Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/EU08.20250239
Published: July 2, 2025

Integration of Water Desalination and Power Generation Using Salinity Gradient Solar Ponds (SGSP) Hybrid Systems and Solar Thermal Systems (STS) in Oman

Mira Chitt
Mechanical Engineering Department
Global College of Engineering and Technology
Muscat, Oman
mira.c@gcet.edu.om

Abstract

Oman's dependence on desalination to meet freshwater demand poses sustainability challenges due to the high energy consumption and carbon emissions associated with conventional methods such as reverse osmosis. As a response, solar desalination technologies are emerging as viable, eco-friendly alternatives. Salinity Gradient Solar Ponds (SGSP) harness the natural salinity gradient within water layers to generate thermal energy, while Concentrated Solar Power (CSP) systems utilize focused solar radiation to achieve high temperatures for thermal desalination. Recent research highlights the potential of integrating SGSP and CSP technologies to improve energy efficiency and freshwater output. In this paper, we study the integration of SGSP and CSP systems to evaluate their combined potential for enhanced desalination performance and simultaneous electricity generation. Solar desalination and power generation present a transformative opportunity for Oman to address critical challenges in water security, energy diversification, and environmental sustainability. By harnessing abundant solar energy, Oman can ensure a reliable freshwater supply, reduce dependence on fossil fuels, and lower greenhouse gas emissions. Although initial investments may be higher, long-term cost savings and enhanced resilience to climate variability make it a financially viable solution. Furthermore, adopting these technologies positions Oman as a regional leader in renewable energy, fostering technological innovation, economic growth, and global competitiveness in the clean energy sector.

Keywords
Solar Desalination, Salinity Gradient Solar Ponds (SGSP), Concentrated Solar Power (CSP), Renewable Energy, Water-Energy Nexus.

1. Introduction
The global energy crisis has intensified the demand for sustainable and efficient alternatives, and solar energy has emerged as a viable solution. Despite the Earth receiving an immense amount of solar radiation daily, much of it remains unexploited. It has been estimated that harnessing just one hour of the sun's energy could fulfill the planet's energy requirements for an entire year. Solar energy's broad range of applications-such as cooking, air heating, power generation, distillation, and more-has made it increasingly attractive, particularly through the use of solar thermal systems. Moreover, tapping into solar power can significantly reduce the reliance on non-renewable fossil fuels.

Among the various solar technologies, solar ponds stand out as an innovative and low-cost method for both capturing and storing solar energy. These systems are particularly suited for long-term thermal energy storage and are promising for providing pollution-free, cost-effective electricity. A solar pond is a layered body of saline water divided into three zones: The Upper Convective Zone (UCZ), Non-Convective Zone (NCZ), and Lower Convective Zone (LCZ). The

UCZ consists of low-salinity water and is prone to heat loss due to convection. Below it, the NCZ acts as an insulating layer, with its salinity increasing with depth, helping to prevent heat loss upwards. The LCZ, which has the highest salt concentration, stores thermal energy and can reach temperatures up to 90°C under favorable conditions. This stored heat is suitable for applications such as electricity generation and industrial heating (Abdullahi et al., 2017; Adediji et al., 2021; Saxena et al., 2011; Adediji et al., 2023; Mbelu et al.).

However, a major drawback of solar ponds is their low thermal efficiency, mainly caused by convective heat losses from the bottom layers to the surface. The salinity gradient is essential for suppressing natural convection and improving energy retention. To overcome performance limitations, researchers have been developing models and conducting numerical and experimental studies. For instance, Runge–Kutta-based simulations, finite volume methods, and experimental prototypes have all been used to analyze and enhance the thermal behavior of salinity gradient solar ponds (SGSPs). Results have shown thermal efficiencies as high as ~30% and electrical efficiencies approaching 9% in some months (Mansouri A et al., 2018; Shahid et al., 2023).

Due to their high heat retention capacity and consistent thermal output, SGSPs are suitable for a wide range of uses, including electricity generation, desalination, building climate control, and industrial process heating. Additionally, SGSPs perform better than flat plate collectors under cloudy conditions due to lower thermal losses. While large-scale implementation remains a challenge, ongoing research continues to focus on improving design stability, thermal efficiency, and cost-effectiveness, especially through better management of the salt gradient and optimization of storage configurations (Tawalbeh et al., 2023).

1.1 Objectives

In response to Oman's growing freshwater demand and its reliance on energy-intensive desalination technologies, there is an increasing interest in sustainable alternatives that leverage the country's abundant solar resources. Among these, Salinity Gradient Solar Ponds (SGSP) and Concentrated Solar Power (CSP) systems have gained attention for their potential to produce freshwater and electricity in an environmentally friendly manner. However, a comprehensive understanding of their individual and combined capabilities, limitations, and suitability for integration is essential before advancing toward practical implementation. This study therefore aims to review and analyze the existing body of knowledge surrounding these technologies. The specific objectives of this literature review are as follows:

- To critically review the current state of solar desalination technologies with a focus on Salinity Gradient Solar Ponds (SGSP) and Concentrated Solar Power (CSP) systems.
- To examine the thermodynamic principles, design configurations, and operational characteristics of SGSP and CSP technologies relevant to freshwater production and energy generation.
- To identify key advantages, limitations, and performance metrics of SGSP and CSP systems based on global case studies and existing deployments.
- To explore the theoretical and practical potential for integrating SGSP and CSP systems, highlighting synergistic effects and opportunities for improved efficiency.
- To assess the applicability and scalability of hybrid SGSP-CSP systems for water and energy needs in arid and semi-arid regions, with a focus on Oman's environmental and socio-economic context.
- To identify knowledge gaps, technical challenges, and future research directions for advancing the integration of solar thermal technologies in sustainable desalination.

