iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 11 **Issue:** X **Month of publication:** October 2023

DOI: https://doi.org/10.22214/ijraset.2023.55965

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 11 Issue X Oct 2023- Available at www.ijraset.com

Optimization of PCM Properties for Thermal Energy Storage in Solar Parabolic Trough Systems: A Review

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Abstract: Solar Parabolic Trough Systems (PTS) are highly efficient solar thermal technologies for converting concentrated solar radiation into thermal energy. However, their intermittent energy production, primarily due to variations in solar availability, underscores the necessity for effective thermal energy storage (TES) solutions. Phase Change Materials (PCMs) have emerged as a promising means to store and release thermal energy efficiently. This study focuses on the critical task of optimizing PCM properties to enhance thermal energy storage within Solar Parabolic Trough Systems.

The selection and fine-tuning of PCM properties are paramount to achieving superior TES performance. Parameters under scrutiny include the melting temperature, latent heat of fusion, thermal conductivity, and cost-effectiveness. Each of these factors plays a pivotal role in the overall efficiency and economic viability of PCM-based TES systems integrated with PTS.

Through a thorough review of existing research and recent advancements in the field, this study sheds light on the profound impact of tailored PCM properties. It demonstrates how optimizing these properties can lead to substantial improvements in energy storage capacity, system efficiency, and overall cost-effectiveness. Such optimizations are crucial not only for enhancing the competitiveness of solar thermal technology but also for promoting sustainable energy utilization.

The investigation presented herein underscores the significance of PCM property optimization as a strategic pathway toward advancing solar thermal technology. By maximizing energy storage capacity, minimizing thermal losses, and optimizing cost factors, we can unlock the full potential of PTS, making them more reliable and accessible for meeting the world's growing energy demands. This research serves as a valuable resource for engineers, researchers, and stakeholders working towards the integration of PCM-based TES with solar thermal systems. Ultimately, it contributes to the realization of a cleaner, more sustainable energy future, addressing the urgent need to reduce greenhouse gas emissions and our reliance on non-renewable energy sources.

Keywords: Solar Parabolic Trough Systems, thermal energy storage, Phase Change Material (PCM), melting temperature, latent heat of fusion, thermal conductivity.

I. INTRODUCTION

The global demand for energy continues to rise, driven by population growth, industrialization, and increasing living standards. In this context, sustainable and renewable energy sources are becoming crucial to mitigate the environmental impacts of conventional fossil fuel-based energy systems. Solar energy, abundant and clean, stands out as a viable solution to meet a significant portion of this growing energy demand. Solar thermal energy, in particular, offers an effective means to harness the sun's power and convert it into usable thermal energy.

One of the key challenges in utilizing solar thermal energy is its intermittent nature due to the variability in solar irradiance. To address this issue and enhance the efficiency and effectiveness of solar thermal systems, integrating solar collectors with thermal energy storage systems is essential. Phase Change Material (PCM) based thermal energy storage is a promising technology that allows the efficient storage and retrieval of thermal energy, providing a continuous and reliable source of heat even during periods of low solar radiation.

This paper explores the integration of a solar parabolic trough collector with a Phase Change Material (PCM) based thermal energy storage system. The parabolic trough collector is a well-established solar thermal technology known for its high efficiency in concentrating solar radiation and converting it into thermal energy. On the other hand, PCM technology offers an efficient means of storing and utilizing thermal energy through phase transitions.

The integration of a PCM-based thermal energy storage system with a solar parabolic trough collector aims to maximize the utilization of solar energy by capturing excess thermal energy during peak solar hours and storing it in PCM. This stored energy can then be utilized during non-solar hours or cloudy periods, ensuring a consistent and reliable energy supply. Additionally, this integration improves the overall efficiency of the solar thermal system and contributes to the reduction of greenhouse gas emissions and reliance on non-renewable energy sources.

In this paper, we present an in-depth analysis of the integration, focusing on the principles, benefits, challenges, and potential applications of combining a solar parabolic trough collector with a PCM-based thermal energy storage system. We also discuss the current state of the technology, recent advancements, and future prospects, emphasizing the importance of this integration in promoting sustainable and efficient solar thermal energy utilization.

A. Solar Thermal Collectors

solar thermal collectors are devices that use the sun's energy to generate heat, typically for the purpose of heating water or air for residential, commercial, or industrial applications. They are a type of solar energy technology that converts sunlight into thermal energy.

