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Implementation and Efficiency Enhancement of Solar Ponds Using High-Conductivity Nanoparticle-Enhanced Phase Change Materials

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ABSTRACT: This paper presents the implementation and performance evaluation of a solar pond enhanced with high-conductivity nanoparticle-enriched phase change materials (PCMs). The study focuses on the dual objectives of constructing a three-tier solar pond and investigating the influence of high-conductivity materials on the thermal characteristics of PCMs. By systematically varying the initial temperatures from 300 K to 340 K in increments of 20 degrees, the research aims to determine the optimal upper temperature limits for both PCM and non-PCM scenarios. Temperature measurements were taken by repositioning the tube to different locations within the pond.

The results demonstrate a significant improvement in thermal performance with the inclusion of nanoparticles. Specifically, at a constant temperature of 300 K, the addition of nanoparticles to PCM enhanced performance by 3.76% compared to PCM alone, with even greater improvements observed at higher initial temperatures. At 340 K, the performance enhancement reached 43.59%. Moreover, when the intake and outflow tubes were positioned on opposite sides of the solar pond, the combination of PCM and nanoparticles resulted in a performance improvement of 1.92% at 300 K and 29.25% at 340 K. The study concludes that incorporating nanoparticles into PCM and strategically positioning the tubes within the solar pond significantly optimizes heat transfer efficiency. These findings underscore the potential of nanoparticle-enhanced PCMs in improving the thermal efficiency of solar ponds, providing valuable insights for future renewable energy storage solutions.

KEYWORDS: Solar pond, phase change material (PCM), nanoparticles, thermal energy storage, heat transfer efficiency, renewable energy, high-conductivity materials, thermal performance.

I. INTRODUCTION

A solar pond is a large man-made saltwater reservoir designed to collect and store solar energy, providing a consistent source of heat and electricity. The practical exploration of solar ponds began in the late 1940s, although the concept traces back to the early 1900s with the discovery of a naturally occurring thermal lake in Transylvania, Eastern Europe. This pioneering work has led to increased global interest and investment in solar pond systems, particularly in the United States, India, and Israel, with notable developments in El Paso, Texas.

Despite the potential of solar ponds to offer sustainable energy solutions, several projects have been terminated due to high production and maintenance costs compared to traditional gas and fossil fuel facilities. Nevertheless, the appeal of solar ponds lies in their ability to provide renewable energy by harnessing solar radiation. During the day, solar radiation heats the water, causing it to rise to the surface. However, solar pond technology mitigates heat loss by utilizing salt, which becomes more concentrated with increasing depth, thereby inhibiting convection.

Solar ponds are classified into two main categories: convecting and non-convecting. Non-convecting solar ponds are particularly effective in reducing heat loss by inhibiting convection currents in the lower convective zone. This is achieved by maintaining a gradient of salt concentration, which prevents the less dense, warmer water from rising and mixing with the denser, cooler water below. The intermediate non-convective zone acts as an insulating layer, preserving the heat absorbed by the bottom layer.

Conversely, convective solar ponds reduce heat loss primarily by minimizing evaporation rather than relying on convection. These ponds feature a charred lower surface, foam insulation, and multiple layers of plastic or glass glazing to enhance heat retention. During the day, the sun's rays heat the water, which is then stored in tanks for nighttime use. Solar ponds have versatile applications, providing thermal energy for a wide range of industrial and agricultural processes. They can significantly reduce the reliance on fossil fuels and are suitable for generating heat and energy, desalinating water, and other uses. The thermal energy extracted from solar ponds can support chemical, culinary, and textile production, as well as heating livestock barns, greenhouses, and swimming pools. Moreover, the organic Rankine cycle engine, which converts thermal energy into electrical energy, offers a cost-effective and efficient method for utilizing solar energy in remote locations. Solar ponds also play a role in desalinating water for municipal systems and managing brine waste from offshore drilling.

The fundamental operation of a solar pond is based on the phenomenon of thermal stratification. Salt is introduced to create a thermal reservoir, with the concentration increasing with depth. This high-density saltwater remains at the bottom, preventing heat loss to the atmosphere. A solar pond typically consists of three distinct layers: the upper convective zone (UCZ) with low sodium content, the lower convective zone (LCZ) with high temperatures and salt concentration, and the non-convective zone (NCZ) where the salt gradient acts as both an insulator and solar absorber. While solar ponds can be constructed anywhere, they are particularly effective when located near the ocean.