2. Literature Review

Solar ponds are innovative thermal energy storage systems that utilize solar radiation to generate and retain heat over extended periods. These ponds function by manipulating the natural convective behavior of water through various mechanisms-most commonly using salinity gradients-to trap thermal energy in lower layers. Solar ponds have attracted considerable attention due to their potential for low-cost, sustainable heat storage and their application in power generation, desalination, industrial heating, and other thermal processes. Over time, several types of solar ponds have been developed to overcome technical limitations, enhance efficiency, and adapt to diverse environmental and operational contexts. The following section provides a review of six major solar pond types: Salt Gradient Solar Ponds (SGSPs), Shallow Solar Ponds (SSPs), Solar Gel Ponds (SGPs), Equilibrium Solar Ponds (ESPs), Membrane Solar Ponds (MSPs), and Partitioned Solar Ponds (PSPs).

Salt Gradient Solar Ponds (SGSPs)
SGSPs are the most extensively studied and widely implemented type of solar pond. They operate based on a salinity-induced density gradient that suppresses natural convection and traps solar heat at the bottom of the pond. Structurally, SGSPs are divided into three layers: The Upper Convective Zone (UCZ), Non-Convective Zone (NCZ), and Lower Convective Zone (LCZ). The UCZ contains fresh water with minimal salt, where initial solar radiation is partially absorbed and partially lost to the environment. The NCZ, characterized by a sharp salinity gradient, serves as an insulating layer that minimizes heat loss and stabilizes the system. The LCZ contains the highest salt concentration and acts as the thermal storage zone, often enhanced by black polyethylene films to absorb more radiation.

While SGSPs are thermodynamically promising, their typical thermal efficiency ranges between 10-30%. Key factors influencing performance include insulation materials, heat loss rates, salt concentration profiles, and exchanger design. Recent advancements-such as using nanoparticles (ZnO, SiO_2), phase change materials, improved insulation, and optimized heat exchanger placement-have shown notable efficiency gains, reaching up to 35%. In some studies, SGSPs have also been used for lithium extraction from brines, highlighting their multipurpose utility (Garg HP, 1987; Tawalbeh et al., 2023).

Shallow Solar Ponds (SSPs)
SSPs represent a simpler and more cost-effective alternative for low-grade thermal energy collection. These ponds are typically 4-15 cm deep and consist of water layers covered by transparent films, often resembling plastic solar cookers or flat-plate collectors. The bottom is painted black to enhance heat absorption, while the top is covered with glazing to minimize radiation and convection losses.

SSPs have reported thermal efficiencies between 33-40%, depending on design features and insulation. Their applications are most common in domestic heating and small-scale industrial processes. Experimental studies have examined variations such as the addition of baffle plates, use of Styrofoam insulation, and integration with heat exchangers. These configurations have achieved water temperatures up to 71 °C. Batch, open, and closed-cycle heat extraction methods have been explored, with open-cycle designs demonstrating the best thermal performance due to continuous heat removal. Innovations in glazing materials, water depth optimization, and insulation design continue to enhance SSP efficiency (Ramadan et al., 2004; Tawalbeh et al., 2023).

Solar Gel Ponds (SGPs)
SGPs are a novel alternative to SGSPs, addressing issues such as salt stratification, evaporation, and maintenance. These systems use polymer gels as the non-convective insulating medium, replacing the salinity gradient. The gel layer, typically made from materials such as polyacrylamide, gelatin, or carboxymethyl cellulose, floats between the water surface and the thermal storage zone, effectively blocking convective currents and maintaining thermal stability. SGPs demonstrate several advantages, including reduced operational complexity, minimized environmental impact, and enhanced thermal insulation. Experimental studies have shown storage temperatures up to 100 °C, with thermal efficiencies reaching around 39%. Gel transparency, low thermal diffusivity, and chemical stability are critical factors for performance. While the higher capital cost is a current limitation, advancements in eco-friendly, cost-effective gel synthesis may allow broader deployment in the future. Analytical models such as the Kooi and Bansal-Kaushik models have helped optimize gel thickness and improve system design (Shaffer et al., 1978; Tawalbeh et al., 2023).

Equilibrium Solar Ponds (ESPs)
Equilibrium Solar Ponds are designed to maintain a self-sustaining salinity gradient using salts with temperature-dependent solubility. These systems operate under the principle that increasing temperature enhances salt solubility, thereby maintaining a stable stratification without the need for frequent salt maintenance. This balance results in a 'zero net salt flux' condition, which greatly reduces operational costs and complexity.

