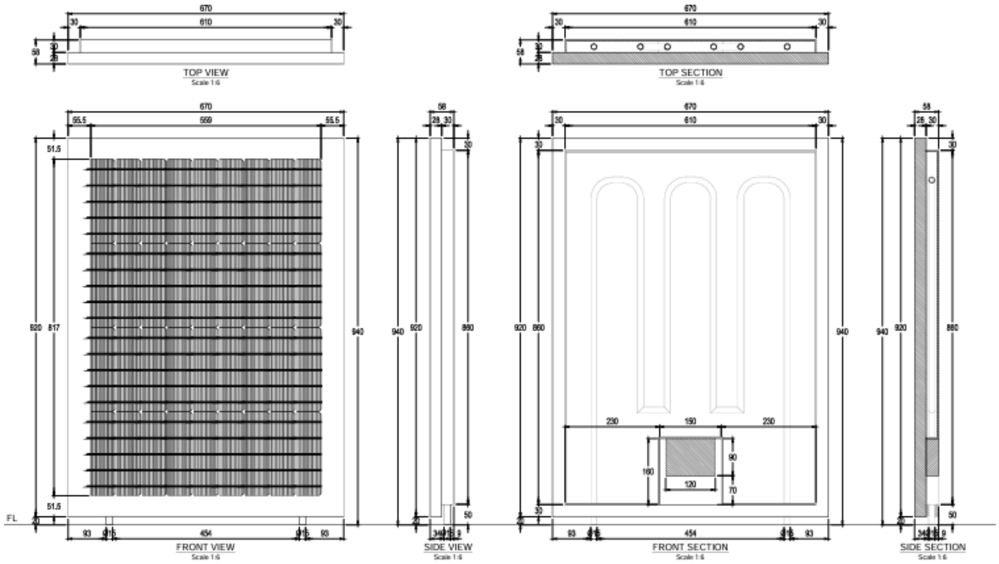


Figure 38: Design and dimensions of the Photovoltaic Thermal PCM system

Figure 39: Front and backside of the Photovoltaic Thermal PCM system

In accordance with the previously discussed designs, the assembly of the container and the arrangement of the piping system, which will encompass the phase change material (PCM), have been fabricated. This assembly will subsequently be positioned behind the selected photovoltaic panel for optimal thermal management:

Figure 40: The container and the copper pipes of the PVT PCM system

Figure 41: Piping system and the container

Figure 42: Back of the container

Figure 43: Container and piping system attatched to the back of the PV (backside)

Figure 44: Front side of the PV-PCM-T system

3.4.1 Determination of the Water Volume within the Pipes and the PCM Volume

As previously mentioned, the container holding the PCM has the following dimensions: 900 x 650 x 30 mm

Therefore, the volume that the container can hold is 17.55 lt

The volume of the piping inside the container and consequently the volume of the water they contain is calculated using the following equation:

$$V = \pi \cdot h \cdot r^2 \quad [20]$$

Where,

π= 3.14

r=0.011 m

h=3 m

So V was calculated to be 0.001398 m^3 = 1.398 lt.

Thus, when the PCM is in its liquid phase, its volume is calculated as the difference between the total volume of the container and the volume of the pipes (and therefore the water they contain): 17.55-1.398 = 16.152 lt

Additionally, the indentation of the container (with dimensions 0.15 x 0.16 x 0.03), as shown in Figure 38, must also be subtracted. Therefore, the final volume of the PCM is 16.152-0.72=15.43 lt

3.5 - ANSYS FLUENT

In this research, ANSYS software was employed to simulate the phase change process of the PCM in the PV-PCM-T system developed for the thesis. ANSYS is a widely used engineering tool for finite element analysis (FEA) and computational fluid dynamics (CFD), ideal for modeling complex physical processes like heat transfer and phase changes. Utilizing ANSYS allowed us to accurately model and assess the PCM's melting behavior under the operating conditions of the PV-PCM-T system, offering crucial insights into its thermal performance.

3.5.1 Phase change model

The equation solved in ANSYS (fluent) model for the PCM is:

$$\frac{\vartheta(\rho H)}{\vartheta_t} + \nabla.(\rho\vec{v}H) = \nabla.(\mathrm{k}\nabla\mathrm{T}) + S \qquad [21]$$

H: Enthalpy of the PCM

ρ: Density

$\vec{v}$: The rate of motion of the fluid

S: Source term

The thermodynamic property known as enthalpy is determined through the application of the subsequent mathematical representation:

$$H = h + \Delta H \qquad [22]$$

h: Sensible enthalpic measurement at a point at a given time.

ΔH: Heat of transformation

Latent heat (ΔH) of a substance L associated with the phase transition during the melting process can be expressed as :

$$\Delta H = \beta L \qquad [23]$$

where :

$$\beta = 0 \ \text{ if } \ T < T_{solid}$$

$$\beta = 1 \ \text{ if } \ T < T_{liquid}$$

$$\beta = \frac{T - T_{solid}}{T_{liquid} - T_{solid}} \ \text{ if } \ T_{solid} < T < T_{liquid} \qquad [24]$$

(Vikas and A. Yadav, 2017) , (Ahmad *et al.*, 2021)

3.5.2 ANSYS Simulation

The computational analysis of the system was executed utilizing ANSYS Fluent 2020 R2 software, with simulations undertaken under three distinct thermal conditions: 50°C, 55°C, and 64.5°C (the peak recorded photovoltaic temperature from the dataset acquired in 2018). The geometrical representation employed in the analysis is illustrated in Figure 38, and the mesh configuration depicted in Figure 42 comprises 4,906,361 nodes. On the upper surface of the container, temperatures of 50°C, 55°C, and 64.5°C were set, interacting directly with the photovoltaic panel, which illustrates the system's utmost operational capability. Furthermore, the conduits within the system contained stationary water, which was initially set at a temperature of 25 degrees Celsius.

The three different temperature cases allowed for a thorough evaluation of the system's thermal management capabilities under varying conditions.

Three critical parameters were monitored to assess the system's performance in all temperature scenarios:

1. The volume-average liquid fraction of the PCM

2. The volume-average The thermal state of the aqueous solution within the copper pipes

3. The average temperature of the PCM

These metrics were essential for evaluating both the potential for energy retention inherent in PCM and its efficiency in transferring and regulating heat within the system. This multi-temperature simulation provides deeper insights into how the system responds to varying thermal loads, ensuring that its performance can be optimized for different environmental conditions.

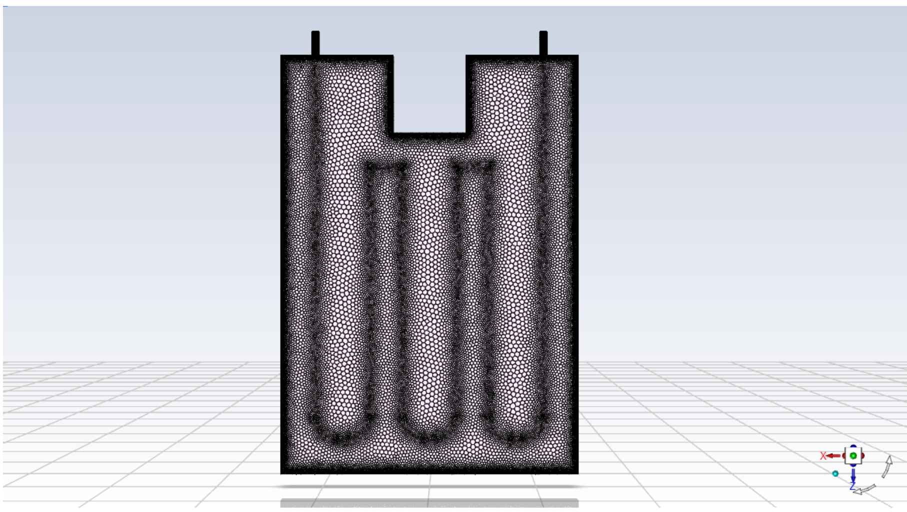


Figure 45: Mesh model.

Chapter 4 - Results Analysis

This chapter presents a thorough investigation of the results obtained the ANSYS simulation and the thermal evaluations conducted in practical environments. The conclusions involve several key parameters, which feature the PCM temperature, the temperature of the solar energy panel, the water temperature, and the duration required for the PCM to melt. A rigorous examination of these variables is crucial for understanding the operational efficacy of the system and for drawing informed conclusions regarding the thermal management effectiveness of the PV-PCM-T system. This extensive appraisal will provide valuable insights into the thermal behavior of the system across various operational scenarios and will lay the groundwork for improving its overall design and operational performance

4.1 ANSYS Results Analysis

This segment delineates a comprehensive examination of the findings derived from a dynamic simulation of a PCM system, which was modeled utilizing ANSYS Fluent. The primary emphasis of the simulation was to assess the thermal efficacy of the PCM (Rubitherm's RT-42 paraffin wax) alongside the dynamics of the circulating water within the copper conduits. This configuration has been deliberately selected to investigate the potential of PCM in augmenting thermal regulation and energy storage functionalities, which are essential in a myriad of industrial and environmental applications.