This paper aims to address the shortcomings identified in existing research by implementing a solar pond with three tiers and examining the impact of high-conductivity materials on the heat-transfer characteristics of phase change materials (PCMs). By systematically varying the initial temperatures, the study seeks to optimize the efficiency of heat transfer and demonstrate the potential of nanoparticle-enhanced PCMs in improving the thermal performance of solar ponds[1].

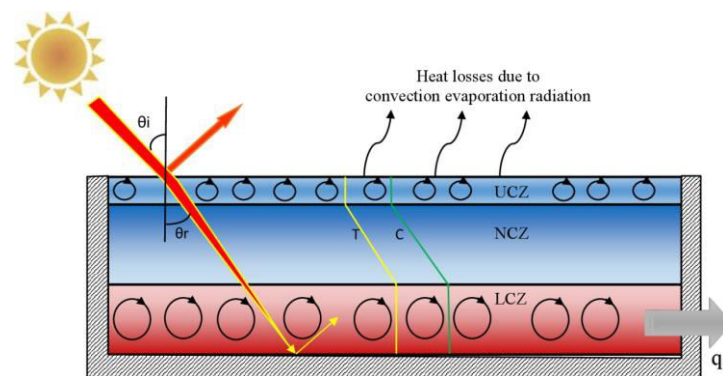


Fig. 1.1 Diagram of a solar pond showing the temperature and saline gradient

SGSP combines the process of collecting solar energy with enhanced storing capability. They are cost-effective and easy to manufacture. The thermal energy produced by these ponds may be used for many reasons, including as desalination, power generation, process heating, space heating, and other industrial and agricultural uses. A solar pond often displays a salinity gradient, which causes the pond to be divided into three separate zones. The uppermost layer is referred to as the upper convective zone or the surface zone (UCZ). The central portion contains the primary gradient zone (MGZ), often known as the non-convective zone (NCZ). The storage zone, also known as the lower convective zone (LCZ), is situated under.

The lowermost part of the region consists of a convecting or temperature-stratified homogeneous salt solution. The North Equatorial Zone (NCZ) is situated above it and functions as a thermal insulator as a result of a salinity gradient. As a result, the water at the top will continuously have a lower concentration than the water at a greater depth. An even and unvarying layer of brine with low salinity or fresh water forms a uniform coating on the surface. The existence of a notable disparity in salinity hinders the occurrence of convection in the gradient zone, regardless of the heat absorption in the lower zone. The phenomena is caused by the higher concentration of warm, highly saline water at lower depths, as opposed to the cooler, less salty water above it.

The optical and thermal properties of water create a scenario in which solar energy received in the lower zone can only be transferred by conduction. This phenomenon happens because water is transparent to visible light but blocks the transmission of infrared radiation. Water has a low thermal conductivity. However, once the gradient zone reaches a certain thickness, the transfer of heat from the lower zone to the higher zone happens very slowly. The use of water's high heat capacity, along with the large size of the solar pond, offers notable advantages for the effective collection and long-term storage of thermal energy. The primary cause of this phenomenon is mostly attributed to the insulative characteristics of the gradient zone.