ESPs benefit from reduced crystallization risk, improved heat absorption, and long-term stability, especially in the lower zone where no solid salt accumulates. Typical salts used include borax, magnesium chloride, calcium chloride, and ammonium nitrate. These ponds have shown improved bottom-zone temperatures and better heat retention compared to saturated or conventional SGSPs. Experimental and theoretical studies have validated the effectiveness of ESPs under varied climatic and hydrological conditions (Subhakar D et al., 1993; Harel et al., 1993; Tawalbeh et al., 2023).

Membrane Solar Ponds (MSPs)
MSPs use transparent physical membranes to separate the water layers instead of relying on a salt gradient. These membranes, made from materials like glass or polymer films, prevent vertical convective mixing while allowing sunlight to penetrate the pond. By providing structural isolation between thermal zones, MSPs enhance layer stability and improve heat storage performance.

However, the presence of membranes can also introduce optical losses due to reflection or reduced transmissivity. Research involving horizontal and vertical membrane configurations has demonstrated average LCZ temperatures around 51 °C, with performance metrics comparable to traditional SGSPs. MSPs offer practical advantages in situations where maintaining a stable salinity gradient is difficult, although they may require specialized materials to minimize optical drawbacks (Tawalbeh et al., 2023).

Partitioned Solar Ponds (PSPs)
PSPs are designed to overcome operational challenges faced by traditional solar ponds, such as algae growth, evaporation, and degradation of salt gradients. These systems use transparent physical partitions (glass or flexible films like Tedlar) to separate convective and non-convective zones, allowing for improved heat extraction and thermal efficiency.

By reducing reflective losses and stabilizing layer interactions, PSPs are especially suited for large-scale industrial applications. Heat exchangers are often placed just below the partitions to enhance thermal transfer. Studies have shown that PSPs can significantly boost system stability and are less affected by environmental fluctuations. Their modular design also supports easier maintenance and integration with hybrid energy systems (Tawalbeh et al., 2023)..

Going back to Salinity Gradient Solar Ponds, SGSPs are passive solar thermal systems designed to capture and store solar energy using the principle of density stratification. These systems act as large-scale thermal batteries, trapping solar heat in the bottom layers of a water body by suppressing convective heat loss. This is achieved by creating a salinity gradient, where denser saltwater resides at the bottom and fresher water remains on top. The selection of salt used to establish and maintain this gradient is critical to the pond’s thermal performance, stability, environmental impact, and operational cost.

Sodium Chloride (NaCl): The Standard Salt
Sodium chloride is the most commonly used salt in SGSPs due to several favorable properties:

- Temperature-dependent solubility: Its solubility increases with temperature, making it suitable for thermal systems.
- High transparency to solar radiation: It allows sunlight to pass through the solution effectively.

- Density-enhancing capabilities: The dissolved salt at high concentrations increases water density, helping to maintain the salinity gradient.
- Thermal stability and affordability: NaCl is thermally stable and widely available, making it cost-effective for large-scale applications.

The use of NaCl facilitates the formation of three thermal zones in SGSPs: the upper convective zone (UCZ) with little to no salt, the non-convective zone (NCZ) with a steep salt concentration gradient, and the lower convective zone (LCZ) with the highest salt concentration. Heat absorbed by the LCZ is retained due to the suppressed convective currents, leading to efficient thermal energy storage. However, NaCl requires careful gradient maintenance and frequent brine replenishment, especially in high evaporation environments (Mbelu et al., 2024).

Alternative and Fertilizer Salts
Due to environmental and economic concerns, alternative salts-particularly fertilizer salts-have been investigated as substitutes for NaCl. These include:

- Urea
- Potassium nitrate (nitrate of potash)
- Ammonium dihydrogen phosphate
- Potassium dihydrogen phosphate

These salts offer high solubility, which supports the formation of stable density gradients and effective heat retention. Jubran et al. (1999) observed that such salts can help create convective liners along the pond walls, promoting vertical thermal stratification. In addition, these fertilizers have the added benefit of supporting aquatic ecosystems by serving as nutrient sources.

From a practical standpoint, these salts are advantageous due to their:

- Widespread availability in agriculture
- Compatibility with existing pond infrastructure
- Potential to reduce operational costs

Thermal experiments showed that urea and nitrate of potash were particularly effective, with fewer convective disturbances on pond walls at different inclinations (90°, 60°, and 30°), enhancing overall thermal stability.

Magnesium Chloride ($MgCl_2$): A Hygroscopic Alternative
Magnesium chloride has emerged as another promising candidate due to its:

- High thermal conductivity and solubility
- Environmental friendliness and low cost
- Hygroscopic nature, which helps maintain surface moisture and reduces salt crust formation

In comparative studies, $MgCl_2$ -based SGSPs delivered similar energy outputs to those using urea or NaCl. Bozkurt et al. (2015) reported a thermal energy efficiency of 27.41% in the LCZ and 19.71% in the NCZ. Its ability to prevent convective mixing and maintain clear optical paths makes it attractive for use in solar thermal applications, especially in arid climates (Mbelu et al., 2024).

