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Utilizing Multiple PCM Reservoirs for Electrical Power Generation in a Concentrated Solar Power Facility

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ABSTRACT

Global warming represents an imminent and pervasive threat to our planet. One abundant and sustainable energy source available to counteract this crisis is solar energy. However, harnessing and efficiently converting this energy into usable forms, such as thermal or electrical power, poses a formidable challenge for scientists and engineers alike. Solar power plants, which convert the sun's radiance into electricity, are hampered by their reliance on daylight hours. Yet, by developing the means to store solar energy, it can extend its availability well into the night, mitigating the time-dependent limitations inherent to solar thermal power plants. The solution to this dilemma lies in the realm of Thermal Energy Storage (TES) technology, which capitalizes on phase change materials (PCMs). PCMs are adept at storing and releasing energy. Initially, they exist in a solid state, absorbing and accumulating heat energy. When required, they transition to a liquid state, releasing stored heat. During nighttime or periods of reduced solar radiation, they revert to their solid state, making them exceptionally suitable for energy storage applications. This study leverages the concentrated solar power (CSP) technology known for its superior efficiency. The core innovation involves the integration of PCM materials, specifically three-phase alternating material reservoirs with distinct melting points arranged in series. A meticulous thermodynamic analysis was conducted to determine the optimal mass flow rate of the heat transfer fluid originating from the lower-temperature PCM reservoir. It is imperative to note that all processes in this endeavour adhere to the ideals of thermodynamic efficiency. This research marks a crucial step toward the widespread adoption of sustainable energy solutions, aiming to combat global warming while ensuring a reliable energy supply.

1. Introduction

Energy acquisition predominantly falls within two distinct categories: renewable and non-renewable energy sources. The conventional utilization of energy resources like natural gas, coal, and petroleum has been associated with significant environmental repercussions.

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Conversely, unconventional energy sources, such as wind, solar, and small-scale hydropower, offer multifaceted advantages, including environmental sustainability. Solar energy, in particular, boasts a rich historical legacy dating back to the 7th century BC. Over millennia, various investigations and innovations have expanded our understanding of harnessing the sun's boundless potential. Notably, in recent decades, there has been a substantial surge of interest in generating electricity from solar energy [1]. Solar power plants represent an eco-conscious technology, often referred to as “green technology”, owing to their minimal environmental impact. In contemporary times, solar energy has experienced resurgence in interest and innovation. The shift towards generating electricity from solar energy, often referred to as photovoltaic or solar PV technology, represents a monumental leap in our utilization of this ancient resource. Solar PV panels, composed of semiconductor materials, convert sunlight directly into electricity through the photovoltaic effect. This technology has gained widespread adoption, particularly in distributed energy generation, residential installations, and off-grid applications.

Solar thermal power plants, on the other hand, employ a distinct approach to harness solar energy. Instead of converting sunlight directly into electricity, they focus on capturing the sun's heat to generate electricity indirectly [2]. This process involves the use of CSP technology, which is characterized by its ability to concentrate sunlight to produce high-temperature heat. Solar energy is harnessed through two primary methods: photovoltaic and solar thermal power plants. This article focuses on the latter, employing solar thermal power plants in conjunction with phase change materials (PCMs) to facilitate electricity generation. Such innovative applications hold the potential to revolutionize the energy landscape. In regions like India, with burgeoning economies, the energy sector assumes paramount significance. Here, solar energy has emerged as a paramount contender among various renewable energy sources. Its appeal is underscored by its remarkable efficiency, satisfaction quotient, and immediate utility compared to alternative options. The advent of CSP plants has propelled solar energy to the forefront of large-scale electricity generation, particularly for grid systems exceeding 100 megawatts (MW). CSP plants leverage their extensive thermal energy storage capacity to provide continuous power supply, making them an attractive choice for addressing energy demands.

This paper delves into the novel concept of employing multiple phase change material reservoirs arranged in series to generate 1 MW of electricity [3]. The study operates under the assumption of ideal processes and incorporates a mathematical analysis to ascertain the optimal mass flow rate for the heat transfer fluid within the charging and discharging circuits. By exploring these innovative approaches, we aim to contribute to the evolving landscape of sustainable energy solutions, further emphasizing the pivotal role of solar energy and its unique integration with PCM technology in achieving uninterrupted and environmentally responsible power production. The processes involved in this approach are conceptualized as ideal, with the aim of showcasing the theoretical potential of the technology. To ensure the practical viability and efficiency of the system, a rigorous mathematical analysis is conducted to determine the optimal mass flow rate of the heat transfer fluid within the charging and discharging circuits. This critical analysis informs the design and operation of the system, maximizing its energy output and overall performance.

2. Solar Energy in India and the Significance of Concentrated Solar Power (CSP) Plants

In rapidly developing economies like India, the energy sector plays a pivotal role in sustaining economic growth and ensuring a reliable power supply. Among the various renewable energy sources, solar energy has garnered significant attention and investment due to its inherent advantages. These include its high efficiency, immediate utility and direct utilization, which distinguishes it from other renewable sources [4]. CSP plants have emerged as a particularly attractive choice for large-scale electricity generation in India. These plants are favored for their ability to provide substantial thermal energy storage capacity, enabling them to deliver a continuous supply of electricity. CSP plants are well-suited for addressing the energy demands of large electric grid systems, especially those exceeding 100 megawatts (MW) in capacity. Some of the significant benefits pointed out by the authors can be noted as follows.

i. CSP plants use sunlight to generate electricity, making them a clean and renewable energy source. They do not produce greenhouse gas emissions or air pollutants during electricity generation, contributing to efforts to combat climate change and reduce environmental pollution.
ii. CSP with energy storage can provide grid stability by offering grid operators a controllable and predictable source of electricity. This can help balance supply and demand, reduce the need for backup power sources, and enhance the resilience of the electrical grid.
iii. CSP technology is scalable and can be adapted to meet various energy needs, from small-scale distributed systems to large utility-scale power plants. This flexibility allows for the deployment of CSP in a wide range of geographic locations and applications.
iv. Unlike some other forms of thermal power generation, CSP plants can be designed to use dry cooling systems, reducing water consumption and minimizing environmental impacts, particularly in arid regions.
v. CSP plants can incorporate thermal energy storage systems that enable the generation of electricity even when the sun is not shining, such as during cloudy days or at night. This makes them dispatchable and capable of providing reliable power to the grid, addressing one of the key challenges of intermittent renewable sources like solar photovoltaic and wind.