There are several types of solar thermal collectors, each with its own design and specific applications. Here are some common types:

1) Flat-Plate Collectors

a) These are the most common type of solar thermal collector and are often used for residential and commercial water heating.
b) Consist of a flat, insulated metal plate with a dark-colored absorber coating to absorb solar radiation.
c) Heat is transferred to a fluid (usually air or water) flowing through tubes or channels in the collector.

2) Evacuated Tube Collectors

a) These collectors are more efficient in capturing solar energy compared to flat-plate collectors.
b) Consist of rows of parallel transparent glass tubes with an absorber tube inside each.
c) The vacuum between the tubes reduces heat loss, making them highly efficient for heating applications.

3) Parabolic Trough Collectors

a) Typically used in large-scale solar power plants to generate electricity.
b) Use parabolic-shaped mirrors to focus sunlight onto a receiver pipe running along the focal line.
c) The receiver pipe contains a heat transfer fluid (often oil) that is heated and used to produce steam to drive a turbine and generate electricity.

4) Fresnel Reflectors

a) Similar to parabolic troughs, but use a series of flat, narrow mirrors (Fresnel lenses) to concentrate sunlight onto a linear receiver.
b) Often used in concentrated solar power (CSP) systems to generate electricity.

5) Concentrated Solar Power (CSP) Systems

a) Utilize mirrors or lenses to concentrate a large area of sunlight onto a small area to generate high temperatures.
b) Common in utility-scale power plants where the concentrated heat is used to generate steam and drive turbines for electricity production.

B. Classification of Solar Thermal Collectors

Solar thermal collectors can be classified based on various criteria, including their design, the way they capture and utilize solar energy, and their specific applications. Here's a classification based on design and application:

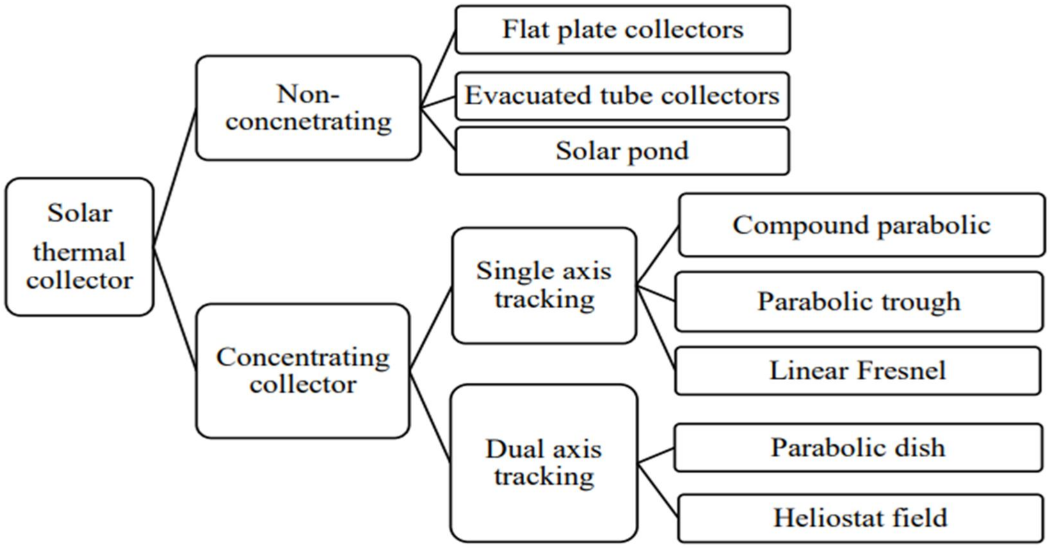

Figure 1: Classification of solar thermal collectors

1) *Based on Design*
a) Flat-Plate Collectors: - Flat-plate collectors are the most common type and consist of a flat absorber plate with a transparent cover and insulation. - The absorber plate absorbs solar energy and transfers it to a fluid (air, water, or another heat transfer fluid) for heating purposes.
b) Evacuated Tube Collectors: - Evacuated tube collectors use rows of transparent glass tubes with an absorber tube inside each. - The vacuum between the tubes reduces heat loss and enhances thermal efficiency. - They are more efficient in capturing solar energy compared to flat-plate collectors.
c) Parabolic Trough Collectors: - Parabolic trough collectors use parabolic-shaped mirrors to focus sunlight onto a receiver tube placed at the focal line of the parabola. - The receiver tube contains a heat transfer fluid (often oil) that is heated by concentrated sunlight. - Commonly used in large-scale solar power plants to generate electricity.
d) Fresnel Reflectors: - Fresnel reflectors use a series of flat, narrow mirrors (Fresnel lenses) to concentrate sunlight onto a linear receiver. - They are often used in concentrated solar power (CSP) systems for electricity generation.