4.1.1 First Case – 50 °C Result Analysis

The simulation covered a period of 30,000 seconds, using a transient approach to capture a comprehensive view of the system's thermal dynamics. The emphasis was placed on three fundamental metrics: the volumetric average liquid fraction of the PCM, the mean volumetric temperature of the water present within the copper conduits, in conjunction with the mean volumetric temperature of the PCM itself. These metrics were crucial for evaluating the PCM's effectiveness in energy storage and thermal regulation capabilities.

The subsequent visual representations systematically depict the phase transition of the phase change material (PCM), with the azure hue symbolizing the solid phase and the crimson hue denoting the liquid phase:

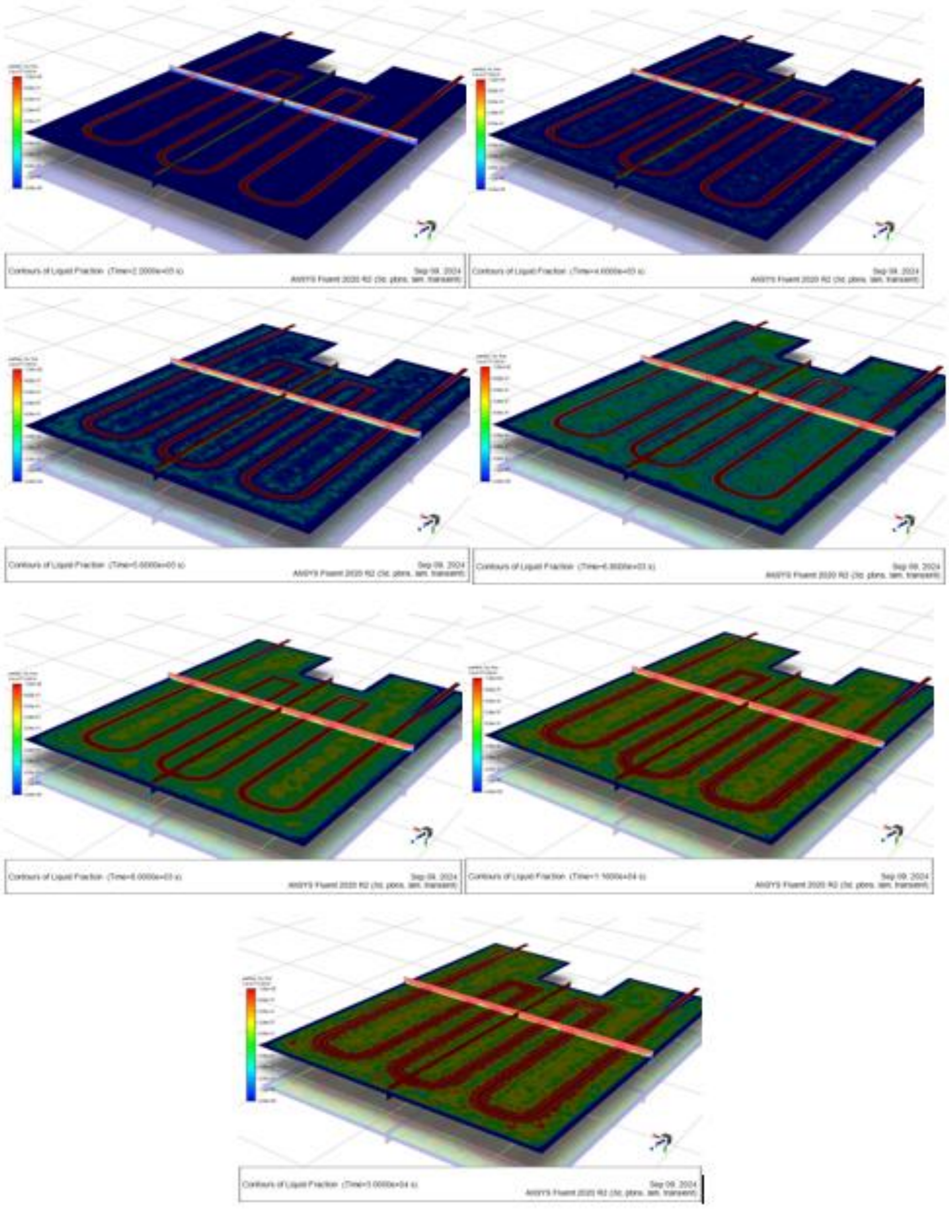


Figure 46: PCM melting process at 50 °C

The first graph *(Diagram 2),* showing the volume-average liquid fraction of the PCM reveals a significant insight into its phase change behavior. The liquid fraction increases steadily from the start, indicating that the PCM begins to absorb heat and melt. However, the curve begins to plateau significantly before reaching 100%, suggesting that the PCM does not fully melt within the 30,000 seconds of simulation time. This plateau indicates that while the PCM is effective in absorbing a considerable amount of heat, it does not achieve complete liquefaction under the conditions provided. Since heat losses to the ambient environment are factored into the system's energy balance, the system may reach a thermal equilibrium. At this juncture, the thermal energy provided for the phase transition phenomenon is counterbalanced by the dissipation to the environment, culminating in a partial liquefaction of the PCM. Thus, without a higher temperature gradient or enhanced heat transfer efficiency, the PCM remains partially solid, as the system stabilizes before sufficient energy is available to complete the melting process.

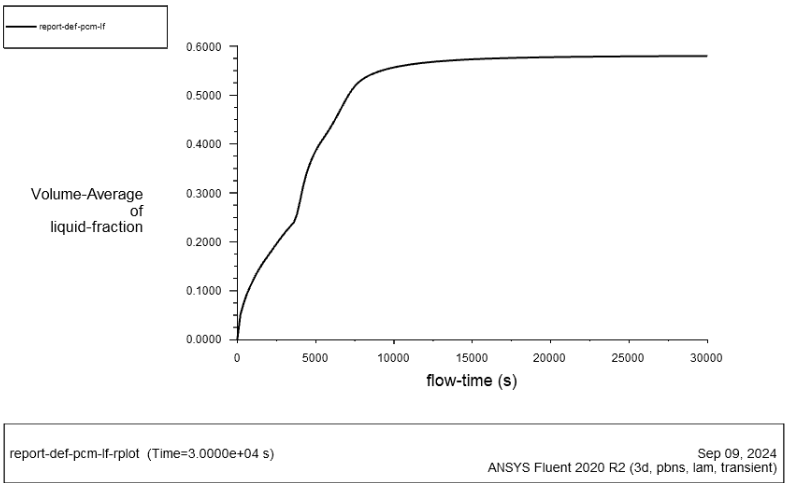


Diagram 2: Liquid Fraction at 50 °C simulation

The subsequent graphical representation (Diagram 3) delineates the thermal profile of the aqueous medium within the copper conduits, which notably illustrates a dynamic interplay between the liquid and the phase change material (PCM). At the outset, the temperature of the water commences at a baseline of 25°C and undergoes a gradual escalation. This elevation in temperature, culminating at approximately 42°C, serves as a testament to the thermal energy being conveyed from the PCM to the water throughout the phase alteration process of the PCM. After the Phase change material releases its absorbed heat and approaches a thermal equilibrium, the water temperature stabilizes. This demonstrates the PCM's ability to effectively transfer stored heat back to the water, maintaining a higher but stable temperature. Such stabilization is beneficial for systems that require a controlled temperature output, as it ensures a consistent delivery of heat which can be crucial for process stability or enhanced energy efficiency in various applications. The efficient thermal exchange between the phase change material (PCM) and the aqueous medium underscores the dual function of the PCM, which involves not only the absorption of surplus thermal energy to alleviate temperature fluctuations but also the emission of heat to sustain ideal operational temperature ranges within the system.

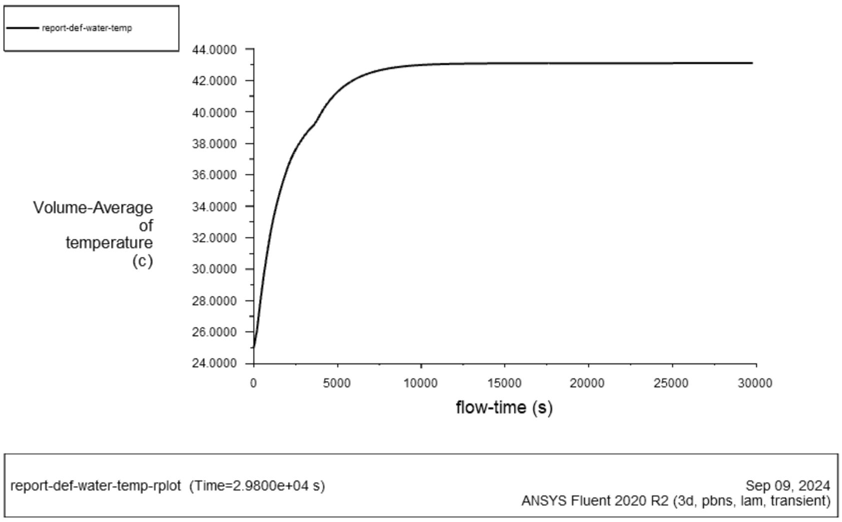


Diagram 3: Water temperature at 50 °C simulation

The third graph (Diagram 4), depicting the thermal profile of the phase PCM, exhibited a comparable pattern to that of the water temperature, indicating an effective thermal interaction between the PCM and the water. The PCM temperature increased from around 25°C and stabilized at about 40°C after the initial 5,000 seconds. This stabilization, while significant, underscores the PCM's capacity to absorb and thereafter maintain heat, which could be critical for prolonged energy utilization and management within a system.