Hence, CSP plants play a significant role in the transition to a cleaner, more sustainable energy future. They offer a reliable and dispatchable source of renewable energy, contribute to environmental conservation, stimulate economic growth, and help address energy challenges, making them a vital component of the global energy mix.

3. The Innovative Approach: Multiple Phase Change Material Reservoirs for Electricity Generation

This paper introduces an innovative approach to harness solar energy and leverage phase change materials (PCMs) for electricity generation [5]. Specifically, the study explores the concept of employing multiple PCM reservoirs with distinct phase change temperatures arranged in series. The ultimate goal is to generate 1 MW of electricity using this groundbreaking methodology. The processes involved in this approach are conceptualized as ideal, to showcase the theoretical potential of the technology. To ensure the practical viability and efficiency of the system, a rigorous mathematical analysis is conducted to determine the optimal mass flow rate of the heat transfer fluid within the charging and discharging circuits [6]. This critical analysis informs the design and operation of the system, maximizing its energy output and overall performance. This paper introduces an innovative approach to harness solar energy and leverage phase change materials (PCMs) for electricity generation. Specifically, the study explores the concept of employing multiple PCM reservoirs with distinct phase change temperatures arranged in series. The ultimate goal is to generate 1 MW of electricity using this groundbreaking methodology. The processes involved in this approach are conceptualized as ideal, with the aim of showcasing the theoretical potential of the technology. To ensure the practical viability and efficiency of the system, a rigorous mathematical analysis is conducted to determine the optimal mass flow rate of the heat transfer fluid within the charging and discharging circuits [7]. This critical analysis informs the design and operation of the system, maximizing its energy output and overall performance.

4. The Role of Phase Change Materials (PCMs) in Solar Thermal Power Plants

Phase change materials (PCMs) play a crucial role in enhancing the efficiency and performance of solar thermal power plants. These materials are used to store and manage thermal energy in various stages of the energy conversion process, making solar thermal power plants more reliable and capable of supplying electricity even when the sun is not shining [8,9]. Thermal energy storage (TES) technology plays a pivotal role in enhancing the viability of solar thermal power plants. The challenge lies in efficiently storing the captured heat energy for use during periods of reduced solar radiation or at night. This is where phase change materials (PCMs) come into play. Phase change materials are substances that exhibit a unique property: they can change their physical state from solid to liquid (and vice versa) while absorbing or releasing a significant amount of latent heat in the process. During the daytime, when the sun is abundant, solar thermal power plants can use solar collectors to heat and melt the PCM, storing the absorbed thermal energy in the form of latent heat [10]. When electricity generation is required at night or during cloudy periods, the PCM releases the stored heat as it solidifies, thus enabling continuous power production. Here's how PCMs are used in solar thermal power plants.

i. Energy Storage: One of the main challenges of solar power generation is intermittent sunlight. PCMs address this issue by storing excess thermal energy generated during sunny periods for use when the sun is not shining. During the day, when sunlight is abundant, solar collectors (such as parabolic troughs or solar towers) collect and focus sunlight to heat a heat transfer fluid (usually a synthetic oil or molten salt). The hot fluid is then used to melt a PCM, storing the thermal energy as latent heat. This energy can be released later when needed.

vi. Thermal Energy Transport: PCMs can also be used as a medium for transferring and transporting thermal energy within the power plant. The phase change process allows PCMs to absorb and release heat at a relatively constant temperature, making them efficient heat transfer agents. This helps in maintaining a stable and uniform temperature profile within the system.

vii. Heat Dispatch: When electricity demand is high or during nighttime, the stored thermal energy in the PCM can be released to generate steam or directly heat a working fluid, such as water, which is used to drive a turbine and produce electricity. This enables the power plant to operate continuously, providing a stable source of electricity even during periods of low or no sunlight.

viii. Improved Efficiency: PCMs can significantly improve the overall efficiency of a solar thermal power plant. They allow for the capture and storage of excess heat, reducing energy wastage during peak solar input and enabling the power plant to operate at higher capacity factors. This translates into more electricity generation and a more cost-effective energy production process.

ix. Reduced Environmental Impact: By increasing the overall efficiency and capacity factor of solar thermal power plants, PCMs can help reduce the environmental impact of energy production. They make solar power more reliable and less dependent on backup fossil fuel systems, ultimately decreasing greenhouse gas emissions and reliance on non-renewable energy sources.

x. Diverse Applications: PCMs can be customized to suit the specific needs of different solar thermal technologies, such as concentrating solar power (CSP) and solar water heating systems. This versatility allows for the optimization of energy storage and heat transfer in various parts of the plant.

In summary, phase change materials are a critical component of solar thermal power plants, enhancing their energy storage capabilities, improving efficiency, and enabling continuous electricity generation [11]. They are a key technology that helps make solar power a more viable and reliable source of renewable energy.