2) *Based on Application*
a) Domestic Water Heating: - Solar collectors designed to provide hot water for residential or small-scale commercial purposes. - Usually flat-plate or evacuated tube collectors are used.
b) Space Heating: - Solar collectors used to provide heat for space heating in buildings. - Flat-plate collectors are commonly used for this purpose.
c) Industrial Process Heat: - Solar thermal systems designed to provide high-temperature heat for industrial processes. - Often use concentrating collectors like parabolic troughs or Fresnel reflectors.
d) Solar Cooling: - Solar collectors used in combination with absorption chillers to provide solar-powered air conditioning or refrigeration. - Absorption chillers are typically powered by high-temperature heat from solar collectors.
e) Electricity Generation (Concentrated Solar Power - CSP): - Solar collectors designed to generate electricity by concentrating sunlight to produce high temperatures and drive turbines. - Parabolic troughs, Fresnel reflectors, and other concentrating collectors are used.

C. *Solar Thermal Energy Storage*
Solar thermal energy storage is a pivotal component allowing capture of solar heat for later use. Sensible heat storage, employing materials like molten salts or rocks, retains heat without a phase change. Latent heat storage uses materials that change phase (solid to liquid or vice versa) while maintaining a constant temperature, such as phase change materials like paraffin wax.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 11 Issue X Oct 2023- Available at www.ijraset.com

Thermochemical storage employs reversible chemical reactions to store and release solar energy. Molten salt storage, a form of sensible heat storage, utilizes melted salt mixtures to store substantial thermal energy for use in concentrated solar power systems. These storage methods bolster solar thermal systems, ensuring a continuous and reliable energy supply.

1) Sensible Heat Storage

Sensible heat storage is a key approach in solar thermal energy storage, crucial for enhancing the reliability and availability of solar energy. This method involves storing thermal energy by changing the temperature of a material, such as a solid or liquid, without changing its phase. Common materials used for sensible heat storage include water, rocks, concrete, and various types of salts.

$$E_s = mc_p dT$$

In a solar thermal system utilizing sensible heat storage, the collected solar energy is used to heat a storage medium, such as water or a heat transfer fluid. This medium absorbs and stores the thermal energy as sensible heat. During periods when sunlight is not available or insufficient, the stored thermal energy is utilized to generate steam or hot air, which can then be used to produce electricity, provide space heating, or power industrial processes.

The efficiency and effectiveness of sensible heat storage systems depend on the specific heat capacity and thermal conductivity of the storage medium. High-density materials with good thermal conductivity are preferred for efficient storage and retrieval of thermal energy.