Natural Brine Sources and Seawater
In coastal regions or areas with natural saltwater lakes, the use of natural brine presents a cost-effective and sustainable alternative to synthetic salt solutions. Hassairi et al. (2001) compared NaCl solutions with natural seawater and found

that NaCl yielded higher LCZ temperatures (55 °C compared to 47 °C). Similarly, Nie et al. (2011) conducted a field study on a large-scale SGSP (2,500 m² and 3 m depth) filled with brine from the Zabuye Salt Lake, where the LCZ reached a temperature of 39.1 °C. While natural brine may result in slightly lower thermal efficiency, its accessibility and minimal processing requirements make it a viable choice in many locations.

Sodium Carbonate (Na_2CO_3): Affordable and Efficient
Sodium carbonate is another salt considered for SGSPs due to its:

- High solubility and specific heat capacity
- Environmental safety
- Compatibility with existing systems

Kurt et al. (2006) demonstrated its ability to form a stable salinity gradient and limit bottom-up convection effectively, allowing for efficient thermal energy storage. Na_2CO_3 has shown promising thermal performance at a low cost, though it is less commonly used than NaCl.

Calcium Chloride ($CaCl_2$): High Thermal Performance, High Cost
Calcium chloride has shown superior thermal results in experimental studies. Berkani et al. (2015) observed that SGSPs using $CaCl_2$ achieved higher temperatures than those using NaCl or Na_2CO_3, without reaching saturation. However, the high cost of $CaCl_2$ restricts its broader use, especially in large-scale applications where affordability is key (Mbelu et al., 2024).

Nanoparticles for Thermal Enhancement
Recent studies have explored the integration of nanoparticles into the storage zone to improve heat retention. Beiki et al. (2019) tested three types: SiO_2, Fe_3O_4, and ZnO. Among them, ZnO nanofluid achieved the highest lower zone temperature (~47 °C) and boosted thermal efficiency by 35.13%. This was attributed to ZnO's superior thermal conductivity and minimal light scattering, which enhanced solar radiation absorption. Nanofluids are thus considered a promising frontier for improving SGSP efficiency.

The type of salt used in SGSPs significantly affects their thermal efficiency, economic viability, and environmental compatibility. While sodium chloride remains the standard due to its proven performance and cost-effectiveness, other salts such as magnesium chloride, sodium carbonate, and fertilizer-based salts present valuable alternatives under specific conditions. Natural brine and nanomaterials also show great promise in enhancing pond performance, especially when tailored to local environmental and economic contexts. Ongoing research continues to explore these materials to optimize SGSP design for sustainable thermal energy storage and water desalination.

The successful deployment and long-term operation of Salinity Gradient Solar Ponds (SGSPs) depend on a range of interdependent factors including site selection, material choices, salt properties, heat extraction techniques, and environmental considerations. Each parameter not only influences the thermal performance of the system but also affects its economic viability, environmental sustainability, and operational resilience. This section presents a detailed review of the critical design and operational elements that must be evaluated when developing SGSPs, supported by current research and practical case studies.

Site Selection
Site selection is a foundational aspect of solar pond design. Optimal locations are characterized by high solar irradiance, low annual rainfall, minimal wind activity, and stable geological conditions. High solar insolation ensures maximum heat absorption, while low precipitation prevents the dilution of the salinity gradient. Additionally, wind speeds must be low to avoid turbulence that can destabilize the stratified layers of the pond (Rghif et al., 2023).

Proximity to salt and water resources significantly reduces logistical costs, as transporting these essential inputs over long distances can be economically and environmentally burdensome. The availability of flat terrain is also advantageous, as it reduces excavation costs and simplifies construction. Finally, environmental impact assessments and legal permits must be secured to ensure long-term viability, especially in ecologically sensitive or populated areas.

Pond Structure and Materials

The structure of a solar pond must be designed to withstand environmental stresses while maintaining the thermal and chemical integrity of the system. Key structural components include:

- Lining material: A high-quality, non-permeable liner such as reinforced polyethylene or PVC is essential to prevent leakage, groundwater contamination, and structural erosion (Ali et al., 2020).
- Insulation: Proper insulation-both at the base and along the sides-minimizes heat loss and maintains the temperature gradient. Materials like polystyrene, sawdust, or synthetic foams are commonly used.
- Durability and corrosion resistance: All construction materials must resist chemical degradation caused by saltwater and withstand UV radiation, microbial growth, and fluctuating thermal loads.
- The geometry and depth of the pond also play a vital role in maximizing the surface-to-volume ratio, thus influencing solar absorption and storage capacity.

Salt Type, Availability, and Performance
The choice of salt is crucial in achieving and sustaining a stable salinity gradient as stated previously. The ideal salt should exhibit:

- High solubility with minimal temperature sensitivity,
- Low diffusion coefficient to minimize mixing between layers,
- High optical clarity to allow maximum solar penetration,
- Environmental safety and cost-effectiveness.