5. Basic Working Principles

Figure 1 illustrates the classification system of different solar thermal power generation methods. In this process, sunlight is first reflected off a mirror onto a receiver, where it is concentrated and transformed into thermal energy [12]. Subsequently, a generator is employed to convert this thermal energy into electricity. The CSP can be classified into the following four systems, a) Parabolic Trough System b) Power Tower System c) Linear Fresnel System d) Parabolic Dish System.

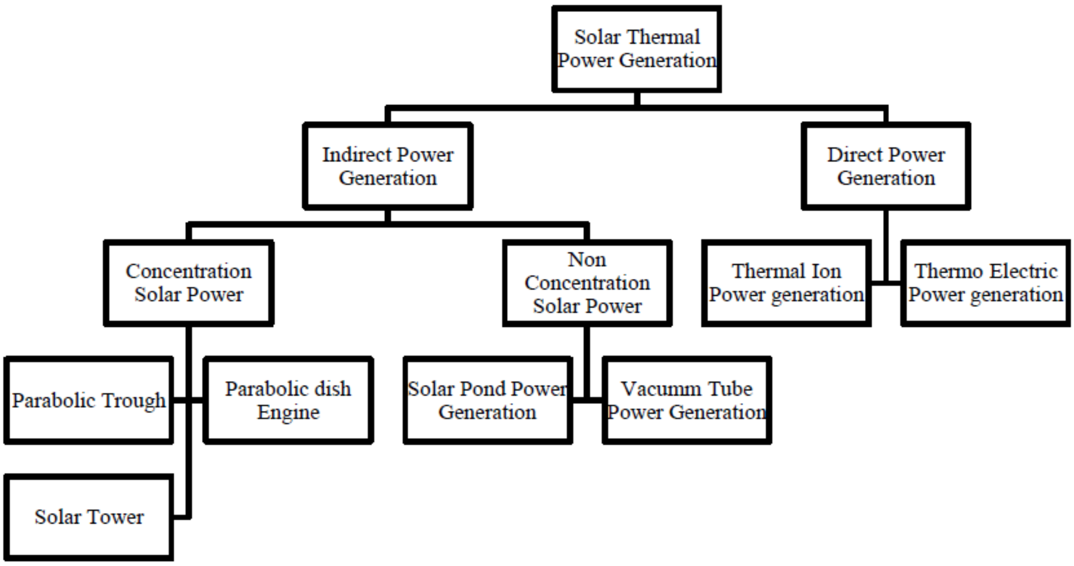

Fig. 1. Classification of solar thermal power generation
(Source: Banerjee et al. [2])

5.1. Parabolic Trough System

At the pinnacle of the reflector, there is a heat collecting element (HCE) responsible for gathering solar radiation. This HCE is positioned along the focal line, where it absorbs the reflected sunlight from extensive rows of parabolic reflectors [13]. To ensure optimal tracking of the sun along its north-south axis, the system adjusts its orientation accordingly. The HCE consists of an internal steel tube enveloped by a solar-absorbing surface, enclosed within an outer glass tube with a vacuum in between. Additionally, a heat transfer fluid (HTF) flows through the inner steel pipe. A heat exchanger is employed to generate steam, utilizing the high-temperature fluid from multiple rows of troughs [1,2]. Figure 2 illustrates the parabolic trough system.

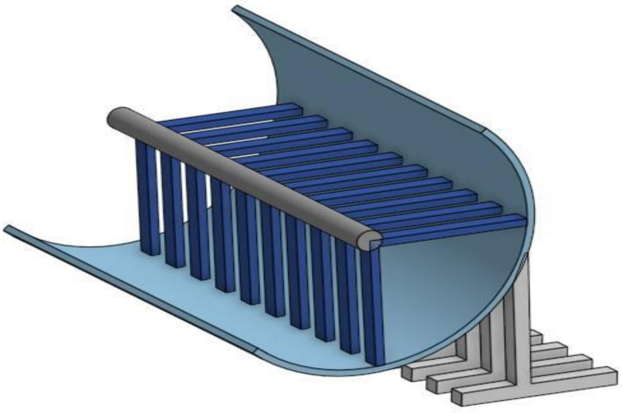

Fig. 2. Schematic diagram of parabolic trough system
(Source: Banerjee et al. [2]; Barlev et al. [24])

5.2. Power Tower System

Central receiver collectors, featuring a focal point receiver, achieve significantly higher temperatures when contrasted with troughs and linear Fresnel reflectors. They can attain temperatures ranging from 800°C to well over 1000°C by concentrating sunlight at a factor of 600 to 1000 times [14]. Solar tower technology employs an array of mirrors, with each mirror tracking the sun and redirecting its rays onto a stationary receiver located at the pinnacle of a tower. Central receivers have historically been employed to generate the high temperatures required for driving steam and gas turbines. Figure 3 provides an illustration of the power tower system.

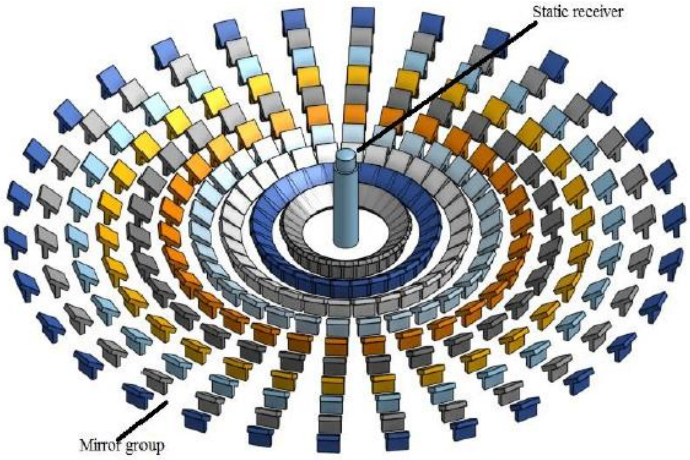

Fig. 3. Schematic diagram of power tower system
(Source: Banerjee et al. [2]; Barlev et al. [24])