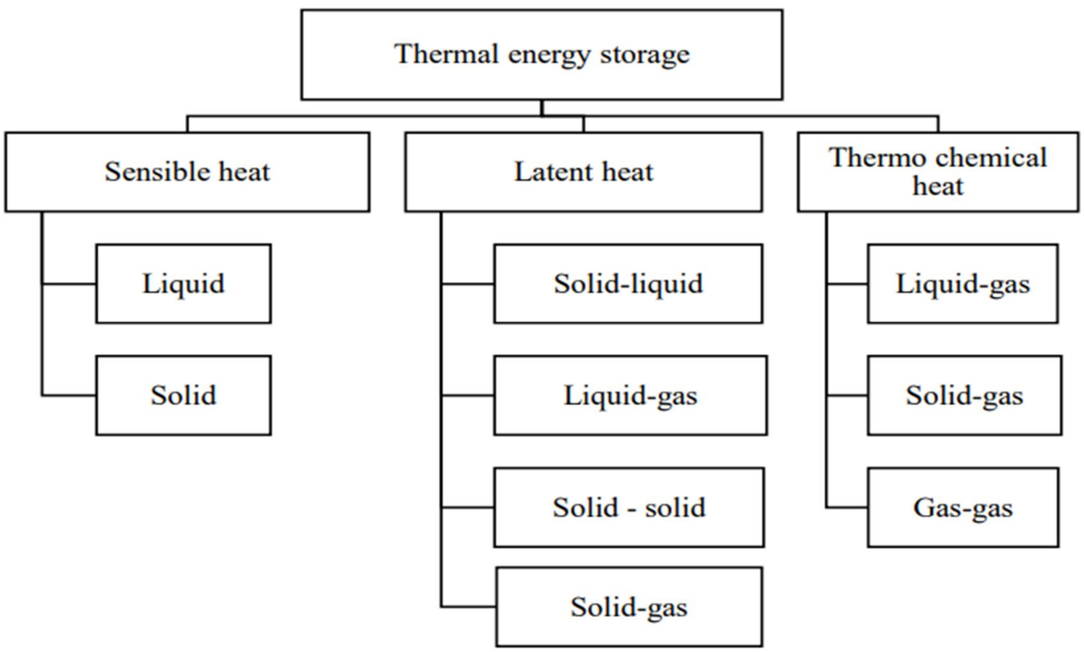

Figure 2: Classification of thermal storage

Sensible heat storage plays a critical role in concentrated solar power (CSP) plants, allowing for continuous electricity generation even when the sun is not shining. It helps to smooth out the fluctuations in solar energy availability, providing a more consistent and reliable source of power. As advancements in materials and technology continue, sensible heat storage systems are becoming more efficient and cost-effective, contributing to the growth and integration of solar thermal energy in our energy landscape.

2) Latent Heat Storage

Latent heat storage is a significant method in solar thermal energy storage, offering an efficient way to capture and store thermal energy for later use. Unlike sensible heat storage that involves changing the temperature of a material, latent heat storage involves changing a material's phase (solid to liquid or vice versa) while maintaining a constant temperature. Phase change materials (PCMs) are commonly used for this purpose.

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During the charging phase when solar energy is available, the PCM absorbs the heat and undergoes a phase change, typically from solid to liquid. This process stores a significant amount of thermal energy in the PCM. During the discharging phase when heat is needed, the PCM solidifies, releasing the stored latent heat. This released heat can be used for various applications such as space heating, hot water production, or to generate electricity.

PCMs offer advantages like high energy storage density and the ability to store and release energy at a nearly constant temperature, making them highly efficient for solar thermal applications. Latent heat storage contributes to the effective utilization of solar energy and improves the reliability and stability of solar thermal systems. An LTES system's thermal energy storage, E_s, is given by,

$$E_s = m\left(c_{ps} \times (t_m - t_s) + mL + c_{pl}\left(t_f - t_m\right)\right)$$

Where c_{ps} and c_{pl} are the phase change material's specific heat at solid and liquid states respectively, L is the latent heat of fusion and t_m, t_s and t_f are the melting state, solid state and final state temperature respectively.

3) Thermochemical energy storage

Thermochemical energy storage is an innovative approach to storing and utilizing solar energy by employing reversible chemical reactions. In this method, energy is stored and released through chemical transformations rather than changes in temperature or phase. When surplus solar energy is available, it's used to drive a chemical reaction, converting reactants into a higher-energy state. Later, when energy is needed, the stored chemicals are allowed to react in the reverse direction, releasing the stored energy in the form of heat.

The advantage of thermochemical storage lies in its potential for high energy density and efficient, long-term energy storage. The choice of reactants and chemical reactions is crucial, aiming for reactions that are both energetically favourable and reversible. Commonly used materials in thermochemical storage systems include metal oxides, metal halides, and redox pairs.

Thermochemical energy storage has great potential for large-scale solar thermal power plants, providing continuous and reliable energy even when sunlight is unavailable.

It addresses the intermittent nature of solar energy, contributing to a more stable and consistent energy supply, making it a promising avenue for advancing solar power technologies.