Heat Extraction Systems
The heat stored in the LCZ must be efficiently transferred to external applications such as industrial process heating, desalination, or electricity generation. Effective heat extraction systems must:

- Use corrosion-resistant materials, such as stainless steel or copper-nickel alloys, to withstand the saline environment.
- Be strategically placed-typically at the bottom or along the walls-to avoid disturbing the NCZ.
- Match the thermal demands of the application, ensuring optimal energy utilization without excessive losses.

Both lateral and bottom heat exchangers have been tested, with dual-placement systems showing effectiveness up to 80% in hot climates (Alcaraz et al., 2016). Designs must also prevent thermal short-circuiting, which can disrupt the pond's stratification and reduce storage efficiency.

Climatic and Geological Influences
Climatic conditions such as solar radiation levels, humidity, ambient temperature, and wind patterns directly influence the energy gain and retention of SGSPs. High evaporation rates are problematic, as they necessitate frequent water replenishment, while heavy rainfall can dilute the pond's salinity gradient and compromise efficiency (Tawalbeh et al., 2023).

Geological factors are equally critical. The soil must have low permeability to avoid seepage and be geotechnically stable to support the pond structure. Sites with high water tables, frequent seismic activity, or unstable clay soils require additional foundation reinforcement or site modification.

Environmental Impact and Lifecycle Assessment
Although SGSPs offer a clean method for thermal energy storage, they do have environmental implications throughout their lifecycle stages-construction, operation, and decommissioning:

- Construction phase: Involves land excavation, liner deployment, and salt processing, which can disrupt local ecosystems and contribute to CO_2 emissions (Hertwich, 2021).
- Operational phase: Risks include brine leakage, habitat disruption, and high water consumption to offset evaporation. The salinity of the pond can also affect local biodiversity if not properly managed (Tan et al., 2023).
- Decommissioning phase: Disposal or recycling of synthetic liners and treatment of saline residues are necessary to avoid long-term environmental damage. Site restoration involves regarding the land, neutralizing the soil, and reestablishing vegetation (Rabaia et al., 2021).

- Lifecycle analysis helps identify the environmental trade-offs associated with SGSP deployment and highlights the importance of integrated sustainability planning.

The following Table 1 shows a summary of Key Parameters Affecting SGSP Performance.

Table 1. Key Parameters Affecting SGSP Performance

Parameter	**Design Objective**	**Impact**
Site location	High solar irradiance, flat terrain, nearby salt/water sources	Affects capital cost, energy yield, maintenance
Salt type	High solubility, thermal stability, environmental safety	Maintains stratification and efficiency
Construction material	Durable, insulated, corrosion-resistant	Ensures long-term performance and low heat loss
Heat extraction	Optimized exchanger placement and materials	Reduces energy loss, prevents salinity disturbance
Climate/geology	Low wind, low rainfall, stable soil	Supports thermal stability and structure longevity
Environmental management	Controlled salt disposal, evaporation control, site rehabilitation	Ensures ecological and regulatory compliance

3. Methods

The integration of Salinity Gradient Solar Ponds (SGSPs) with Solar Thermal Systems (STS) offers a promising hybrid approach for addressing two critical challenges in arid and semi-arid regions: freshwater scarcity and sustainable energy generation. SGSPs function as both solar collectors and thermal energy storage systems by utilizing a density-based salinity gradient that suppresses convection and retains solar heat in the lower convective zone (LCZ). Meanwhile, STS technologies-such as flat-plate collectors, parabolic troughs, and concentrating solar power (CSP)-are designed to convert solar radiation into usable thermal energy at higher temperatures and efficiencies.

Combining SGSPs with STS enhances overall system performance by enabling simultaneous power generation and freshwater production, leveraging the strengths of both technologies. The SGSP can serve as a low-cost thermal battery, while the STS components can supply high-temperature energy inputs for advanced desalination processes such as multi-effect distillation (MED), multi-stage flash (MSF), or thermal vapor compression (TVC). In this study, the methodological approach is informed by prior empirical and simulated case studies that demonstrate the viability of these integrated systems. These studies guide the configuration, sizing, and evaluation criteria used to design and assess the proposed hybrid system.

Bhuj Solar Pond Project, India (1984-1990)

One of the earliest large-scale implementations of SGSP technology, this 6000 m² solar pond in Bhuj, Gujarat, was constructed to provide thermal energy for a 5 kW Rankine cycle engine and for industrial process heating. The SGSP reached temperatures of up to 90°C in the LCZ. While not integrated with desalination, this project demonstrated the feasibility of long-term heat storage and electricity generation from solar ponds.

El Paso Solar Pond, Texas, USA

Developed as part of a research initiative by the University of Texas at El Paso, this project explored the use of a SGSP integrated with a desalination system using MED. The pond covered an area of 3700 m² and reached LCZ temperatures of around 85°C. The hybrid system produced electricity via an organic Rankine cycle and provided thermal energy for freshwater generation. The El Paso case demonstrates the effectiveness of SGSPs in supporting thermal desalination and serves as a precedent for sizing and process integration in hybrid configurations.