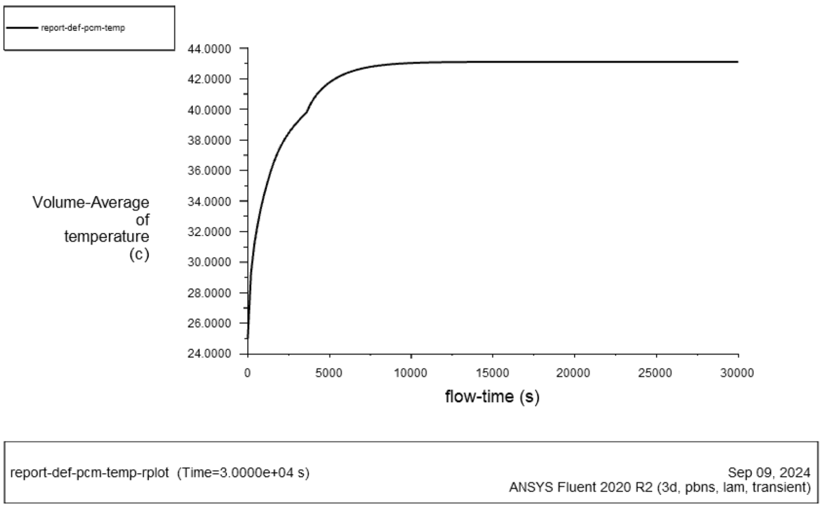


Diagram 4: PCM temperature at 50 °C simulation

The behavior of the PCM and the impact it has on the system efficiency is quite evident from the results. During peak absorption, the PCM effectively moderated the temperatures within the system, absorbing excess thermal energy and preventing temperature spikes that could degrade system performance. Nonetheless, the partial melting indicates an imperative for additional optimization, which may involve the selection of a PCM exhibiting a reduced melting point, improved thermal conductivity, or alterations to the system aimed at augmenting heat transfer to the phase change material.

4.1.2 Second Case- 55 °C Results Analysis

Analyzing at an operational temperature of 55°C reveals insightful dynamics based on the provided diagrams. These illustrate the PCM's phase change, the the water temperature flowing through the copper pipes, and also the PCM's response over a simulated period of 25,000 seconds.

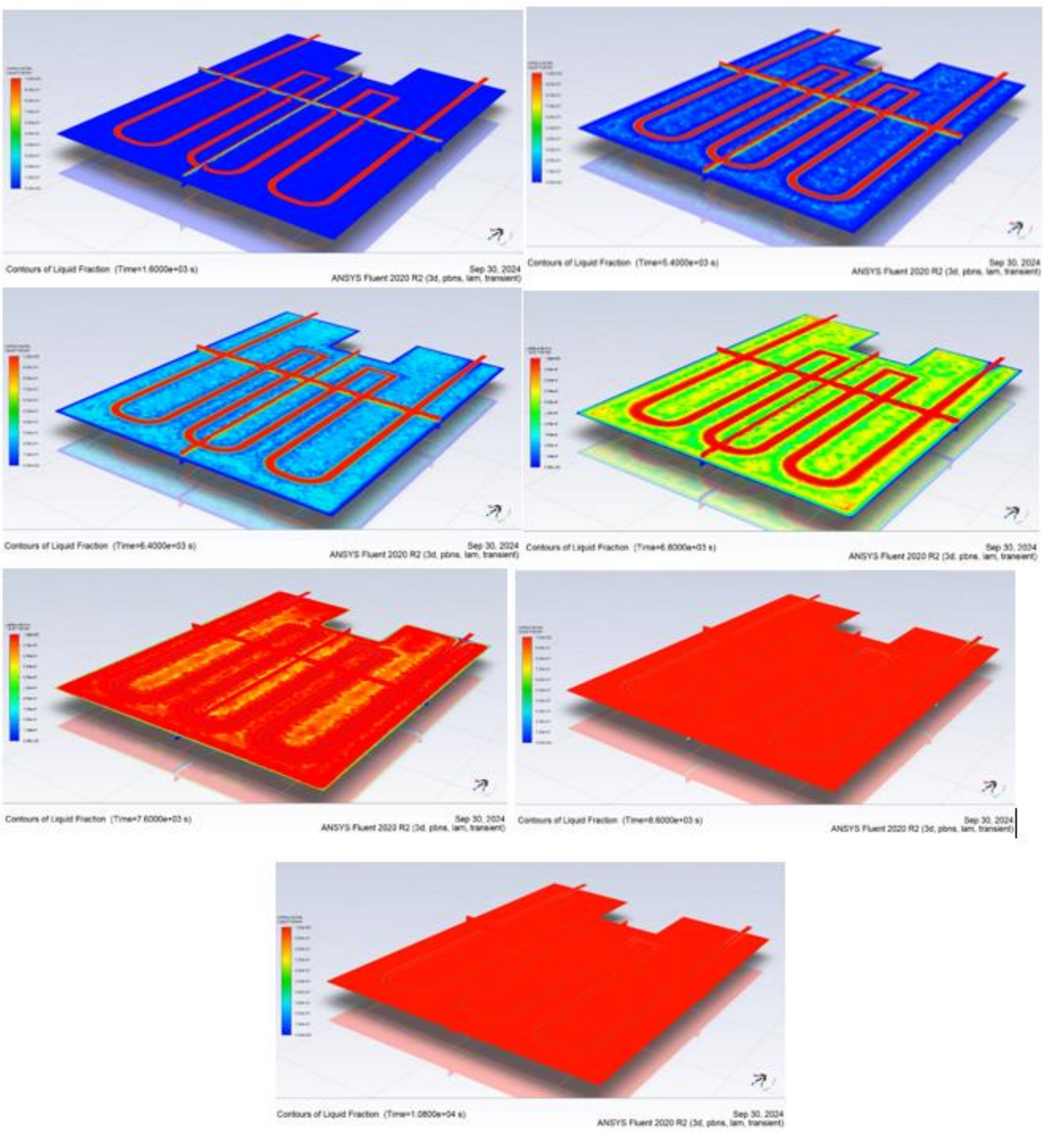


Figure 47: PCM melting progress at 55°C

The first diagram (*Diagram 5*), which displays the volume-average liquid fraction of the PCM, clearly shows a gradual increase in the PCM's liquid fraction, reflecting its absorption of heat. The curve steadily rises and ultimately achieves complete liquefaction at approximately 22,400 seconds (6.22 hours).

During this interval, the phase change material sequesters the surplus thermal energy and undergoes phase transition, resulting in its melting. This process allows the photovoltaic panel to maintain a stable operating temperature of 55°C (typical for summer months in Crete) for an extended duration of approximately 6.22 hours without further temperature increase. Following this phase, water recirculation will be initiated, enabling the PCM to absorb additional heat, thereby prolonging the steady-state temperature of the photovoltaic panel. This methodology guarantees a more effective thermal management and augments the system's comprehensive functionality by mitigating the risk of overheating during extended durations of solar radiation.

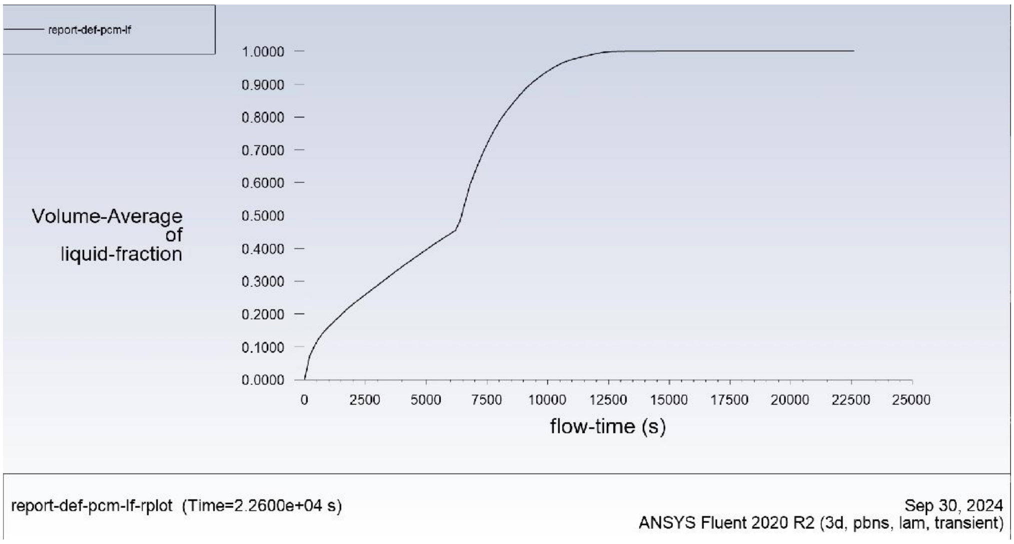


Diagram 5: Liquid fraction of PCM at 55°C

The second diagram *(Diagram 6)* details the temperature profile of the water within the copper pipes. It begins at about 27.5°C and exhibits a rapid increase, reaching around 45°C in the initial phase of the simulation. After this sharp rise, the water temperature stabilizes at approximately 47°C. This stabilization suggests that once the PCM begins to melt, it efficiently absorbs excess heat from the water, which helps prevent further temperature increases. This effective heat absorption and subsequent stabilization are crucial for maintaining the efficiency of the photovoltaic cells by avoiding overheating, which typically decreases their efficiency. Moreover, the water exiting the system at a temperature of 47°C can be effectively utilized for domestic applications or industrial processes.