5.3. Linear Fresnel System

Linear Fresnel reflectors employed in CSP technology operate in a manner akin to the parabolic trough collector system. These systems employ extensive rows of flat mirrors outfitted with linear Fresnel reflectors to concentrate sunlight onto a linear receiver [15,16]. Typically positioned on a tower and measuring between 10 to 15 meters in height, the receiver collects the focused sunlight. The mirrors can be mounted on one or two-axis tracking systems. One key advantage over the parabolic trough collector is the ability to use multiple Fresnel reflectors while having the receiver as a separate component, eliminating the need for a tracking system. This design simplifies tracking, enhancing its precision and efficiency [17]. The heat transfer fluid (HTF) flows through the receiver, capturing thermal energy, which is then conveyed to the power block. Figure 4 provides a visual representation of the linear Fresnel system.

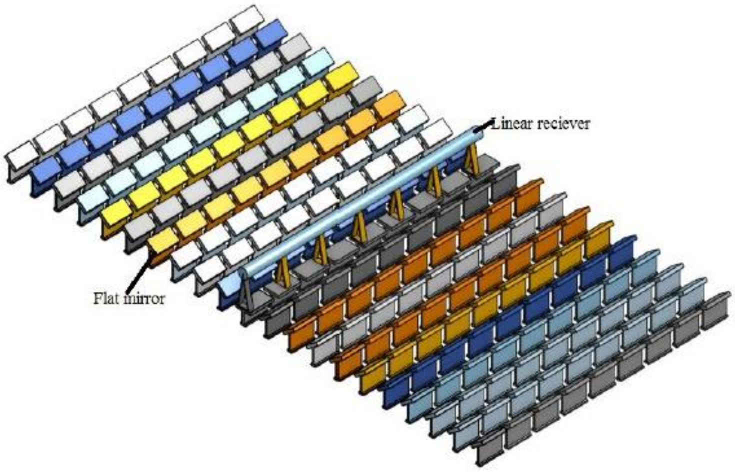

Fig. 4. Schematic diagram of linear Fresnel system
(Source: Barlev et al. [24])

5.4. Parabolic Dish System

The mirror system is well-suited for applications demanding elevated temperatures, owing to its excellent optical reflecting properties. Dish systems are designed in a parabolic shape, with the receiver stationed at the focal point while moving in tandem with the dish. Among all CSP variations, mirror systems boast the highest optical efficiency, as they directly align the full aperture with the sun, thus minimizing the cosine loss effect [18]. For further details regarding operating temperatures, tracking methods, and typical power block sizes of various concentrating solar thermal power technologies, please refer to Table 1. Figure 5 provides an illustration of the parabolic dish system.

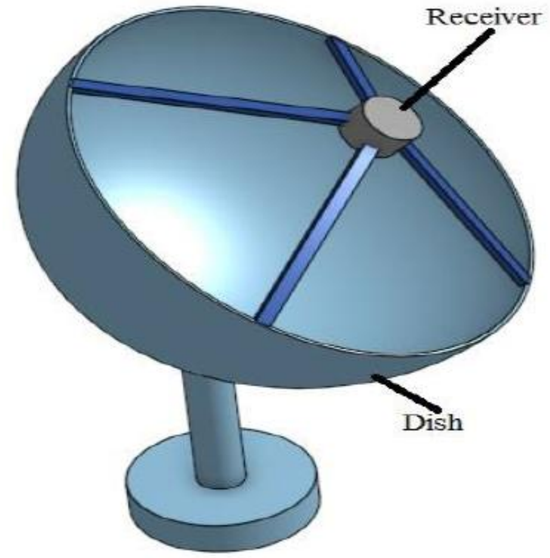

Fig. 5. Schematic diagram of parabolic dish system
(Source: Barlev et al. [24])

Table 1
Operating temperature, tracking, and average power block size for each type of concentrating solar thermal power technologies

Technology	Operating Temperature solar concentration (°C)	Tracking	Average power block size
Parabolic Trough System	145 - 410	Linear	144 (kW)
Power Tower System	305 - 1210	Point	63 kW)
Linear Fresnel System	149 - 305	Linear	25 (kW)
Parabolic Dish System	310 - 1552	Point	1 (kW)

(Source: Banerjee et al. [2]; Boretti et al. [6])

6. Phase Change Material

Phase change materials (PCMs) present an efficient means of energy storage. Initially in a solid state, they absorb thermal energy and transition into a liquid state. During the night time or when needed, PCMs release heat as they freeze and return to a solid state [19]. Figure 6 illustrates the temperature changes over time in different types of PCMs. PCM, as a heat storage medium, offers an advantageous solution, particularly through latent heat systems, primarily due to two key benefits: high energy storage capacity and low temperature differentials. Figure 7 depicts the various phase transitions of PCMs in current technology. In recent years, there has been growing interest in thermal energy storage devices utilizing metallic PCMs, despite their challenges stemming from high density and low specific heat, which are less than ideal characteristics. Mehmood et al. [20] have noted an increasing use of high-temperature phase change materials. Elfeky et al. [21] conducted research on graphite-based PCMs, which are employed in heat sinks and have demonstrated effectiveness in solar PV systems, representing an enhanced heat storage technique. Furthermore, Ma et al. [22] conducted a comparative study involving two different roofing systems and PCMs, collecting data in the United States. Figure 6 visually illustrates the variations of PCMs at different temperature zones and Table 2 represents all the specifications of the PCMs used in this article. The authors offer insights for future advancements in this technology. Elfeky et al. [23] provided descriptions of various encapsulated PCMs known for their improved corrosion resistance and performance-enhancing qualities. Figure 8 presents a schematic layout of a typical solar thermal power plant (STPP).