Dead Sea Solar Pond, Jordan

A landmark project covering 250,000 m², the Dead Sea SGSP was primarily used for industrial process heating in potash and bromine production. A study done by Saleh et al., 2010 investigated the technical viability and performance of integrating a salinity gradient solar pond (SGSP) with a desalination plant under the climatic conditions of the Dead

Sea region in Jordan. The unique environmental characteristics of this location-such as high solar radiation intensity, elevated ambient temperatures throughout the year, and the abundance of naturally occurring brine-make it an optimal candidate for solar-thermal desalination applications. The core concept explored in this work is the utilization of thermal energy stored in the lower convective zone (LCZ) of an SGSP to power a flash desalination unit. A 3000 m² solar pond was selected as the system size, consistent with the surface area of the well-documented El Paso solar pond in the United States, thereby providing a baseline for direct comparative performance analysis.

The authors employed a modified steady-state model, known as the Kooi model, to simulate the thermal behavior of the SGSP. The pond was conceptualized in the classic three-layer structure: the upper convective zone (UCZ), the non-convective zone (NCZ), and the lower convective zone (LCZ). The thickness of the NCZ, the LCZ temperature, and ambient conditions such as temperature and solar irradiance were treated as key input parameters. The model assumes unidirectional vertical heat transfer and neglects lateral heat losses due to the large surface-to-depth ratio. The performance of the pond is optimized by adjusting the NCZ thickness to achieve maximum heat extraction and efficiency, while maintaining the LCZ temperature at around 77°C-sufficient for use in thermal desalination systems. One of the significant findings of the simulation is that under Dead Sea climatic conditions, the SGSP with an optimized NCZ thickness of 1.9 meters demonstrated a considerably higher thermal performance than the El Paso configuration. The system achieved an annual average heat extraction rate of approximately 191.2 kW and a collection efficiency of 27.7%, compared to 131.5 kW and 18.45% for the El Paso system. The improvement in performance is primarily attributed to the elevated ambient temperatures and increased solar radiation levels in the Jordanian context, which reduce thermal losses from the UCZ and enhance the solar absorption capacity of the pond. Additionally, the availability of high-concentration brine from the Dead Sea eliminates the need for salt import and continuous replenishment, significantly reducing operational costs and improving the sustainability of the system.

The extracted heat from the LCZ is used to preheat brine feedwater via a heat exchanger before entering a flash desalination unit. The performance of the desalination component was evaluated using empirical correlations based on flow rates and brine temperatures. With a brine circulation rate scaled proportionally to the SGSP's heat extraction rate, the Jordanian system supports a higher feed flow of approximately 140.7 L/min, compared to 97 L/min in the El Paso system. Consequently, the average distilled water production rate increases to 4.3 L/min in the Dead Sea system, versus 3.3 L/min for El Paso—marking an approximate 30% improvement. Furthermore, performance ratios were estimated to be in the range of 2.5 pounds of distillate per 1000 Btu of thermal energy, indicating a highly efficient thermal desalination process when coupled with optimized SGSP conditions.

Beyond numerical results, the study emphasizes the practical advantages of deploying SGSPs in regions like the Dead Sea. The proximity to natural brine sources, favorable weather conditions, and relatively flat terrain contribute to a system design that is both cost-effective and operationally robust. The SGSP acts not only as a thermal energy collector but also as a long-duration storage medium, effectively mitigating the intermittency associated with solar energy. The authors argue that the deployment of such hybrid systems in Jordan could offer a sustainable solution to water scarcity, particularly for remote or off-grid communities where freshwater demand is growing and conventional energy resources are limited or costly. Moreover, the findings are extensible to other arid regions globally that exhibit similar solar and geological profiles.

Their study demonstrates that integrating a salinity gradient solar pond with a flash desalination unit is not only feasible but also advantageous under Jordanian climatic conditions. With optimized thermal and hydraulic parameters, the SGSP can outperform similar systems in other regions, offering improved freshwater yields and higher thermal efficiencies. The approach holds strong potential for decentralized water and energy solutions, and the successful implementation near the Dead Sea serves as a reference model for sustainable development in water-stressed, solar-rich environments.

Solar Pond with Vacuum Membrane Distillation (VMD), Iraq (Sayer et al., 2021)
A more recent study in Nasiriyah, Iraq, integrated a small-scale SGSP with a vacuum membrane distillation (VMD) desalination unit. The pond achieved an LCZ temperature of 65°C, which was sufficient to drive the VMD process. Paraffin wax was used to reduce evaporation losses, and performance was evaluated over 50 days. This project highlights the potential of SGSPs for decentralized desalination in remote regions and provides parameters for thermal coupling between the SGSP and membrane systems.

Hybrid SGSP-CSP System for Desalination (Modeling Study, Egypt)
In a simulation-based study conducted in Egypt, researchers modeled a hybrid system combining SGSP and CSP technologies to power a thermal desalination plant. The study showed that SGSPs could reduce the CSP system's energy load during nighttime or cloudy conditions by acting as a thermal reservoir. This case supports the hybrid operational logic used in the current methodology, especially in regulating load demands and improving system resilience.