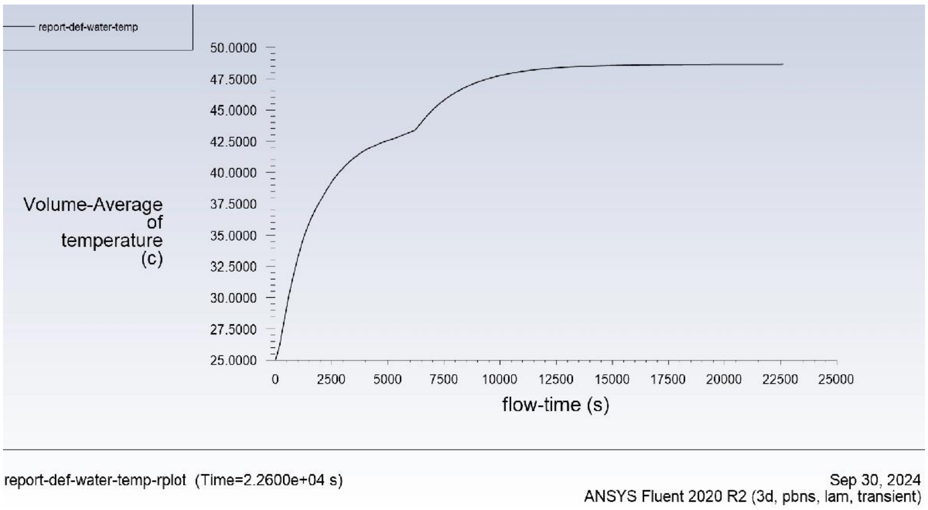


Diagram 6: Water temperature diagram at 55°C

The third diagram *(Diagram 7)* tracks the temperature profile of the PCM itself, which closely aligns with the changes in the water temperature, albeit with a slight delay. The PCM's temperature starts at the same base level as the water and also rises, ultimately stabilizing at around 44°C after the PCM has fully melted. This stabilization of the PCM's temperature at a relatively high level indicates its capability to absorb significant heat from the PV, store it, and maintain a consistent temperature, which is vital for continuous energy management within the system.

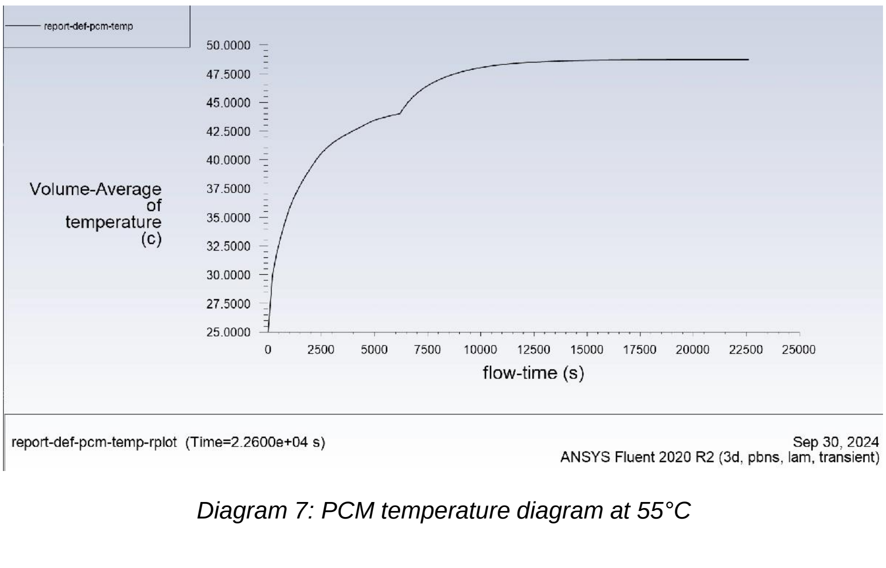


Diagram 7: PCM temperature diagram at 55°C

4.1.3 Third Case - 64.5 °C Results Analysis

Analyzing at an operational temperature of 64.5°C reveals insightful dynamics based on the provided diagrams. These data exemplify the transition of PCM, the thermal profile of the water circulating within the copper conduits, and the corresponding thermal response of the PCM observed over a simulated duration of 14,000 seconds.

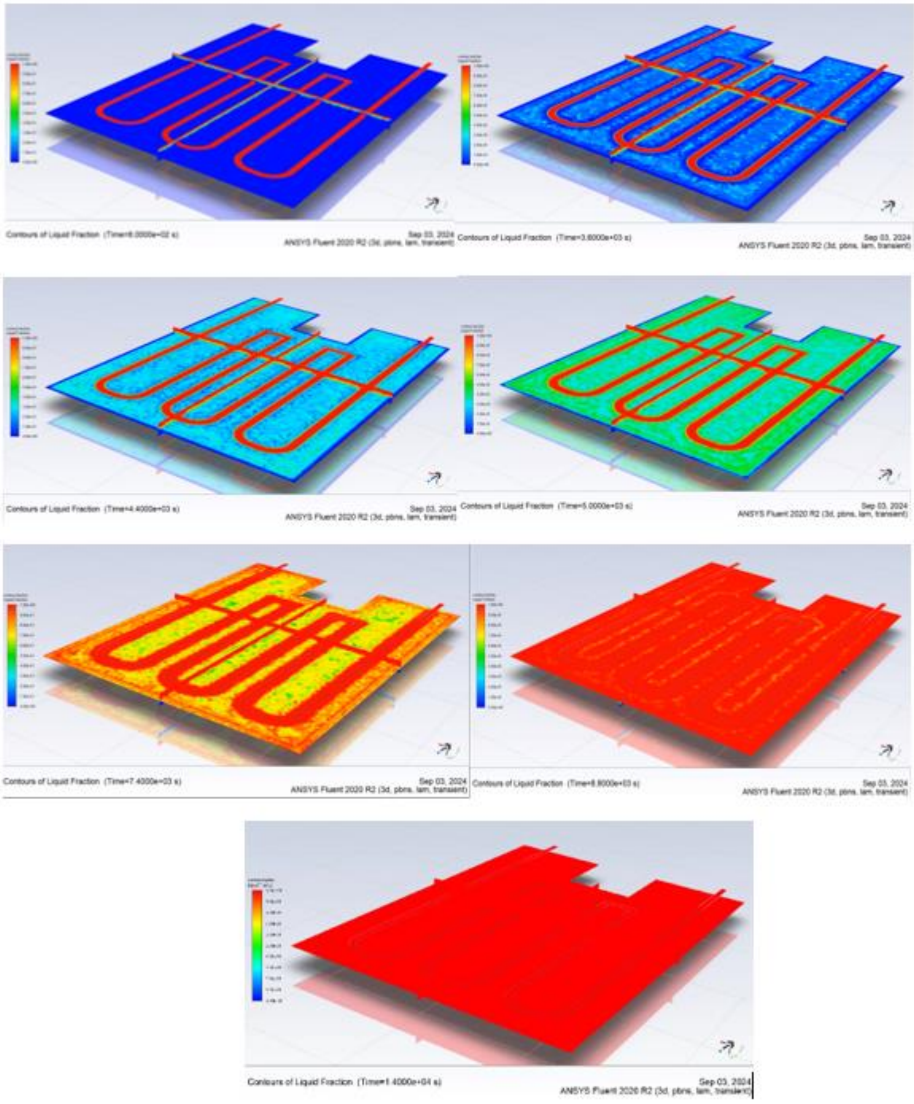


Figure 48: Pcm melting process at 64.5 °C

The graph presented in *Diagram 8* provides a clear visual representation of the PCM's transformation from solid to liquid, indicated by the progressive increase in the volume-average liquid fraction. Commencing at a value of zero, indicative of a fully solidified state, the graph delineates a consistent increase in the liquid fraction, thereby effectively depicting the phase transition associated involving the transition of the PCM. The graph highlights a sustained increase in the liquid fraction up to about 12,000 seconds, marking a significant phase of heat absorption. During this period, the phase change material (PCM) effectively captures significant quantities of thermal energy while sustaining a comparatively stable temperature, utilizing the principle of latent heat storage. As the curve begins to plateau around 12,000 seconds (3.30 hours), it indicates that the PCM is nearly fully melted, signifying a state of thermal equilibrium.

This indicates that, even under the highest recorded temperature for the solar panel, the system can hold a constant temperature for an extended timeframe of 3.3 hours. Throughout this interval, the phase change material (PCM) will persist in absorbing surplus thermal energy, thereby obstructing any further escalation in the temperature of the photovoltaic module. It is only subsequent to this time frame that the PCM will attain its thermal absorption threshold, at which juncture the temperature of the photovoltaic panel may commence an upward trajectory.