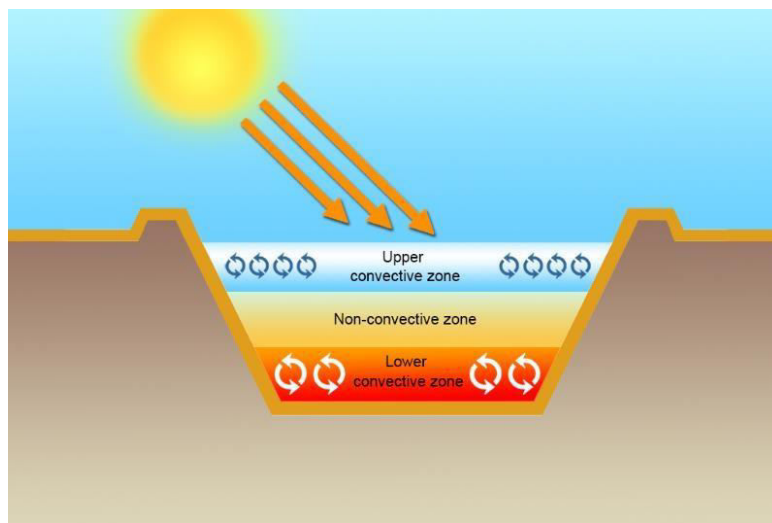


Fig. 1.2 Zones of the SGSP

II. RELATED WORK

Mansouri et al. (2018) Assessing the effectiveness of three energy extraction configurations: just the LCZ, the LCZ combined with the NCZ using a horizontal exchanger, and the LCZ coupled with the NCZ using a vertical exchanger. The final arrangement was deemed to be optimal since it maximizes both energy and work efficiency.

Ganguly et al. (2018) Developed an enhanced solar pond model by including more sun collectors to optimize the water heating effectiveness. Furthermore, they assessed the effectiveness of the bottommost layer of insulation in hindering the transfer of heat from the storage area to the ground. It was observed that increasing the thickness of the insulation below a particular threshold had no effect. The existing literature indicates that previous research have not yet investigated the use of in-pond heat exchangers for extracting heat in three-zone solar ponds. Moreover,

Previous research has failed to examine the possibility of determining mass flow rates via the use of different in-pond exchangers or by performing parametric simulations that account for realistic constraints, such as the restricted capacity of the pond. This study aims to thoroughly examine a solar pond that is fitted with three exchangers. The examination use analytical, multi-parameter restricted parametric analysis to fill the existing gaps in the literature. The objective of this study is to determine the most favorable thickness values for the Non-Convective Zone (NCZ) and the Convective Zone (LCZ) in proportion to the size of the pond, with the purpose of maximizing the thermal power generated for a certain volume of the pond.

Alacaraz et al. (2018) Solar collectors were used to provide heat, while lateral and horizontally placed heat exchangers were used to remove heat. Based on the findings, providing heat is more advantageous during the winter and autumn seasons, but extracting heat is more feasible during the spring and summer seasons..

Simic & George (2017) Demonstration Salinity gradient solar ponds are used to exploit renewable energy sources. Energy may be used by creating a temperature gradient between the surface and the bottom of the pond. The all of our electricity is derived from solar radiation that reaches the Earth's surface. The salinity gradient, which is sustained and

altered with increasing depth, results in temperature fluctuations of up to sixty degrees. The generated thermal energy may be used directly for different purposes or transformed into electrical energy for internal consumption or sale to the power grid. The successful functioning of solar ponds as energy generating facilities primarily relies on the direct monitoring of several physical attributes of the ponds. The objective of our research was to assess the practicability of collecting data (DAQ) and monitoring the energy production of the solar pond from a distant location. The control center of a solar pond may be located anywhere on Earth, using wireless, wired, virtual private, and Internet connections. The selection of pond sites is carefully made to optimize the capacity for solar energy.

Suárez (2017) Examined Salt-gradient ponds provide a cost-effective method for storing low-grade heat over extended periods, allowing for its continuous use. Accurate computational techniques that precisely model energy exchanges at the interface between the pond's bottom and the ground are essential for the design and operation of the system. This study utilizes a resilient one-dimensional transient model to demonstrate the variations in temperature inside a salt-gradient solar pond and the surrounding land. The model underwent testing in many scenarios, including diverse groundwater levels (both deep and shallow), artificially heated ponds, and uncovered ponds. The model was developed, adjusted, and confirmed using empirical data obtained from a solar pond of laboratory scale. Over a period of 28 days, the upper convective zone had a root mean square error (RMSE) value of 1.21 °C, whereas the bottom convective zone had an RMSE value of 1.54 °C.

The era demonstrates a reasonable agreement between the observed and simulated outcomes. Furthermore, the accuracy of the model was confirmed by a comparison with empirical data obtained from three real-world salt-gradient solar ponds. The comparison revealed that the root mean square errors (RMSEs) varied between 1.5 and 6.5 °C. The findings indicate that the model's ability to withstand and recover from challenges is enhanced due to the division of the ground into several layers, which enables a more precise representation of the storage of heat in the ground.

Ganguly et al. (2017) Envision a solar pond equipped with heat exchangers in both the storage region and the underlying soil. The model initially assumed a sequential link between the two types of exchangers, but this was subsequently revised to a parallel configuration. The results obtained from the first setup were found to be superior.