4. Results and Discussion

This section explores the results and discussion so far in the project.

4.1 Results

Although experimental implementation has yet to be completed, this study draws upon simulated outcomes and literature-based benchmarking to estimate the feasibility and expected performance of a hybrid SGSP-STS system for desalination and power generation in Oman. The environmental conditions in regions such as Duqm, Al Wusta, and the coastal zones of Dhofar are broadly comparable to those of the Dead Sea area, where SGSPs have been shown to operate with high thermal efficiency. Oman receives annual solar irradiation exceeding 2200 kWh/m²-higher than that reported in Jordan-suggesting even greater energy capture potential from solar ponds.

Taking the Dead Sea study as a performance benchmark, it is reasonable to project that a 3000 m² SGSP in Oman could reach lower convective zone (LCZ) temperatures above 80°C, enabling it to power low-temperature desalination processes such as single-effect distillation or membrane distillation. Given the higher ambient temperatures and relatively stable atmospheric conditions in Oman, we expect a distilled water production rate of 4.5 to 4.8 L/min, surpassing both the El Paso and Jordanian models.

The integration of concentrated solar power (CSP) or flat-plate collectors with the SGSP system may further enhance system flexibility. While SGSPs offer stable, long-duration thermal storage, CSP components can provide high-intensity heat during peak daylight hours, increasing the availability of high-grade thermal energy for multi-effect distillation (MED) or even for driving organic Rankine cycle (ORC) turbines for electricity generation.

Key advantages identified for Oman include:
Proximity to natural brine sources (saline groundwater, coastal seawater), reducing operational costs.
Availability of flat, arid land in inland and coastal regions, suitable for large-scale pond construction with minimal site preparation.

Water scarcity and increasing demand for decentralized solutions in rural and semi-urban regions, making hybrid systems attractive for off-grid deployment. Low precipitation and low wind speeds, which help maintain salinity gradients and minimize evaporative losses from SGSPs.

4.2 Discussion

The integration of CSP or flat-plate collectors with SGSPs allows the system to meet varying thermal demand levels. While SGSPs maintain base-load heating, STS components can generate peak thermal input to drive high-temperature distillation or electricity generation processes. This hybridization improves system flexibility, increases thermal yield, and supports multi-functional applications-powering desalination, heating, and electricity simultaneously.

However, several challenges must be addressed:

Initial capital investment for pond construction, lining, and heat exchangers is significant.
Start-up periods for salinity gradient formation and thermal stability can span weeks to months.
Water use for evaporation compensation and brine discharge management may present environmental and logistical barriers.

Still, these challenges are outweighed by long-term benefits: low operational costs, carbon neutrality, and increased resilience to energy and water supply disruptions. Moreover, environmental concerns can be mitigated through appropriate site selection, salt recycling, and waste brine management strategies.

5. Conclusion

The integration of Salinity Gradient Solar Ponds (SGSP) with Solar Thermal Systems (STS) presents a technically and economically viable approach to addressing Oman's dual challenge of freshwater scarcity and the need for clean, decentralized energy. Based on regional climate analysis and comparative performance data, a hybrid SGSP-STS system implemented in Oman is projected to exceed the freshwater production rates reported in Jordan, with enhanced thermal efficiencies due to superior solar resources.

This system supports simultaneous electricity generation and desalination, offering a sustainable, off-grid solution particularly well-suited for inland or coastal remote areas. The approach leverages Oman's abundant solar irradiance, natural saline resources, and strategic policy direction toward green energy and water resilience. The anticipated benefits-low-carbon operation, reduced fuel dependency, and long-term cost efficiency-justify further development and pilot-scale deployment of this technology in Oman.

Future work will focus on experimental validation, site-specific modeling using TRNSYS or similar platforms, and techno-economic feasibility studies to support full-scale implementation and integration into national water and energy strategies.

References

Abdullahi, D., Suresh, S., Renukappa, S. and Oloke, D., Key barriers to the implementation of solar energy in Nigeria: A critical analysis. IOP Conference Series: Earth and Environmental Science, 83(1), p.012015. 2017.

Adediji, Y.B., Bamigboye, A., Aboderin, J.O., Lekwa, O.A. and Uzim, E.O., Estimation of global solar radiation on horizontal surfaces using temperature-based model in Ilorin, Nigeria. Engineering Archive. 2021.

Adediji, Y.B., Adeyinka, A.M., Yahya, D.I. and Mbelu, O.V., A review of energy storage applications of lead-free $BaTiO_3$-based dielectric ceramic capacitors. Energy, Ecology and Environment. 2023.

Ali, M.M., Ahmed, O.K. and Abbas, E.F., Performance of solar pond integrated with photovoltaic/thermal collectors. Energy Reports, 6, pp.3200–3211. 2020.

Alcaraz, A., Valderrama, C., Cortina, J.L., Akbarzadeh, A. and Farran, A., Enhancing the efficiency of solar pond heat extraction by using both lateral and bottom heat exchangers. Solar Energy, 134, pp.82–94. 2016.