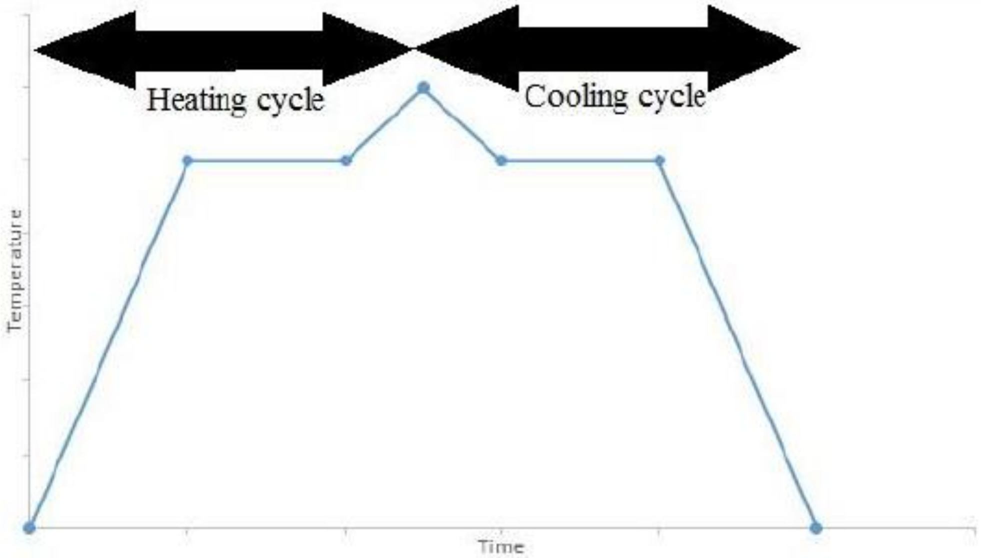

Fig. 6. Schematic heat curve for Phase change material
(Source: Banerjee et al. [2])

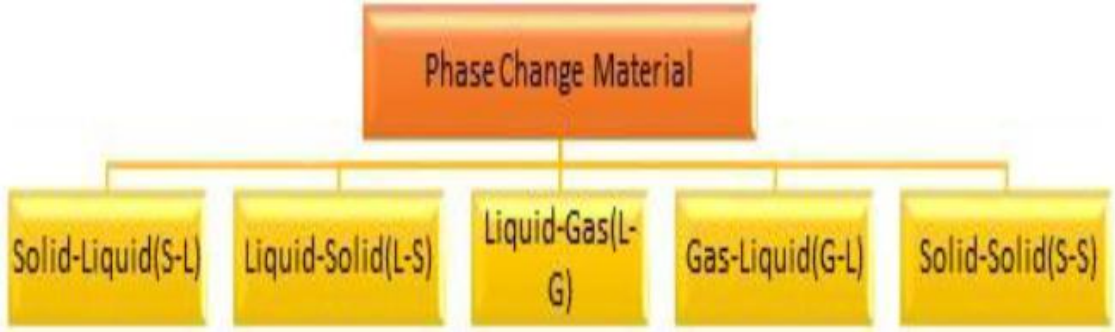

Fig. 7. Classifications of PCMs
(Source: Banerjee et al. [2])

Table 2
Specifications of the PCMs

PCMs	Melting Temperature (°C)	Latent heat of melting (kJ/kg)	Specific heat (kJ/kg K)
Sodium Chloride + Nickel Chloride	571	550	1.67
Magnesium Chloride + Strontium Chloride	532	242	1
Magnesium + Copper + Zinc	455	350	1.2

(Source: Kenisarin [17])

7. Design & Methodology

Concentrated sunlight is directed towards the solar receiver, where the heat transfer fluid (HTF) absorbs thermal energy before descending. During daylight hours, the high-temperature HTF follows two distinct paths with mass flow rates $m1$ and $m2$, respectively. $m1$ flows directly into the heat exchanger, where it comes into contact with cold water [24]. This interaction causes the water temperature to rise gradually, eventually reaching a superheated steam state. This superheated steam is then directed into the turbine, where it drives the generation of electricity using a standard Rankine cycle. Simultaneously, another mass flow rate $m2$ enters the high-temperature phase change material (PCM) reservoir before transitioning to the low-temperature PCM reservoir. During this process, the low-temperature PCM receives heat from the high-temperature HTF, causing it to melt. This melting phase continues until evening hours for both PCM reservoirs. During nighttime, the low-temperature HTF, which returns from the heat exchanger, flows with a mass flow rate $m3$. At this point, the low-temperature HTF first enters the low-temperature PCM reservoir and subsequently the high-temperature PCM reservoir. In this sequence, the high-temperature PCM releases its stored heat, warming the low-temperature HTF. As a result, the temperature of the HTF gradually rises. Finally, the outgoing HTF from the high-temperature PCM reservoir is directed back to the heat exchanger, where it is used to produce electricity in a manner similar to the daytime process.