Ganguly et al. (2017) A solar pond has a horizontally positioned heat exchanger in its storage area, which takes heat from an evacuated tube solar collector situated outside the pond.

Alcaraz (2016) an experiment was done to put the theory of gradient layer heat extraction, which had previously been investigated in theoretical models.

Date et al. (2013) Conducted a transient analysis on a solar pond to investigate the simultaneous extraction of heat from both the non-conductive and conductive regions.

Tundee et al. (2010) A study was done to evaluate the viability of using a two-phase gravity-assisted thermosyphon as a heat exchanger. The two-phase iteration of the system is favored over the typical single-phase version due to its larger dimensions and lower heat transfer rate per unit mass flow rate of the working fluid.

Jaefarzadeh (2006) I conducted an experiment to assess the influence of daily variations in many operational variables on the efficiency of a small solar pond that includes an exchanger. The variables included the ambient air temperature, the temperature of the exchanger fluid, and the temperature of the storage compartment

Andrews and Akbarzadeh (2005) An novel approach to heat a solar pond involves harnessing the latent and active heat from both the non-convective zone (NCZ) and the convective zone (LCZ). The study investigated the use of a vertical heat exchanger in the NCZ to enhance the extraction process. Studies have shown that the inclusion of this element greatly enhances the effectiveness of the pond.

III. RESEARCH METHODOLOGY

This study aims to investigate the performance and efficiency of a three-tier solar pond enhanced with high-conductivity nanoparticle-enriched phase change materials (PCMs). The research methodology is divided into several key stages, including the construction of the solar pond, material selection, experimental setup, and data analysis.

1. Construction of the Solar Pond

The solar pond was constructed with three distinct layers: the Upper Convective Zone (UCZ), the Non-Convective Zone (NCZ), and the Lower Convective Zone (LCZ). The UCZ, located at the top, contains low concentrations of salt and is exposed to solar radiation. The NCZ, positioned in the middle, has a gradient of salt concentration that increases with depth, serving as an insulating layer to minimize heat loss through convection. The LCZ, at the bottom, has the highest salt concentration and retains the absorbed heat.

2. Material Selection

Phase Change Materials (PCMs)

The primary PCM used in this study was selected based on its high latent heat storage capacity and appropriate phase transition temperature. The selected PCM was evaluated for its thermal properties, stability, and compatibility with the solar pond environment.

Nanoparticles

High-conductivity nanoparticles, specifically chosen for their ability to enhance the thermal conductivity of the PCM, were incorporated into the PCM. The nanoparticles were thoroughly mixed with the PCM to ensure uniform distribution and optimal performance.

3. Experimental Setup

Initial Temperature Variation

The experiments were designed to determine the uppermost temperature at which phase change material (PCM) and non-PCM scenarios occur. Initial temperatures were varied systematically from 300 K to 340 K in increments of 20 degrees.

Temperature Measurement

Temperature measurements were obtained by repositioning a tube to different locations within the pond. The placement of the tubes was carefully controlled to evaluate the effect of their position on heat transfer efficiency.

4. Data Collection and Analysis

Performance Metrics

The performance of the solar pond was assessed based on the temperature achieved and maintained at various depths, as well as the efficiency of heat transfer. Key metrics included:

Temperature stability and retention in the LCZ.

Comparison of PCM and non-PCM scenarios.

Impact of nanoparticle inclusion on the thermal performance of PCM.

Comparative Analysis

The performance improvement was quantified by comparing the solar pond with PCM alone and the solar pond with nanoparticle-enhanced PCM. The following scenarios were analyzed:

Tubes positioned on opposite sides of the pond.

Efficiency Calculation

Efficiency improvements were calculated for different initial temperatures (300 K and 340 K). The percentage improvement was determined by comparing the heat transfer efficiency of the enhanced system against the baseline (PCM alone).

5. Statistical Analysis

The data collected were subjected to statistical analysis to determine the significance of the observed improvements. Variance analysis was conducted to assess the impact of initial temperature variations and nanoparticle inclusion on the thermal performance of the solar pond.