Beiki, H. and Soukhtanlou, E., Improvement of salt gradient solar ponds' performance using nanoparticles inside the storage layer. Applied Nanoscience, 9(2), pp.243–254. 2019.

Bozkurt, I., Deniz, S., Karakilcik, M. and Dincer, I., Performance assessment of a magnesium chloride saturated solar pond. Renewable Energy, 78, pp.35–41. 2015.

Cuce, E., Cuce, P.M., Saxena, A., Guclu, T. and Besir, A.B., Performance analysis of a novel solar desalination system—Part 1: The unit with sensible energy storage and booster reflector without thermal insulation and cooling system. Sustainable Energy Technologies and Assessments, 37, p.100566. 2020.

El Mansouri, A., Hasnaoui, M., Amahmid, A. and Hasnaoui, S., Feasibility analysis of reverse osmosis desalination driven by a solar pond in Mediterranean and semi-arid climates. Energy Conversion and Management, 221, p.113190. 2020.

Ganesh, S. and Arumugam, S., Performance study of a laboratory model shallow solar pond with and without single transparent glass cover for solar thermal energy conversion applications. Ecotoxicology and Environmental Safety, 134, pp.462–466. 2016.

Garg, H.P., In: Advances in Solar Energy Technology: Volume 3 – Heating, Agricultural and Photovoltaic Applications of Solar Energy. Dordrecht: Springer Netherlands, pp.116–169. 1987.

Harel, Z., Tanny, J. and Tsinober, A., The equilibrium solar pond: A laboratory model for the gradient layer. Journal of Solar Energy Engineering, 115(1), pp.32–36. 1993.

Hassairi, M., Safi, M.J. and Chibani, S., Natural brine solar pond: An experimental study. Solar Energy, 70(1), pp.45–50. 2001.

Hertwich, E.G., Increased carbon footprint of materials production driven by rise in investments. Nature Geoscience, 14(3), pp.151–155. 2021.

Jubran, B.A., Ajlouni, K.S. and Haimour, N.M., Convective layers generated in solar ponds with fertilizer salts. Solar Energy, 65(5), pp.323–334. 1999.

Kurt, H., Ozkaymak, M. and Binark, A.K., Experimental and numerical analysis of sodium-carbonate salt gradient solar-pond performance under simulated solar-radiation. Applied Energy, 83(4), pp.324–342. 2006.

Mbelu, O.V., Adeyinka, A.M., Yahya, D.I., Adediji, Y.B. and Njoku, H., Advances in solar pond technology and prospects of efficiency improvement methods. Sustainable Energy Research, 11(1), p.18. 2024.

Rabaia, M.K.H., Abdelkareem, M.A., Sayed, E.T., Elsaid, K., Chae, K.J., Wilberforce, T. and Olabi, A.G., Environmental impacts of solar energy systems: A review. Science of The Total Environment, 754, p.141989. 2021.

Rghif, Y., Colarossi, D. and Principi, P., Salt gradient solar pond as a thermal energy storage system: A review from current gaps to future prospects. Journal of Energy Storage, 61, p.106776. 2023.

Ramadan, M.R.I., El-Sebaii, A.A., Aboul-Enein, S. and Khallaf, A.M., Experimental testing of a shallow solar pond with continuous heat extraction. Energy and Buildings, 36(9), pp.955–964. 2004.

Saleh, A., Qudeiri, J.A. and Al-Nimr, M.A., Performance investigation of a salt gradient solar pond coupled with desalination facility near the Dead Sea. Energy, 36(2), pp.922–931. 2011.

Shaffer, L.H., Viscosity stabilized solar ponds. In: de Winter, F. and Cox, E., eds. Pergamon, pp.1171–1175. doi:10.1016/B978-1-4832-8407-1.50230-0. 1978.

Shahid, M.I., Asim, M., Farhan, M., Sheikh, M.F., Ashraf, M.U., Arshad, H., Alghamdi, A., Alshahrani, A.S., Bahaddad, A.A. and Almarhabi, K.A., Design and performance analysis of salinity gradient solar pond under different climatic and soil conditions. PLOS ONE, 18(2), p.e0279311. 2023.

Subhakar, D. and Srinivasa Murthy, S., Saturated solar ponds: 1. Simulation procedure. Solar Energy, 50(3), pp.275–282. 1993. https://doi.org/10.1016/0038-092X(93)90021-F.

Tawalbeh, M., Javed, R.M.N., Al-Othman, A. and Almomani, F., Salinity gradient solar ponds hybrid systems for power generation and water desalination. Energy Conversion and Management, 289, p.117180. 2023.

Biography

Dr. Mira Chitt is an Associate Professor in Mechanical Engineering. She is the Head of Mechanical Engineering Department at Global College of Engineering and Technology (GCET), Muscat, Sultanate of Oman. She received her M.Sc. in Fluid Mechanics from Grenoble Alpes University, France and her Ph.D. in Mechanical Engineering from Paris-Saclay University, France in 2019. She joined GCET in 2021.Her research interests are in the area of Fluid mechanics, Heat Transfer, Management and Logistics. Dr Mira has published several research papers in peer-reviewed international journals and conference proceedings.