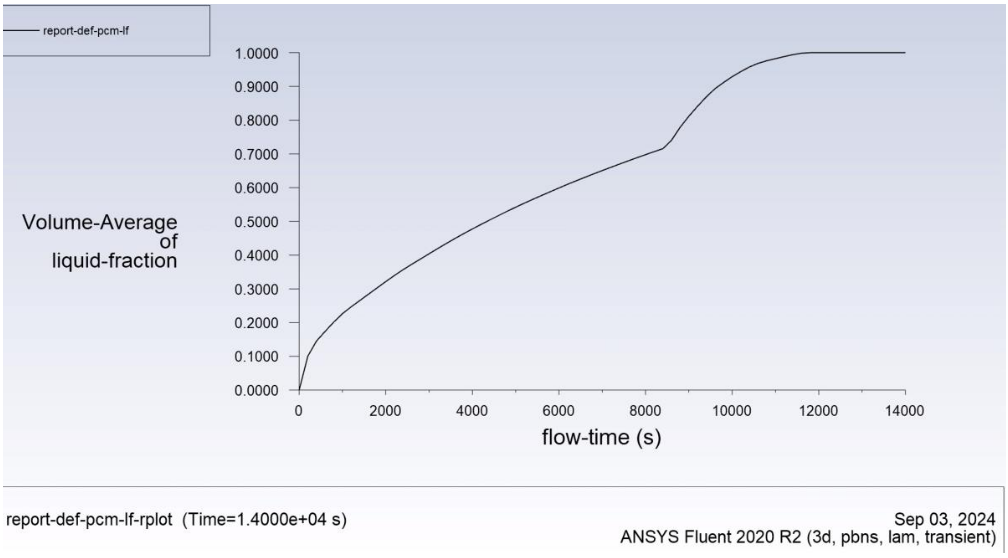


Diagram 8: Liquid fraction of PCM

Diagram 9 provides a detailed representation of the temperature pattern of the water flowing through the tubes in the Photovoltaic-Thermal (PVT) PCM system. It showcases an initial sharp rise in temperature, a clear indication of an intense heat transfer from PCM to the water. This rapid increase, where the temperature surges from an initial ambient condition of around 25°C to approximately 50°C within the first few thousand seconds, is crucial. The flattening of the curve at around 12000 seconds indicates that the system is reaching a thermal equilibrium, a state where the water’s ability to relinquish heat aligns with the PCM's reduced ability to absorb further heat. This issue can be addressed by implementing a recirculation process for the water whenever it reaches the temperature threshold of the fully melted PCM, approximately 50°C. This approach ensures the efficient regulation of thermal loads within the system, preventing overheating and optimizing heat transfer for more than 3.30 hours.

This moderated temperature of the water, stabilizing around 50°C, opens up potential applications in domestic settings. Water at this temperature is ideal for uses such as heating spaces and providing hot water for household use, which typically require temperatures within the 40°C to 60°C range. Using the temperature-controlled water from the PVT system offers an eco-friendly and energy-efficient option for residential heating needs. This approach increases the system's overall usefulness while also helping to lower traditional energy usage for heating. This efficient use of waste heat exemplifies the PVT system's ability to integrate seamlessly into the energy ecosystem of a home, enhancing both its environmental and economic viability.

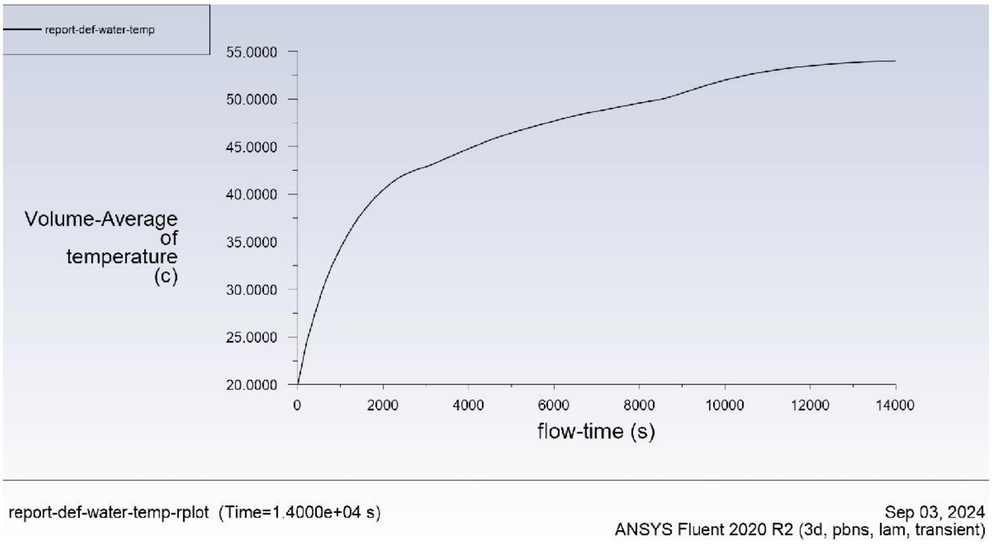


Diagram 9: Water temperature

The last Diagram *(Diagram 10)* provides a comprehensive analysis of the PCM's temperature profile within the Photovoltaic-Thermal (PVT) system, which notably begins by closely following the temperature trajectory of the water, albeit with a discernible delay. Initially mirroring the water's temperature increase from 25°C, the PCM's temperature gradually increases because of its high thermal inertia, which results from the latent heat absorbed during the crucial phase change from solid to liquid. This delay is a vital feature of the PCM's ability to manage energy, enabling it to store heat efficiently without a quick temperature spike.

As the simulation progresses, the PCM's temperature is observed gradually stabilizing. This temperature profile shows a slow but steady climb, with the PCM's temperature reaching approximately 45°C as it approaches a fully liquid state. This point is critical, as it signals a reduction in the PCM's heat absorption capacity, indicating that it is nearing or has reached its thermal saturation point. Beyond this point, the temperature increase plateaus, marking the end of the effective energy storage phase for this operational cycle.

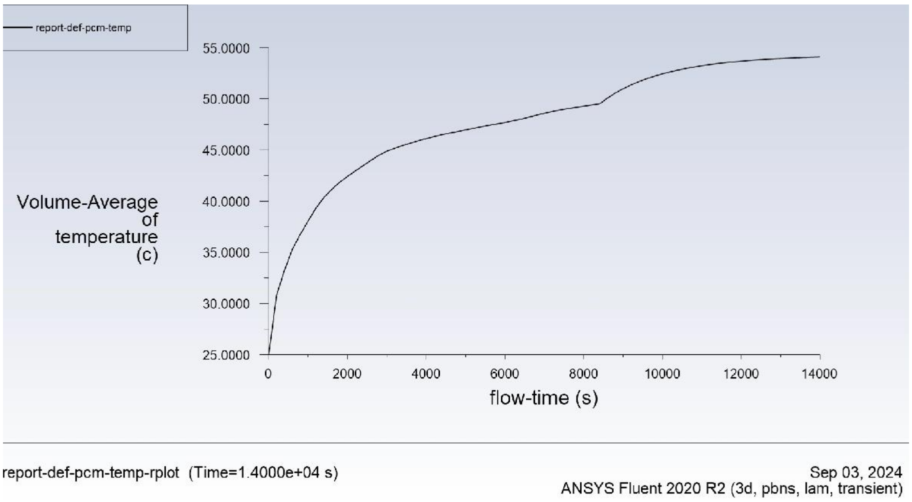


Diagram 10: Pcm temperature

4.1.4 Calculation and Comparison of the Electrical power generated by the PV and the Heat transferred to the PCM.

The power output P_{phot} for the three cases (temperature 50°C, 55°C, 64.5°C) can be calculated by using the equations [13] and [14] and the values of the parameters are presented in *Table 5.*

Solar Irradiance G_T , it is presumed to be 997 W/m², which corresponds to the solar irradiance at the point when the photovoltaic panel reaches its maximum operating temperature.

Based on the aforementioned data, the following calculations for each case are derived:

Case 1 - 50°C: n_T= 0.888 and P_{phot}= 100 W.

Case 2 -55°C : n_T= 0.865 and P_{phot} = 98.71 W.

Case 3- 64.5°C: n_T= 0.823 and P_{phot} = 93.89 W.

The amount of heat transferred to the PCM in the three scenarios can be calculated using equation [15].