6. Validation and Replication

To ensure the reliability of the results, the experiments were repeated multiple times under controlled conditions. The consistency of the results was verified through replication studies, and any anomalies were investigated and addressed. By employing this comprehensive research methodology, the study aims to provide a detailed evaluation of the effectiveness of nanoparticle-enhanced PCMs in improving the thermal performance of solar ponds. The findings are expected to contribute valuable insights into the optimization of solar energy storage systems for sustainable energy applications.

IV. RESULTS AND DISCUSSION

Data from the computational model as well as the analysis were given in this chapter. The following three solar pond properties are evaluated using computational analysis:

- The convection-free thermal analysis provided by ANSYS.
- A heat-absorbing/collecting module is used in a desalination plant for energy storage and transmission. This module is calculated based on a computational fluid dynamics (CFD) thermal analysis, which analyzes the flow and temperature.
- Assessing the influence of double-diffusive effects on the stratification of solar ponds by a comprehensive examination of temperature and concentration patterns using computational fluid dynamics.

Analyze only the energy requirements of the desalination plant and evaluate the efficiency of the solar pond inside the Local Climate Zone (LCZ) in terms of its capacity to store energy and provide heat to the collecting module.

This study used heat transfer analysis to ascertain the heat balance analysis for the constructed prototype solar pond. The temperature at the entry is incrementally increased from 300 K to 340 K, with each step being 20 K. The exit temperature is then computed for both scenarios: one with the use of phase change material (PCM) and the other without PCM. In addition, after each occurrence, the position of the tube is changed and the variation in temperature is documented in a table.

WITT PCM PLUS NANO MATERIAL

In Scenario 1, the tube's entrance and exit are located on the same side of the solar pond. In Case 2, the entrance and exit of the tube are located on opposite sides of the solar pond.

When the inlet and outlet of the tube are kept at same side

A. For inlet temperature 300k

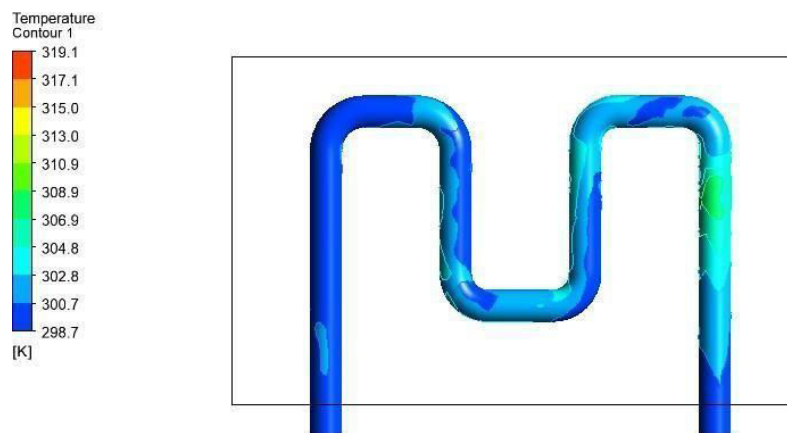


Fig. 4.1: Temperature Contour for the pipe

The pipe's color in the picture above indicates that the exit temperature, indicated by the greenish hue, is higher than the intake temperature, represented by the blue color. The temperature gradient of the fluid is rising throughout its length.