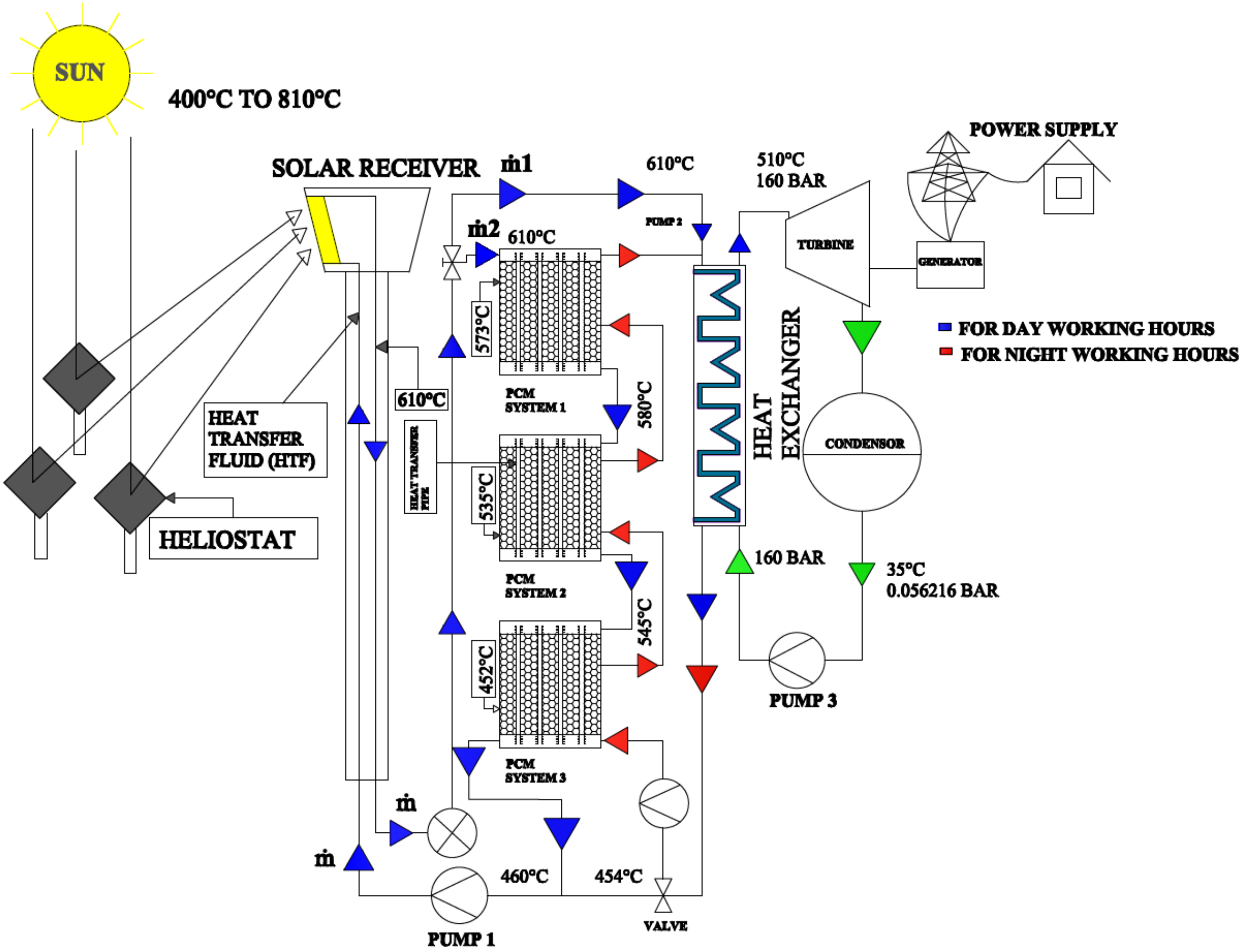

Fig. 8. A schematic representation of a typical layout of a solar thermal power plant (STPP)
(Source: Banerjee et al. [2])

This work is based on 1MW electrical output. The height temperature of steam used in Rankine Cycle is 515^{0}C. At that temperature, Enthalpy (h_1) = 3326.7 kJ/kg [The value of h1 is taken from Steam table]. And corresponding value of Entropy (S_1) = 6.3515 kJ/kg.

$$S_1 = S_{2,}\ S_2 = Sf_3 + X^*Sf_g \tag{1}$$

$$X = \frac{S_2 - Sf_3}{Sf_g} = \frac{6.3515 - 0.5049}{7.8494} = \frac{5.8466}{7.8494} = 74.48\%$$

$$h_2 = hf_3 + X^*\ hf_g \tag{2}$$

$$h_2 = 146.65 + 0.7448\ (2418.8) = 1948.17 \text{kJ/kg}$$

Turbine work, $W_T = h_1 - h_2 = 3326.7 - 1948.17 = 1378.53$ kJ/kg

Again, Pump work,
$W_p = V_3 * (P_4 – P_3)$ (V_3 at 35^{0}Cis 0.001 m^3/kg) [Data taken from steam table]

$W_p = 0.001(16000000 – 56216)$

W_p = 15943.784 J/kg [Pressure at 35^0C is 0.056216 bar = 56216 Pa]
≈ 16 kJ/kg

h_3 = 146.65 kJ/kg, h_4 = h_3 + W_P = 146.65 + 16 = 162.65kJ/kg

For 1 MW electrical produced, $\dot{m} = \frac{10^6}{W_T - W_P} = \frac{10^3 \text{kJ/s}}{1378.63-16}$ = 0.7339 kg/s is the water mass flow rate.

$Q_1 = h_1 - h_2$ = 3326.7 – 162.65 = 3164.05 kJ/kg

Total heat added in boiler = 0.728 * 3164.05 = 2303.43 kJ/s

$$Q1 = \dot{m}_1 *(610 - 460) * S \tag{3}$$

$2303.43 = \dot{m}_1 (610 - 460) * 1.89$

or, $\dot{m}_1$ = 8.72 kg/s, this is the mass flow rate of heat transfer fluid (HTF) in Path 1.