P_{sol} was measured at 540.805 W for each case

$P_{rad,F}$ was measured at 0.535449 W for each case

$P_{conv,F}$ was measured at 351.4527 W for each case

P_{Phot} is calculated for each case

Case 1-50°C: n_T= 0.888 , P_{phot} =100 W , P_c = 88.82 W

Case 2 -55°C : n_T= 0.865 , P_{phot} = 98.71 W , P_c = 90.107 W

Case 3- 64.5°C: n_T= 0.823 , P_{phot} = 93.89 W , P_c = 94.927W

Utilizing the aforementioned values, the following diagram was generated:

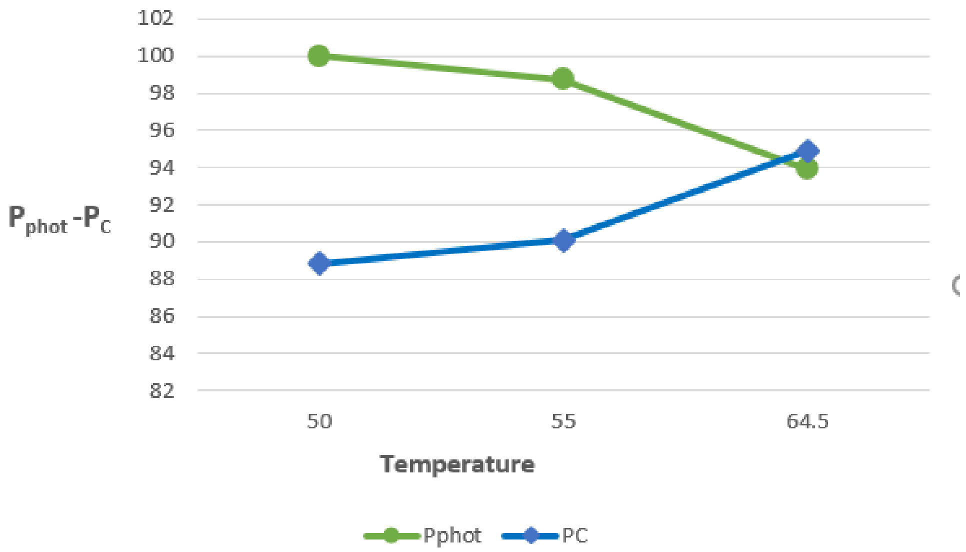


Diagram 11: Comparison of the power output Pphot and the Heat transferred to the PCM

As presented in Diagram 11, the electrical power output (P_{phot}) decreases with increasing temperature. This decline is expected in PV systems as the efficiency of photovoltaic cells typically decreases with temperature due to increased carrier recombination rates and decreased open-circuit voltage. The heat transfer to the PCM (Pc) initially increases with the rise in temperature, likely due to an increased thermal gradient driving more heat into the PCM.

P_c and P_{phot} are inversely related in terms of their response to temperature changes within the system. Effective management of these dynamics is crucial. While the PCM helps mitigate thermal effects up to a point, beyond this, other cooling or system optimization strategies may be necessary to maintain or improve the PV system's efficiency. Understanding this balance is essential for designing PV-PCM-T systems that maximize both thermal regulation and electrical output, particularly in environments where high temperatures could significantly impact performance.

At 64.5°C**,** the power generated by the PV panel and the heat absorbed by the PCM become equal. This suggests that the PCM is operating optimally at this temperature, efficiently removing heat from the PV panel to maintain a balance between heat absorption and power generation.

This graph highlights the importance of integrating PCM into PV systems. As the temperature increases, the PCM helps mitigate the loss of power by absorbing excess heat. While the power generated by the PV panel still decreases with temperature, the PCM's heat absorption helps slow down the rate of efficiency loss, ultimately improving the system's overall performance in high-temperature conditions.

CHAPTER 5- CONCLUSIONS

The results showcased in this study show that incorporating PCM in the Photovoltaic-Thermal (PVT) system markedly elevates its thermal functions. The configuration of the system, characterized by a meticulously structured serpentine layout of copper piping integrated within the PCM, has been substantiated as an effective methodology for enhancing heat dissipation and maintaining lower operational temperatures. By employing PCM to sequester excess thermal energy during daylight hours, the system successfully achieved lower operating temperatures for a duration exceeding 3.3 hours under the most extreme temperature conditions. This prolonged phase of stable operation at diminished temperatures is vital for averting degradation of the photovoltaic (PV) module, thereby effectively prolonging its operational lifespan and sustaining elevated levels of electrical generation. The PCM functions as a thermal buffer, progressively melting and absorbing the thermal energy that would otherwise accumulate on the PV module. This mechanism effectively delays the escalation of temperature, particularly during peak solar radiation periods when PV modules are susceptible to overheating, thereby allowing the system to produce electricity with enhanced efficiency over time.

Once the PCM has fully melted, the system is designed to extend the cooling process through the circulation of water within the serpentine copper pipes. This active cooling strategy is activated subsequent to the completion of the phase change process, ensuring that excess thermal energy continues to be dissipated, thus enabling lower PV temperatures to be maintained for an extended period. The synergistic effect of passive cooling via PCM and active cooling through water circulation significantly amplifies the system's capability to maintain the PV module at optimal operational temperatures during the most critical hours of the day, thereby maximizing both electrical efficiency and thermal regulation.

In addition to enhancing electrical performance, the system exhibited superior thermal energy production capabilities. The heated water generated by the system attained temperatures as elevated as 50°C, yielding a considerable by-product that could be harnessed for residential or commercial heating applications. The dual functionality of the solar-PCM-T system, which generates both electricity and usable thermal energy simultaneously, highlights its versatility and practical applications. This hybrid capability facilitates a more comprehensive utilization of energy, diminishing the necessity for separate systems dedicated to heat and electricity generation. The effective exploitation of solar energy in both thermal and electrical forms renders the PV-PCM-T system an appealing solution, particularly in regions characterized by high solar irradiance and elevated energy demands, such as the area of Chania in Crete during peak tourist seasons.

Furthermore, the system illustrated its effectiveness in functioning under real-world scenarios, as substantiated by the data collected in Chania, where solar irradiance levels remain consistently elevated. In such settings, conventional PV systems frequently experience efficiency declines attributable to elevated operating temperatures. However, with the incorporation of PCM, the solar-PCM-T system was able to sustain lower temperatures for extended durations, thereby optimizing the equilibrium between heat absorption and electricity production. This attribute is particularly pertinent in Mediterranean climates, where intense solar exposure poses a risk of overheating for PV modules, adversely affecting their operational performance. This PCM effectively addresses the overheating concern while assuring that the system remains operational during the peak heat hours.

The results of this study align with existing literature, which confirms that incorporating Phase Change Materials (PCM) into Photovoltaic-Thermal (PVT) systems significantly improves thermal regulation and prolongs optimal operating temperatures. Similar to previous findings, the PCM in our system effectively absorbs excess heat, delaying temperature rise and preventing PV module overheating during peak solar radiation. The serpentine copper pipe configuration enhances heat dissipation, while the combination of passive PCM cooling and active water circulation agrees with studies showing dual cooling strategies improve efficiency.

Nevertheless, despite these encouraging results, there exists the potential for additional enhancements. Utilizing immediate electrical metrics could uncover more substantial perspectives on the system's functions amidst fluctuating scenarios, thereby aiding in finer tuning and elevation of its operations. Also, the undertaking of life cycle assessments (LCA) could offer significant details related to the ecological and economic sustainability of the system as time progresses, thus ensuring its financial prudence and durability over a longer span. A further significant avenue for enhancement is the adoption of environmentally benign materials for the phase change material (PCM), which would mitigate the overall ecological footprint of the system. Lastly, structural modifications, such as refining the PCM container's design or optimizing the cooling system with water, could significantly enhance how efficiently the system operates.

CHAPTER 6 – Bibliography

[1] Ahmad, A. *et al.* (2021) 'Evaluation of new pcm/pv configurations for electrical energy efficiency improvement through thermal management of pv systems', *Energies*, 14(14). Available at: https://doi.org/10.3390/en14144130.

[2] Aneli, S., Arena, R. and Gagliano, A. (2021) 'Numerical simulations of a PV module with phase change material (PV-PCM) under variable weather conditions', *International Journal of Heat and Technology*, 39(2), pp. 643–652. Available at: https://doi.org/10.18280/ijht.390236.

[3] Ar, M., Bilgin, F. and Ni, S. (2018) 'Phase change material based cooling of photovoltaic panel : A simpli fi ed numerical model for the optimization of the phase change material layer and general economic evaluation', 189, pp. 738–745. Available at: https://doi.org/10.1016/j.jclepro.2018.04.057.

[4] Arefin, M.A. (2019) 'Analysis of an Integrated Photovoltaic Thermal System by Top Surface Natural Circulation of Water', *Frontiers in Energy Research*, 7(September). Available at: https://doi.org/10.3389/fenrg.2019.00097.

[5] Arıcı, M. *et al.* (2018) 'Phase change material based cooling of photovoltaic panel: A simplified numerical model for the optimization of the phase change material layer and general economic evaluation', *Journal of Cleaner Production*, 189, pp. 738–745. Available at: https://doi.org/10.1016/j.jclepro.2018.04.057.

[6] Armstrong, S. and Hurley, W.G. (2010) 'A thermal model for photovoltaic panels under varying atmospheric conditions', *Applied Thermal Engineering*, 30(11–12), pp. 1488–1495. Available at: https://doi.org/10.1016/j.applthermaleng.2010.03.012.

[7] Asefi, G., Ma, T. and Wang, R. (2023) 'Techno-economic evaluation of photovoltaic thermal system integrated with porous phase change materials: Case studies in China', *Energy Conversion and Management*, 290(November 2022), p. 117227. Available at: https://doi.org/10.1016/j.enconman.2023.117227.

[8] Bassam, A.M. *et al.* (2023) 'Experimental analysis of photovoltaic thermal collector (PVT) with nano PCM and micro-fins tube counterclockwise twisted tape nanofluid', *Case Studies in Thermal Engineering*, 45. Available at: https://doi.org/10.1016/j.csite.2023.102883.