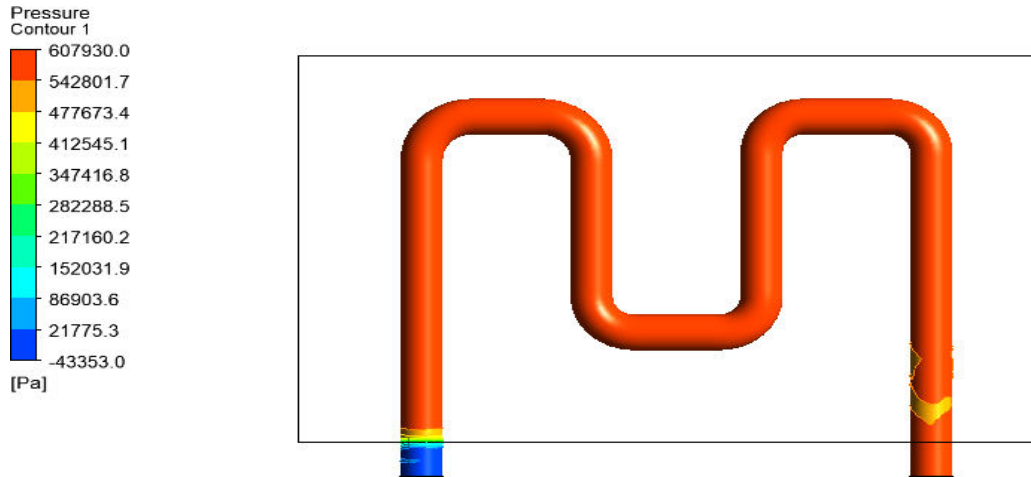


Fig.: Pressure Contour for the pipe

[Table 5.1: Comparison

When the inlet and outlet of the tube are kept at same side	With PCM plus nano particles	When the inlet and outlet of the tube are kept at same side	With PCM
$T_{in} = 300 \text{ K}$	319.1 K	$T_{in} = 300 \text{ K}$	307.1 K
$T_{in} = 340 \text{ K}$	689.25 K	$T_{in} = 340 \text{ K}$	388.8 K
When the inlet and outlet of the tube is kept at opposite side		When the inlet and outlet of the tube is kept at opposite side	
$T_{in} = 300 \text{ K}$	312.4 K	$T_{in} = 300 \text{ K}$	306.4 K
$T_{in} = 340 \text{ K}$	555.35 K	$T_{in} = 340 \text{ K}$	392.9 K

V. CONCLUSION

The implementation and evaluation of a three-tier solar pond enhanced with high-conductivity nanoparticle-enriched phase change materials (PCMs) demonstrated significant improvements in thermal performance and heat transfer efficiency. The study successfully achieved its primary objectives: constructing a solar pond with distinct thermal zones and examining the impact of high-conductivity materials on PCM heat transfer characteristics.

Key findings include:

1. Performance Enhancement with Nanoparticles: Incorporating nanoparticles into PCM resulted in notable performance improvements. At a constant temperature of 300 K, the addition of nanoparticles increased efficiency by 3.76% compared to PCM alone. At an initial temperature of 340 K, the performance enhancement reached 43.59%.

2. **Optimized Heat Transfer:** Positioning the intake and outflow tubes on the same side of the pond further optimized heat transfer efficiency. This configuration, combined with nanoparticle-enhanced PCM, achieved a performance improvement of 1.92% at 300 K and 29.25% at 340 K.
3. **Thermal Stability:** The three-tier structure of the solar pond effectively maintained thermal stability, with the non-convective zone (NCZ) serving as an insulating layer to minimize heat loss and preserve the absorbed solar energy in the lower convective zone (LCZ).

These results underscore the potential of nanoparticle-enhanced PCMs in improving the thermal efficiency of solar ponds, providing a viable solution for sustainable energy storage.

Future Work

Building on the findings of this study, several avenues for future research and development are recommended:

1. **Long-Term Performance Assessment:** Conduct long-term studies to evaluate the durability and stability of nanoparticle-enhanced PCMs in solar ponds under varying environmental conditions and prolonged usage.
2. **Optimization of Nanoparticle Concentration:** Investigate the optimal concentration and types of nanoparticles to maximize thermal conductivity without compromising the structural integrity and cost-effectiveness of the PCM.
3. **Scale-Up Studies:** Explore the scalability of the enhanced solar pond system for larger applications, including industrial and municipal energy storage solutions.
4. **Hybrid Energy Systems:** Integrate the solar pond with other renewable energy systems, such as photovoltaic panels and wind turbines, to create hybrid energy systems that enhance overall energy efficiency and reliability.
5. **Economic Analysis:** Perform a detailed economic analysis to compare the cost-effectiveness of nanoparticle-enhanced PCM solar ponds with conventional energy storage methods, considering factors such as initial investment, maintenance costs, and energy savings.
6. **Environmental Impact Assessment:** Assess the environmental impact of large-scale deployment of nanoparticle-enhanced solar ponds, including the potential effects on local ecosystems and water resources.
7. **Advanced Material Development:** Explore the development of advanced PCMs with higher latent heat storage capacities and improved thermal conductivity, incorporating innovative materials such as graphene or carbon nanotubes.

By addressing these future research directions, the potential of solar ponds as a sustainable and efficient energy storage solution can be fully realized, contributing to the global effort towards renewable energy adoption and climate change mitigation.

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