D. Phase Change Materials processes

Phase Change Materials (PCMs) undergo a phase transition (solid to liquid or vice versa) while maintaining a nearly constant temperature during the transition. This unique characteristic makes them valuable for thermal energy storage and management. Here are the processes involved in utilizing Phase Change Materials (PCMs) in various applications:

1) *Selection of PCM:* Choose an appropriate PCM based on the specific application, considering factors such as desired transition temperature, energy storage capacity, thermal conductivity, cost, and safety.
2) *Encapsulation or Integration:* PCM can be encapsulated in various ways, such as microencapsulation, macroencapsulation, or using porous structures to prevent leakage and facilitate handling.
3) *Charging (Melting) Process:* During the charging process, the PCM absorbs thermal energy from its surroundings (e.g., solar energy or waste heat), transitioning from a solid to a liquid state while storing this energy.
4) *Discharging (Solidification) Process:* In the discharging process, the stored thermal energy is released as the PCM transitions from a liquid to a solid state, providing heat to its surroundings.
5) *Application-Specific Processes:* Depending on the application, PCMs can be integrated into various systems, such as:
a) *Building Materials:* Incorporate PCMs into building structures (walls, ceilings) to regulate indoor temperature by absorbing excess heat during the day and releasing it at night.
b) *Solar Thermal Systems:* Use PCMs to store excess solar heat, providing a continuous heat source during cloudy periods or at night.
c) *Thermal Energy Storage Systems:* Employ PCMs in storage tanks or containers to store and release thermal energy efficiently for industrial or residential heating or cooling.
6) *Thermal Cycling:* PCMs should be designed to withstand repeated thermal cycling (melting and solidifying) without degradation or significant loss in their energy storage capacity.
7) *Efficiency Optimization:* Optimize the design of PCM systems to enhance energy storage and retrieval efficiency, considering factors like container design, insulation, and PCM compatibility.

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E. Phase Change Materials

Phase Change Materials (PCMs) are substances that can absorb or release a significant amount of thermal energy when they change from one phase (usually solid) to another phase (usually liquid) and vice versa. This phase transition occurs at a specific and well-defined temperature known as the phase change temperature or transition temperature.

Here are some key points about Phase Change Materials:

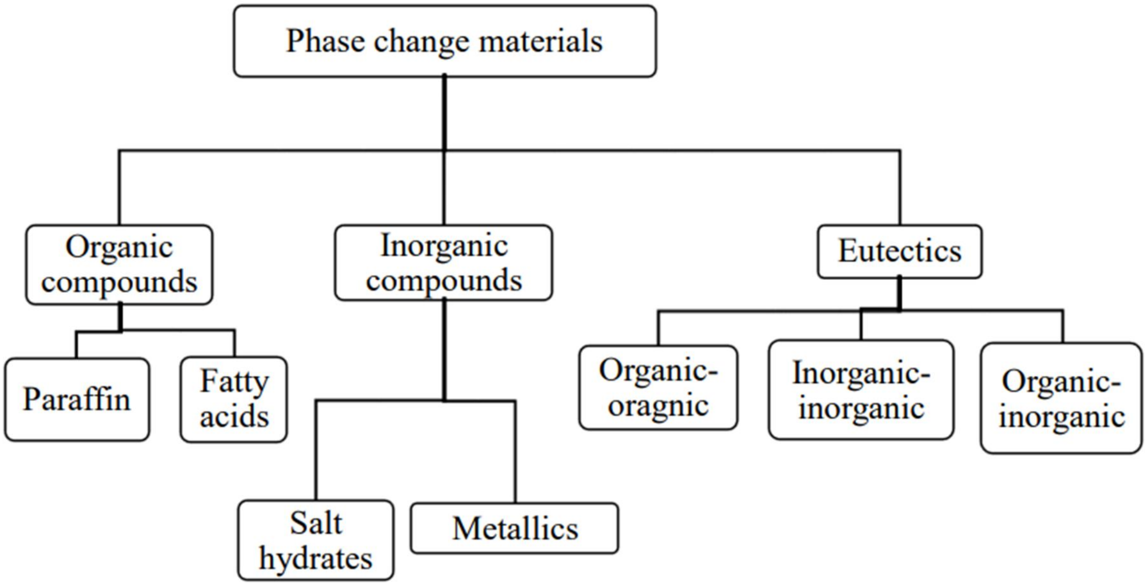

Figure 3: Classification of phase change materials

1) *Types of Phase Change*
   a) Melting: The PCM absorbs heat and changes from a solid to a liquid state (endothermic process).
   b) Solidification: The PCM releases heat and changes from a liquid to a solid state (exothermic process).
2) *Applications:*
   a) Thermal Energy Storage: PCMs are used for storing and releasing thermal energy in various applications such as building cooling and heating systems, solar thermal energy storage, and waste heat recovery.
   b) Temperature Regulation: PCMs can help in temperature regulation by absorbing excess heat when the environment is too warm and releasing stored heat when the environment is too cold.
   c) Cold Chain Management: PCMs play a crucial role in the transportation and storage of temperature-sensitive goods, like pharmaceuticals and food, maintaining their required temperature during transit.
3) *Selection Criteria:*
   a) Phase Transition Temperature: Choose a PCM with a phase change temperature matching the desired operating temperature of the application.
   b) Heat of Fusion: Consider the amount of energy absorbed or released during the phase change, known as the heat of fusion, to determine the energy storage capacity.
   c) Thermal Conductivity**:** Higher thermal conductivity facilitates faster heat transfer during the phase change.
4) *Types of PCMs:*
   a) Organic PCMs: Derived from hydrocarbons, such as paraffin wax.
   b) Inorganic PCMs: Include salt hydrates (e.g., sodium sulfate decahydrate) and metals and their alloys (e.g., gallium).
   c) Eutectic Mixtures: Combining different PCMs to create a mixture with a sharp and well-defined phase change temperature.
5) *Encapsulation and Packaging:*

PCMs can be encapsulated to prevent leakage and improve handling. Microencapsulation and macroencapsulation are common techniques.

6) *Advantages:*

a) Efficient thermal energy storage and release.
b) Enable temperature regulation and control.
c) Enhance energy efficiency and sustainability in various applications.

II. REVIEWS

Idowu David Ibrahim at el.(2022). This study presents the development of a novel smart parabolic trough solar collector system tailored for efficient water heating. The collector employs advanced tracking mechanisms and reflective coatings to optimize solar energy absorption. Additionally, a hybrid polymeric composite water storage tank is introduced to enhance heat retention and minimize energy loss. The integration of these innovative components aims to significantly improve the overall performance and sustainability of solar water heating systems. The research explores the design, fabrication, and testing of this integrated solution, offering a promising avenue for sustainable and effective renewable energy utilization in water heating applications.

W.G.J.H.M. van Sark at el.(2022). This study investigates the optical performance of quantum dot luminescent solar concentrator (LSC) structures through single, double, and triple configurations using ray tracing simulations. Quantum dots, efficient light emitters, are strategically placed within the LSC to enhance photon absorption and conversion. Through meticulous analysis of photon transport within these structures, we quantify the light absorption, concentration efficiency, and photon escape probability. By varying quantum dot concentrations and layering arrangements, we discern optimal configurations for heightened light harvesting and conversion. The insights garnered in this research contribute to advancing the design and efficiency of luminescent solar concentrators for sustainable energy applications.

Wissam H. Alawee at el.(2022). This study conducted at Kafrelsheikh University, Faculty of Engineering, Department of Mechanical Engineering, focuses on experimentally enhancing the performance of a tubular solar still using multiple innovative approaches. A rotating cylinder, nanoparticles' coating, parabolic solar concentrator, and phase change material are integrated into the system to optimize solar energy absorption and utilization. The experimental investigation assesses the impact of these enhancements on water evaporation, condensation, and overall productivity. Through rigorous testing and analysis, this research provides valuable insights into combining various technologies to improve the efficiency and output of tubular solar stills, offering potential for sustainable water production in arid regions.

Venkata Ramayya Ancha at el.(2022). This study presents a predictive analysis of the transient performance of a solar dish concentrator system integrated with a Stirling engine and Thermoelectric Generator (TEG) for small-scale irrigation. The coupling of solar concentration technology with Stirling and TEG technologies aims to enhance the overall efficiency and power generation capacity for sustainable irrigation. Detailed modeling and simulation are employed to forecast the system's behaviour under varying solar conditions and operational parameters. The results offer valuable insights into the potential of this integrated system to provide reliable and efficient power generation for powering small-scale irrigation systems using solar energy.

Anjum Munir at el.(2022). This study conducts a comparative thermal analysis of solar milk pasteurizers, integrating solar concentrators and evacuated tubes to optimize the pasteurization process. Solar concentrators enhance the solar energy input, while evacuated tubes improve heat absorption. Through rigorous modeling and simulations, we evaluate the thermal performance, energy efficiency, and pasteurization capabilities of these integrated systems. The results provide valuable insights into the effectiveness of each configuration in achieving desired milk pasteurization temperatures and energy utilization. This research aims to guide the design and selection of solar-based pasteurization systems for sustainable milk processing with improved efficiency and reduced environmental impact.