[9] Bhakre, S.S., Sawarkar, P.D. and Kalamkar, V.R. (2023) 'Numerical study on photovoltaic thermal phase change material system in hot climatic conditions', *Applied Thermal Engineering*, 227(February), p. 120423. Available at: https://doi.org/10.1016/j.applthermaleng.2023.120423.

[10] Carmona, M., Palacio Bastos, A. and García, J.D. (2021) 'Experimental evaluation of a hybrid photovoltaic and thermal solar energy collector with integrated phase change material (PVT-PCM) in comparison with a traditional photovoltaic (PV) module', *Renewable Energy*, 172, pp. 680–696. Available at: https://doi.org/10.1016/j.renene.2021.03.022.

[11] Chaichan, M.T. *et al.* (2021) 'Controlling the melting and solidification points temperature of PCMs on the performance and economic return of the water-cooled photovoltaic thermal system', *Solar Energy*, 224, pp. 1344–1357. Available at: https://doi.org/10.1016/j.solener.2021.07.003.

[12] Chen, G. and Wan, L. (2011) *Research and application of thermal storage with phase change materials*, *Advanced Materials Research*. Available at: https://doi.org/10.4028/www.scientific.net/AMR.250-253.3541.

[13] Du, K. *et al.* (2018) 'A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges', *Applied Energy*, 220(October 2017), pp. 242–273. Available at: https://doi.org/10.1016/j.apenergy.2018.03.005.

[14] Dubey, S. and Tay, A.A.O. (2013) 'Testing of two different types of

photovoltaic-thermal (PVT) modules with heat flow pattern under tropical climatic conditions', *Energy for Sustainable Development*, 17(1), pp. 1–12. Available at: https://doi.org/10.1016/j.esd.2012.09.001.

[15] Ehyaei, M.A. and Farshin, B. (2017) 'Optimization of photovoltaic thermal (PV/T) hybrid collectors by genetic algorithm in Iran's residential areas', *Advances in Energy Research*, 5(1), pp. 31–55. Available at: https://doi.org/10.12989/eri.2017.5.1.031.

[16] Elsheniti, M.B. *et al.* (2020) 'Novel enhanced conduction model for predicting performance of a PV panel cooled by PCM', *Energy Conversion and Management*, 205(December 2019), p. 112456. Available at: https://doi.org/10.1016/j.enconman.2019.112456.

[17] Elsheniti, M.B. *et al.* (2023) 'Experimental Evaluation of a Solar Low-Concentration Photovoltaic/Thermal System Combined with a Phase-Change Material Cooling Technique', *Applied Sciences (Switzerland)*, 13(1). Available at: https://doi.org/10.3390/app13010025.

[18] Emmanuel, B. *et al.* (2021) 'A review on the influence of the components on the performance of PVT modules', *Solar Energy*, 226(July), pp. 365–388. Available at: https://doi.org/10.1016/j.solener.2021.08.042.

[19] Fayaz, H. *et al.* (2019) 'Numerical and outdoor real time experimental investigation of performance of PCM based PVT system', *Solar Energy*, 179(July 2018), pp. 135–150. Available at: https://doi.org/10.1016/j.solener.2018.12.057.

[20] Grabo, M. *et al.* (2019) 'Numerical Investigation of the Temperature Distribution in PCM-integrated Solar Modules', *Chemical Engineering Transactions*, 76(2014), pp. 895–900. Available at: https://doi.org/10.3303/CET1976150.

[21] Hamada, A. *et al.* (2023) 'Investigating the performance of a water-based PVT system using encapsulated PCM balls: An experimental study', *Energy*, 284, p. 128574. Available at: https://doi.org/10.1016/J.ENERGY.2023.128574.

[22] Hasan, A. *et al.* (2015) 'Increased photovoltaic performance through temperature regulation by phase change materials: Materials comparison in different climates', *Solar Energy*, 115, pp. 264–276. Available at: https://doi.org/10.1016/j.solener.2015.02.003.

[23] Hasan, A., Alnoman, H. and Rashid, Y. (2016) 'Impact of integrated photovoltaic-phase change material system on building energy efficiency in hot climate', *Energy and Buildings*, 130, pp. 495–505. Available at: https://doi.org/10.1016/j.enbuild.2016.08.059.

[24] Hossain, M.S. *et al.* (2023) 'A Comparative Investigation on Solar PVT- and PVT-PCM-Based Collector Constancy Performance', *Energies*, 16(5). Available at: https://doi.org/10.3390/en16052224.

[25] Hossain, M.S. *et al.* (2024) 'Solar PV high-penetration scenario: an overview of the global PV power status and future growth', *Energy Systems* [Preprint]. Available at: https://doi.org/10.1007/s12667-024-00692-6.

[26] Huang, M.J., Eames, P.C. and Norton, B. (2004) 'Thermal regulation of building-integrated photovoltaics using phase change materials', *International Journal of Heat and Mass Transfer*, 47(12–13), pp. 2715–2733. Available at: https://doi.org/10.1016/j.ijheatmasstransfer.2003.11.015.

[27] Huang, M.J., Eames, P.C. and Norton, B. (2006) 'Phase change materials for limiting temperature rise in building integrated photovoltaics', *Solar Energy*, 80(9), pp. 1121–1130. Available at: https://doi.org/10.1016/j.solener.2005.10.006.

[28] Huang, X. *et al.* (2017) 'Morphological characterization and applications of phase change materials in thermal energy storage: A review', *Renewable and Sustainable Energy Reviews*, 72(November 2016), pp. 128–145. Available

at: https://doi.org/10.1016/j.rser.2017.01.048.
[29] Jathar, L.D. *et al.* (2023) ‘Comprehensive review of environmental factors influencing the performance of photovoltaic panels: Concern over emissions at various phases throughout the lifecycle’, *Environmental Pollution*, 326(February), p. 121474. Available at: https://doi.org/10.1016/j.envpol.2023.121474.
[30] Jones, A.D. and Underwood, C.P. (2002) ‘A thermal model for photovoltaic systems’, *Fuel and Energy Abstracts*, 43(3), p. 199. Available at: https://doi.org/10.1016/s0140-6701(02)85831-3.
[31] Khan, Zakir, Khan, Zulfiqar and Ghafoor, A. (2016) ‘A review of performance enhancement of PCM based latent heat storage system within the context of materials, thermal stability and compatibility’, *Energy Conversion and Management*, 115, pp. 132–158. Available at: https://doi.org/10.1016/j.enconman.2016.02.045.
[32] Khanna, S., Reddy, K.S. and Mallick, T.K. (2018) ‘Optimization of finned solar photovoltaic phase change material (finned pv pcm) system’, *International Journal of Thermal Sciences*, 130(April), pp. 313–322. Available at: https://doi.org/10.1016/j.ijthermalsci.2018.04.033.
[33] Klugmann-Radziemska, E. and Wcisło-Kucharek, P. (2017) ‘Photovoltaic module temperature stabilization with the use of phase change materials’, *Solar Energy*, 150, pp. 538–545. Available at: https://doi.org/10.1016/j.solener.2017.05.016.
[34] Kong, X. *et al.* (2022) ‘Experimental thermal and electrical performance analysis of a concentrating photovoltaic/thermal system integrated with phase change material (PV/T-CPCM)’, *Solar Energy Materials and Solar Cells*, 234(August 2021), p. 111415. Available at: https://doi.org/10.1016/j.solmat.2021.111415.
[35] Leong, K.Y., Abdul Rahman, M.R. and Gurunathan, B.A. (2019) ‘Nano-enhanced phase change materials: A review of thermo-physical properties, applications and challenges’, *Journal of Energy Storage*, 21(October 2018), pp. 18–31. Available at: https://doi.org/10.1016/j.est.2018.11.008.
[36] Li, M. *et al.* (2023) ‘Investigation on Thermal and Electrical Performance of Late-Model Plate-and-Tube in Water-Based PVT-PCM Collectors’, *Sustainability (Switzerland)*, 15(7). Available at: https://doi.org/10.3390/su15075988.
[37] Li, Z. *et al.* (2019) ‘Experimental study and performance analysis on solar photovoltaic panel integrated with phase change material’, *Energy*, 178, pp. 471–486. Available at: https://doi.org/10.1016/j.energy.2019.04.166.
[38] Lu, W. *et al.* (2018) ‘Investigation on designed fins-enhanced phase change materials system for thermal management of a novel building integrated concentrating PV’, *Applied Energy*, 225(May), pp. 696–709. Available at: https://doi.org/10.1016/j.apenergy.2018.05.030.
[39] Ma, T. *et al.* (2015) ‘Using phase change materials in photovoltaic systems for thermal regulation and electrical ef fi ciency improvement : A review and outlook’, *Renewable and Sustainable Energy Reviews*, 43, pp. 1273–1284. Available at: https://doi.org/10.1016/j.rser.2014.12.003.
[40] Ma, T., Li, M. and Kazemian, A. (2020) ‘Photovoltaic thermal module and solar thermal collector connected in series to produce electricity and high-grade heat simultaneously’, *Applied Energy*, 261(June 2019), p. 114380. Available at: https://doi.org/10.1016/j.apenergy.2019.114380.
[41] Ma, T., Zhao, J. and Li, Z. (2018) ‘Mathematical modelling and sensitivity analysis of solar photovoltaic panel integrated with phase change material’, *Applied Energy*, 228(June), pp. 1147–1158. Available at: https://doi.org/10.1016/j.apenergy.2018.06.145.
[42] Maghrabie, H.M. *et al.* (2023) ‘Performance enhancement of PV panels

using phase change material (PCM): An experimental implementation', *Case Studies in Thermal Engineering*, 42(January), p. 102741. Available at: https://doi.org/10.1016/j.csite.2023.102741.