For 12 hrs, heat required to be added in the heat exchanger

$$Q_1 * 12 * 3600 \text{ kJ} = 2303.42 * 12 * 3600 = 99507744 \text{ kJ} \tag{4}$$

Total mass of phase change material (PCM) to be melted

$$PCM_1 * LH_1 + PCM_2 * LH_2 + PCM_3 * LH_3 = 99507744 \text{ kJ} \tag{5}$$

After that 3 equations are got,

$$12 * 3600 * \dot{m}_1 * S\ (610\text{-}580) = PCM_1 * LH_1 \tag{6}$$

$$12 * 3600 * \dot{m}_2 * S\ (580\text{-}545) = PCM_2 * LH_2 \tag{7}$$

$$12 * 3600 * \dot{m}_3 * S\ (545\text{-}460) = PCM_3 * LH_3 \tag{8}$$

Now, dividing equation (6) by equation (7), one gets, $\frac{PCM1*LH1}{PCM2*LH2} = \frac{610-580}{580-545} = \frac{PCM_1*558}{PCM_2* 239} = \frac{30}{35}$

$$35PCM_1 * 19530 = 30PCM_2 * 7170 \text{ or, } PCM_2 = 3.178PCM_1 \tag{9}$$

Again, dividing equation (7) by equation (8), one gets, $\frac{PCM2*LH2}{PCM3*LH3} = \frac{580-545}{545-460} = \frac{239\ PCM2}{354\ PCM3} = \frac{35}{85}$

$$20315PCM_2 = 12390\ PCM_3 \text{ or, } PCM_2 = 0.61PCM_3 \tag{10}$$

Putting the value of PCM_2 in equation (10), one may get, $PCM_3 = 5.2098PCM_1$ (11)

Putting the value of PCM_2& PCM_3 in equation (5), one gets,

$(PCM_1 * 558) + (3.178PCM_1 * 239) + (5.2098PCM_1 * 354) = 99507744$

3161.8112 PCM_1 = 99507744 or, PCM_1 = 31471.75 kg

Again, putting the value of PCM_1 and PCM_3 in equation (5), one may get,

(31471.75 * 558) + 239PCM_2 + (5.2098PCM_1 * 354) = 99507744

239 PCM_2+75603615.66=99507744 or, PCM_2 = 100017.27 kg

Again, putting the value of PCM_1 and PCM_2 in equation (5), one gets,

17558496.72 + (100017.27 * 239) + 354 PCM_3 = 99507744

354PCM_3 = 58045119.75 or, PCM_3 = 163969.26 kg

Now, calculated the rate of melting mass of phase change materials, PCM_1, PCM_2 and PCM_3, as under expressed in kg/s

$\dot{m}PCM_1 = \frac{31471.75}{12*3600} = 0.729$ kg/s

$\dot{m}PCM_2 = \frac{100017.27}{12*3600} = 2.32$ kg/s

$\dot{m}PCM_3 = \frac{163969.26}{12*3600} = 3.80$ kg/s

Now, found out mass flow rate ($\dot{m}_2$) in path 2 as under

$$\dot{m}_2 * S * (610 - 460) = \dot{m}PCM_1 * LH_1 + \dot{m}PCM_2 * LH_2 + \dot{m}PCM_3 * LH_3 \quad (12)$$

$\dot{m}_2$ * 1.89 * 150 = (0.729 * 558) + (2.32 * 239) + (3.80 * 354)

$\dot{m}_2$ = 8.136 kg/s

Total mass flow rate, $\dot{m} = \dot{m}_1 + \dot{m}_2$ = 8.70 + 8.136= 16.836 kg/s

So, Plant Efficiency ($\acute{\eta}$) = $\frac{(h_1-h_4)-(h_2-h_3)}{(h_1-h_4)} = \frac{(3226.7-162.65)-(1948.17-146.65)}{(3226.7-162.65)}$ = 42.75%

8. Results & Discussions

The power generation of the system is significantly influenced by the exit temperature of the heat transfer fluid (HTF). Figure 9 illustrates the relationship between heat supply and temperature, revealing that the net power output of a solar power plant equipped with three phase change material (PCM) reservoirs decreases as the HTF exit temperature raises. This graph highlights distinct power output levels corresponding to five different HTF exit temperatures, pinpointing the optimal HTF exit temperature for maximum efficiency. Additionally, Figure 10, along with its associated heat input data, illustrates the performance curve of the system, demonstrating that an increase in heat input leads to a corresponding rise in power output.

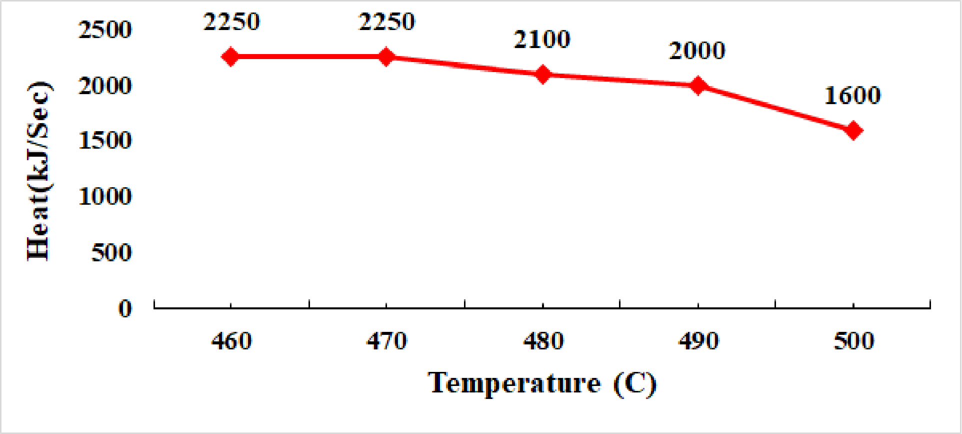

Fig. 9. Relationship between heat supply and temperature
(Source: Author's own elaboration)