Daniel Aragão Ribeiro de Souza at el.(2022). This study presents a predictive analysis of the transient performance of a solar dish concentrator system integrated with a Stirling engine and Thermoelectric Generator (TEG) for small-scale irrigation. The coupling of solar concentration technology with Stirling and TEG technologies aims to enhance the overall efficiency and power generation capacity for sustainable irrigation. Detailed modeling and simulation are employed to forecast the system's behavior under varying solar conditions and operational parameters. The results offer valuable insights into the potential of this integrated system to provide reliable and efficient power generation for powering small-scale irrigation systems using solar energy.

Milad Rastkar Mirzaei at el.(2022). This study conducts a comparative thermal analysis of solar milk pasteurizers, integrating solar concentrators and evacuated tubes to optimize the pasteurization process. Solar concentrators enhance the solar energy input, while evacuated tubes improve heat absorption. Through rigorous modeling and simulations, we evaluate the thermal performance, energy efficiency, and pasteurization capabilities of these integrated systems. The results provide valuable insights into the effectiveness of each configuration in achieving desired milk pasteurization temperatures and energy utilization.

This research aims to guide the design and selection of solar-based pasteurization systems for sustainable milk processing with improved efficiency and reduced environmental impact.

Irraivan Elamvazuth at el.(2022). This research delves into advancing renewable energy prospects for a sustainable future, focusing on efficient luminescent solar concentrators (LSCs) to harness solar power. LSCs efficiently capture and concentrate sunlight through luminescent materials, optimizing electricity production. Investigating the latest developments and innovations in LSC technology, this study explores their potential to revolutionize solar energy harvesting. By analyzing performance metrics, light absorption, and conversion efficiency, we present insights into the viability and promise of LSCs in driving a green energy revolution. The research contributes to promoting cleaner, more sustainable energy solutions and accelerating the transition towards a greener future.

III. RESEARCH GAPE

Optimizing Phase Change Materials (PCMs) properties for thermal energy storage in solar parabolic trough systems is a crucial research area aimed at enhancing the efficiency and effectiveness of Concentrated Solar Power (CSP) technology.

Several research gaps and potential areas for further investigation in this domain can be identified:

1) *Enhanced Heat Transfer Rates:* Investigate methods to enhance heat transfer rates during the charging and discharging processes to and from the PCMs. Enhancements in thermal conductivity and convective heat transfer can lead to faster and more efficient energy storage and retrieval.
2) *Tailored Phase Transition Temperatures:* Explore techniques to tailor the phase transition temperatures of PCMs to match the optimal operating temperatures of solar parabolic trough systems. This alignment can improve overall system efficiency and energy utilization.
3) *Long-Term Stability and Durability:* Research the long-term stability and durability of PCMs under cyclic thermal loading and unloading conditions. Understanding any potential degradation or phase change hysteresis over multiple cycles is critical for reliable and sustained performance.

IV. CONCLUSION

In conclusion, this review has provided a comprehensive overview of the optimization of phase change material (PCM) properties for thermal energy storage in solar parabolic trough systems. The investigation has underscored the significance of PCM-based thermal energy storage in advancing the efficiency and sustainability of concentrated solar power (CSP) technologies. Several key findings and insights emerge from the synthesis of literature and research in this field.

First and foremost, the selection of an appropriate PCM material is crucial for achieving optimal performance in solar parabolic trough systems. The choice of PCM should consider factors such as melting point, latent heat of fusion, thermal conductivity, and stability under cyclic charging and discharging conditions. The ongoing research efforts in developing new PCMs with tailored properties are promising, as they offer the potential to overcome existing limitations and enhance system performance.

Furthermore, the review highlights the importance of numerical modeling and simulation techniques in predicting and optimizing the behaviour of PCM-based thermal energy storage systems.

Numerical tools enable the design and analysis of various system configurations, aiding in the selection of the most suitable PCM and storage tank geometry to meet specific operational requirements. Additionally, the integration of PCMs in solar parabolic trough systems not only enhances energy storage capacity but also contributes to load levelling and improved dispatchability. This capability addresses one of the major challenges of CSP technologies, enabling consistent and reliable power generation.