[43] Malvi, C.S., Dixon-Hardy, D.W. and Crook, R. (2011) 'Energy balance model of combined photovoltaic solar-thermal system incorporating phase change material', *Solar Energy*, 85(7), pp. 1440–1446. Available at: https://doi.org/10.1016/j.solener.2011.03.027.

[44] Mavromatakis, F. *et al.* (2010) 'Modeling the photovoltaic potential of a site', *Renewable Energy*, 35(7), pp. 1387–1390. Available at: https://doi.org/10.1016/j.renene.2009.11.010.

[45] Menon, G.S. *et al.* (2022) 'Experimental investigations on unglazed photovoltaic-thermal (PVT) system using water and nanofluid cooling medium', *Renewable Energy*, 188, pp. 986–996. Available at: https://doi.org/10.1016/j.renene.2022.02.080.

[46] Ni, S. (2021) 'Implementation of phase change materials for thermal regulation of photovoltaic thermal systems : Comprehensive analysis of design approaches a cevi', 228. Available at: https://doi.org/10.1016/j.energy.2021.120546.

[47] Notton, G. *et al.* (2005) 'Modelling of a double-glass photovoltaic module using finite differences', *Applied Thermal Engineering*, 25(17–18), pp. 2854–2877. Available at: https://doi.org/10.1016/j.applthermaleng.2005.02.008.

[48] Pang, W. *et al.* (2020) 'Cross sectional geometries effect on the energy efficiency of a photovoltaic thermal module: Numerical simulation and experimental validation', *Energy*, 209, p. 118439. Available at: https://doi.org/10.1016/j.energy.2020.118439.

[49] Prasetyo, S.D. *et al.* (2023) 'Optimization of Photovoltaic Thermal Collectors Using Fins: A Review of Strategies for Enhanced Solar Energy Harvesting', *Mathematical Modelling of Engineering Problems*, 10(4), pp. 1235–1248. Available at: https://doi.org/10.18280/mmep.100416.

[50] Preet, S., Bhushan, B. and Mahajan, T. (2017a) 'Experimental investigation of water based photovoltaic/thermal (PV/T) system with and without phase change material (PCM)', *Solar Energy*, 155, pp. 1104–1120. Available at: https://doi.org/10.1016/j.solener.2017.07.040.

[51] Preet, S., Bhushan, B. and Mahajan, T. (2017b) 'Experimental investigation of water based photovoltaic/thermal (PV/T) system with and without phase change material (PCM)', *Solar Energy*, 155, pp. 1104–1120. Available at: https://doi.org/10.1016/j.solener.2017.07.040.

[52] Rajamony, R.K. *et al.* (2024) 'Progress in research and technological developments of phase change materials integrated photovoltaic thermal systems: The allied problems and their mitigation strategies', *Sustainable Materials and Technologies*, 40(5), p. e00921. Available at: https://doi.org/10.1016/j.susmat.2024.e00921.

[53] Rosli, M.A.M. *et al.* (2022) 'Performance Optimization of a Simulation Study on Phase Change Material for Photovoltaic Thermal', *CFD Letters*, 14(9), pp. 32–51. Available at: https://doi.org/10.37934/cfdl.14.9.3251.

[54] Sánchez Barroso, J.C. *et al.* (2016) 'A computational analysis of coupled thermal and electrical behavior of PV panels', *Solar Energy Materials and Solar Cells*, 148, pp. 73–86. Available at: https://doi.org/10.1016/j.solmat.2015.09.004.

[55] Savvakis, N. and Tsoutsos, T. (2021) 'Theoretical design and experimental evaluation of a PV+PCM system in the mediterranean climate', *Energy*, 220, p. 119690. Available at: https://doi.org/10.1016/j.energy.2020.119690.

[56] Schiro, F. *et al.* (2017) 'Improving photovoltaics efficiency by water

cooling: Modelling and experimental approach', *Energy*, 137, pp. 798–810. Available at: https://doi.org/10.1016/j.energy.2017.04.164.

[57] Sharma, D.K., Rathod, M.K. and Bhale, P. V. (2023) *Numerical Study on Operating Temperature of PV and PV-PCM Systems*, *Lecture Notes in Mechanical Engineering*. Springer Nature Singapore. Available at: https://doi.org/10.1007/978-981-19-7214-0_19.

[58] Sheik, M.A. *et al.* (2022) 'A comprehensive review on recent advancements in cooling of solar photovoltaic systems using phase change materials', *International Journal of Low-Carbon Technologies*, 17(May 2022), pp. 768–783. Available at: https://doi.org/10.1093/ijlct/ctac053.

[59] Shojaeefard, M.H. *et al.* (2023) 'Experimental and Numerical Investigation of the Effect of Water Cooling on the Temperature Distribution of Photovoltaic Modules Using Copper Pipes', *Energies*, 16(10). Available at: https://doi.org/10.3390/en16104102.

[60] Simón-Allué, R. *et al.* (2022) 'Performance evaluation of PVT panel with phase change material: Experimental study in lab testing and field measurement', *Solar Energy*, 241(April), pp. 738–751. Available at: https://doi.org/10.1016/j.solener.2022.05.035.

[61] Singh, G.K. (2013) 'Solar power generation by PV (photovoltaic) technology: A review', *Energy*, 53, pp. 1–13. Available at: https://doi.org/10.1016/j.energy.2013.02.057.

[62] Singh, R., Sadeghi, S. and Shabani, B. (2019) 'Thermal conductivity enhancement of phase change materials for low-temperature thermal energy storage applications', *Energies*, 12(1). Available at: https://doi.org/10.3390/en12010075.

[63] Sopian*, K., Alwaeli, A.H.A. and Kazem, H.A. (2019) 'Novel Designs of Photovoltaic Thermal (PV/T) Systems', *International Journal of Recent Technology and Engineering (IJRTE)*, 8(4), pp. 6223–6229. Available at: https://doi.org/10.35940/ijrte.d5144.118419.

[64] Sun, X. *et al.* (2022) 'Optimized design of a distributed photovoltaic system in a building with phase change materials', *Applied Energy*, 306(PA), p. 118010. Available at: https://doi.org/10.1016/j.apenergy.2021.118010.

[65] Syahirah, N. *et al.* (2022) 'Sustainable Development Perspectives of Solar Energy Technologies with Focus on Solar Photovoltaic—A Review', *Energies*, pp. 1–15.

[66] Tao, M., Zhenpeng, L. and Jiaxin, Z. (2019) 'Photovoltaic panel integrated with phase change materials (PV-PCM): technology overview and materials selection', *Renewable and Sustainable Energy Reviews*, 116(September), p. 109406. Available at: https://doi.org/10.1016/j.rser.2019.109406.

[67] Torres-Ramírez, M. *et al.* (2014) 'Study on analytical modelling approaches to the performance of thin film PV modules in sunny inland climates', *Energy*, 73, pp. 731–740. Available at: https://doi.org/10.1016/j.energy.2014.06.077.

[68] Tyagi, V. V. *et al.* (2013) 'Progress in solar PV technology: Research and achievement', *Renewable and Sustainable Energy Reviews*, 20, pp. 443–461. Available at: https://doi.org/10.1016/j.rser.2012.09.028.

[69] Usama Siddiqui, M. *et al.* (2012) 'Three-dimensional thermal modeling of a photovoltaic module under varying conditions', *Solar Energy*, 86(9), pp. 2620–2631. Available at: https://doi.org/10.1016/j.solener.2012.05.034.

[70] Venkateswari, R. and Sreejith, S. (2019) 'Factors influencing the efficiency of photovoltaic system', *Renewable and Sustainable Energy Reviews*, 101(December 2017), pp. 376–394. Available at: https://doi.org/10.1016/j.rser.2018.11.012.

[71] Vikas and A. Yadav, S.K.S. (2017) 'Simulation of Melting Process of a

Phase Change Material (PCM) using', *International Research Journal of Engineering and Technology*, 4(5). Available at: c:%5CUsers%5Cdell%5CDocuments%5CCitavi 6%5CProjects%5CPhD_ Akumulacja ciepła%5CCitavi Attachments%5CSimulation of Melting Process of a Phase Change Material (PCM) using.pdf.

[72] Wei, G. *et al.* (2018) 'Selection principles and thermophysical properties of high temperature phase change materials for thermal energy storage: A review', *Renewable and Sustainable Energy Reviews*, 81(May 2017), pp. 1771–1786. Available at: https://doi.org/10.1016/j.rser.2017.05.271.

[73] Xu, H. *et al.* (2021) 'Energy conversion performance of a PV/T-PCM system under different thermal regulation strategies', *Energy Conversion and Management*, 229. Available at: https://doi.org/10.1016/j.enconman.2020.113660.