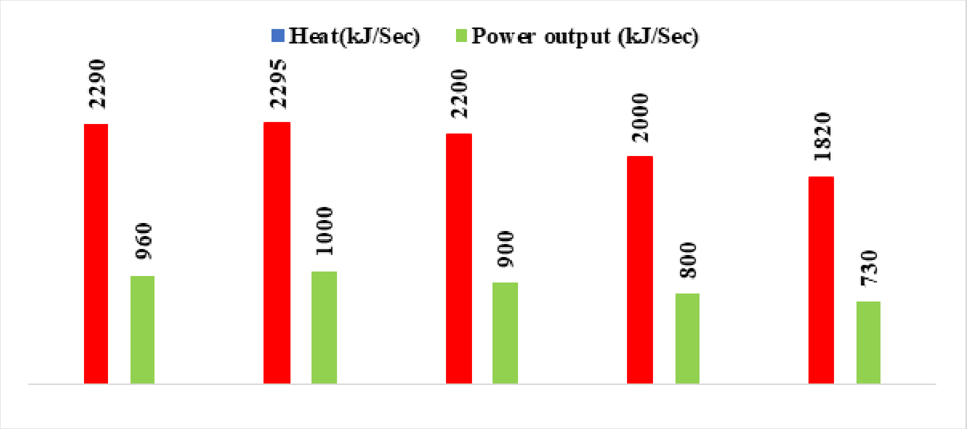

Fig. 10. Rise in power output with respect to the increase in heat input
(Source: Author's own elaboration)

9. Pioneering Sustainable Energy Solutions

In conclusion, the pursuit of sustainable and environmentally responsible energy solutions has become an imperative in our era. As we confront the pressing challenges posed by global warming and environmental degradation, the harnessing of renewable energy sources takes center stage. Solar energy, with its ancient origins and modern applications, stands as a testament to the enduring potential of nature's gifts. Solar thermal power plants, powered by CSP technology and bolstered by the incorporation of PCMs, exemplify the convergence of tradition and innovation [25]. These plants not only capture the sun's energy efficiently but also store it for use during periods of low sunlight, ensuring uninterrupted power production. In regions like India, the adoption of CSP plants with PCM reservoirs holds the promise of transforming the energy landscape. By providing continuous and reliable electricity supply on a large scale, these systems address the energy needs of growing economies while mitigating environmental harm. The pioneering research discussed in this paper, centered on the utilization of multiple PCM reservoirs in series for electricity generation, exemplifies our commitment to advancing sustainable energy solutions [26]. As we continue to explore and refine these groundbreaking technologies, we move closer to a future where clean, renewable energy powers our world, harmonizing human progress with the preservation of our planet.

10. Conclusion

The primary hurdle in solar thermal power plants lies in the intermittent nature of solar energy availability, which varies with time. In this study, a solution is implemented by incorporating three reservoirs containing distinct phase change materials with differing melting points, ensuring uninterrupted electricity production. These phase change materials are strategically selected and arranged based on their respective melting points, effectively mitigating system irreversibility stemming from significant temperature differentials between the working fluid and the phase change material. A thorough thermodynamic analysis is conducted to determine the optimal operational parameters and to assess the power generation's dependency on the working fluid's temperature.

10.1. Managerial Implications

Utilizing multiple PCM reservoirs for electrical power generation in a CSP facility can have several practical implications, both positive and potentially challenging. CSP with PCM storage is a promising technology for storing and dispatching solar energy, but it comes with its own set of considerations. Here are some practical implications to consider.

i. Enhanced Energy Storage: Multiple PCM reservoirs allow for greater energy storage capacity. This can extend the duration of electricity generation beyond daylight hours, making CSP facilities more reliable and dispatchable.
i. Improved Load Matching: With multiple PCMs, it becomes possible to optimize energy dispatch to match electricity demand more effectively. This can enhance grid stability and reduce the need for backup power sources.
ii. Higher Efficiency: Multiple reservoirs can be designed to operate at different temperature ranges, optimizing energy extraction and conversion efficiency. This can lead to higher overall system efficiency.
iii. Reduced Cycling Damage: By distributing energy storage across multiple PCMs, you can reduce the cycling stress on individual materials. This can extend the lifespan of the storage system and decrease maintenance costs.
iv. Enhanced Grid Integration: CSP facilities with multiple PCMs can provide various grid services, such as frequency regulation and grid support, due to their dispatchable nature. This can make the CSP plant more valuable to the grid operator.

10.2. Limitations

Multiple PCM reservoirs for electrical power generation in a CSP facility offer several advantages, but it also comes with certain limitations and challenges that need to be considered.

i. Cost: One of the primary limitations is the increased cost associated with the implementation of multiple PCM reservoirs. Each reservoir requires its own set of materials, heat exchangers, and control systems, adding to the capital and operational expenses of the CSP plant.
ii. Complexity: Managing multiple PCM reservoirs can significantly increase the complexity of the CSP system. This complexity includes the need for advanced control strategies, thermal management, and coordination between reservoirs. It may require more sophisticated monitoring and control systems.
iii. Maintenance and Repairs: Multiple PCM reservoirs mean more components that can potentially require maintenance and repairs. Ensuring that each reservoir operates efficiently and addressing malfunctions promptly can be challenging and resource-intensive.

iv. Environmental Considerations: PCM materials, if not managed properly, can pose environmental risks. Leakage or contamination of PCM materials could lead to environmental damage, requiring careful containment and disposal procedures.

v. Heat Transfer and Efficiency: Efficient heat transfer between different PCM reservoirs is essential for maintaining overall system efficiency. Poor heat transfer can lead to energy losses and reduced system performance.

While utilizing multiple PCM reservoirs in a CSP facility can enhance energy storage and grid integration, it introduces complexities, cost considerations, and technical challenges that must be carefully managed. A thorough feasibility study and engineering expertise are essential to address these limitations and maximize the benefits of this technology.

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Conflict of Interest

There is no conflict of interest to disclose.

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