In terms of future directions, further research is warranted to explore advanced materials and novel techniques for enhancing the thermal properties of PCMs. Additionally, a focus on real-world applications and field testing will be essential to validate the theoretical advancements discussed in this review.

In summary, the optimization of PCM properties for thermal energy storage in solar parabolic trough systems holds great promise in advancing the deployment and sustainability of CSP technologies. The ongoing efforts in materials research, coupled with advanced modeling and experimental validation, are expected to drive innovation in this field, ultimately contributing to a more efficient and environmentally friendly energy landscape.

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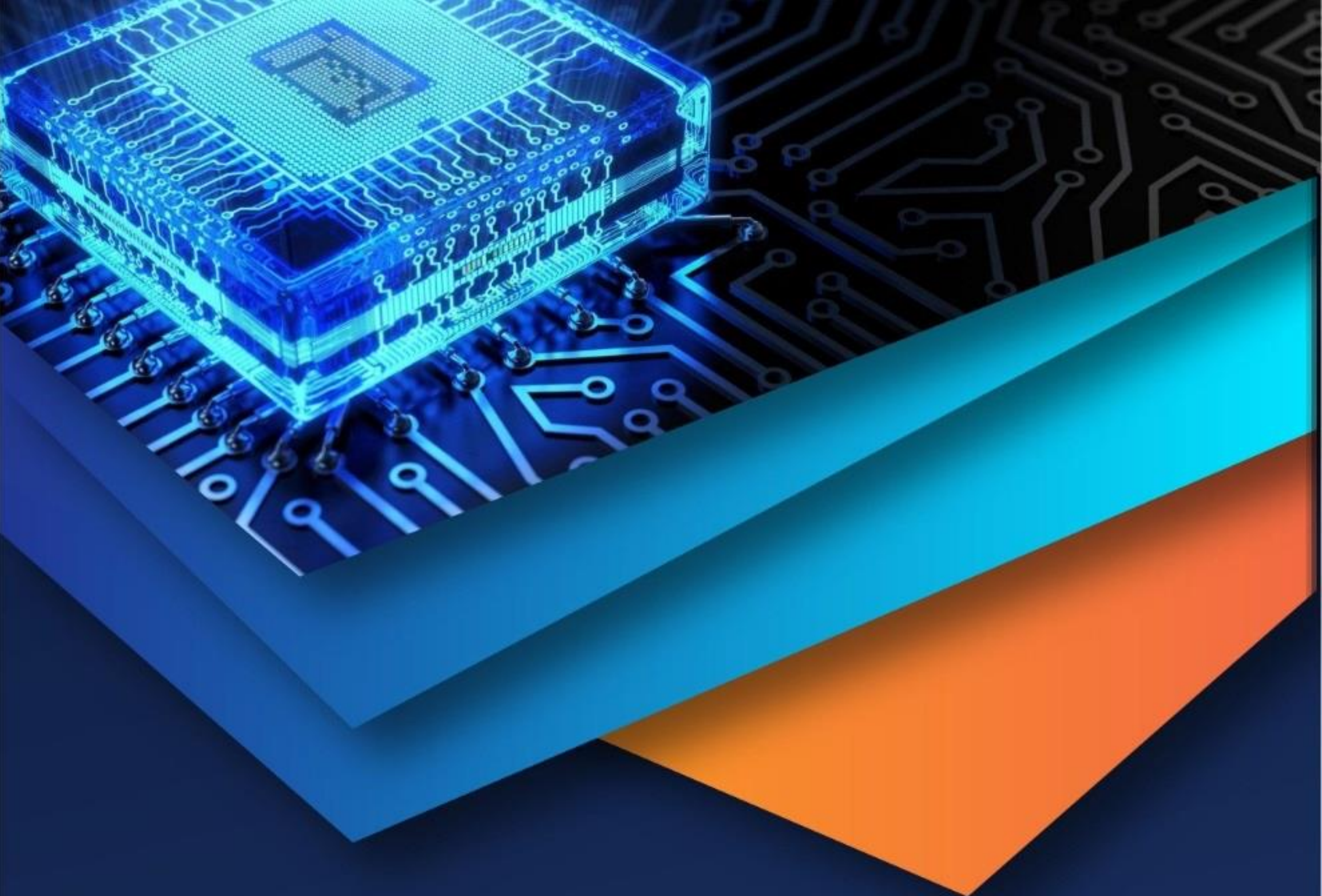

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