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Review Article

Salinity-gradient solar pond: History and progress review

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ABSTRACT

A salinity gradient solar pond (SGSP) is a large and deep artificial basin of layered brine, that collects and stores simultaneous solar energy for use in various applications. Experimental and theoretical studies have been launched to understand the thermal behavior of SGSPs, under different operating conditions. This article then traces the history of SGSPs, from their natural discovery to their current artificial applications and the progress of studies and research, according to their chronological sequence, in terms of determining their physical and dynamic aspects, their operation, management, and maintenance. It has extensively covered the theoretical and experimental studies, as well as the direct and laboratory applications of this technology, especially the most famous and influential in this field, classified according to the aspect covered by the study, with a comparison between the different results obtained. In addition, it highlighted the latest methods to improve the performance of an SGSP and facilitate its operation, such as the use of a magnetic field and the adoption of remote data acquisition, with the aim of expanding research and enhancing the benefit of this technology.

Keywords: solar pond; thermal energy; salt gradient, storage zone; non-convective zone; innovative technology

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1. Introduction

Solar energy, an abundant (about 800 W/m^2) and ubiquitous renewable energy, has potentially interested researchers due to the possibility of exploiting it by transforming it into electrical, thermal, chemical, etc. forms. But despite this characteristic, the drawback of expensive storage equipment did not allow it to eliminate fossil energy[1]. However, it has been found that SGSP can be a reasonable overall cost option, as it simultaneously collects and stores solar energy as sensible heat of saline water; and it features a time-independent operating system thanks to its built-in thermal energy storage[2,3].

Experimental, analytical, and numerical studies of solar ponds date back to Kalecsinsky, who was the first to detect a temperature of 70 °C at a depth of about 1.32 m in late summer, in the natural Medve Lake in Transylvania. While the minimum temperature, at the beginning of spring, was 26 °C. This phenomenon comes down to the presence of a salt gradient in the Medve Lake and was reported in other different regions[4–12].

In an ordinary lake or pond, water heated by the sun's rays rises and transfers its heat to the surrounding environment. In 1948, Block proposed the use of a salinity gradient by dissolving salt in the bottom of the pond to weigh down the lower layer and trap it at the bottom, thus inhibiting the phenomenon of convection. Therefore, 25% of solar rays reaching the bottom remain at the bottom, isolated by the salt gradient[2]. Thus, the SGSP, an artificial basin filled with brine whose concentration increases with depth, consists of three distinct thermal zones: a non-convective zone (NCZ) characterized by strong temperature and salinity gradients separating two convective zones, upper (UCZ) and lower (LCZ)[13]. The UCZ is the surface layer that contains the least dense cold brine. The bottom LCZ, also known as the heat storage zone (HSZ), contains the densest hot brine (almost saturated) representing thermal energy to benefit from it for multiple applications[14]. The temperature difference between these two zones can record 50–60 °C[3]. The performance of the SGSP is only verified by the separation of these two zones, by adding salt to LCZ and fresh water to UCZ, i.e., by maintaining the density profile[13,15].

2. Experimental and theoretical studies

The technology of artificial solar ponds was first mooted in 1954 on the Dead Sea. Australia then launched a solar pond project. In 1974, studies on innovative technology were launched at the Ohio State University, USA by Nielsen[12]. Zangrando established methods for installing 10 to 10,000 m^2 solar ponds[16]. Then, SGSPs were installed in different countries, such as India, Canada, Turkey, etc.[12].

Experimental and theoretical studies have been launched to understand the thermal behavior of SGSPs, under different operating conditions. Experimental investigations analyzed the SGSP thermal behavior[13,17–24]. Thus, many research studies have been conducted studies with a small scale, for better control[14,25–27]. These investigations make it possible to highlight the differences in performance between small-scale and large-scale SGSPs in order to predict performance in real conditions[28]. Apparently simple, SGSPs operate under a number of complicated physical phenomena. Many theoretical studies have evoked the phenomena of heat and salt diffusion to analyze the stability of solar ponds, and their performance, and predict temperature variations[12,18,29–35].

A key task in thermal performance modeling is to estimate the total incident solar radiation[36]. The oldest model of radiation flux estimation, dating from 1964, fitted a curve for transmission data from the Dead Sea and was based on Schmidt's calculation, guiding a mathematical formulation of the behavior of an SGSP. Many physical processes important for the stability of the NCZ (absorption of solar radiation by the brine, losses towards the surroundings, effect of double diffusion) were identified and analyzed[37]. This model was later followed by Dake and Harleman; and Akbarzadeh and Ahmadi[38,39]. A few other investigations included the studies of Viskanta and Toor; Tsilingiris; Kanayama and Baba; and Afeef and Mullet[40–45].

2.1. Thermal behavior studies

Eliseev et al. presented finite difference solutions for the temperature distribution in 10–80 cm deep SGSPs while neglecting the UCZ[46]. Four years later, Rabl and Nielsen divided the solar spectrum into 4 parts and also considered negligible UCZ with a finite LCZ thickness[47]. On the other hand, Bryant and Colbeck discussed the sunlight attenuation equation[48] and Kooi theoretically treated the SGSP as a flat plate collector and studied its thermal characteristics[49]. Later, Hull modeled the thermal performance of SGSP by dividing the spectrum into 40 parts[18] while Sodha et al. divided it into 5 parts[50].

In 1981, Kooi accounted for the reflectivity of the bottom of the pond, without the multiple bottom-surface reflections[51], Hawlader and Brinkworth assumed that 40% of the 0.6 mm wavelength radiation was completely absorbed in the first 6 cm of the pond, analyzed the effect of varying the LCZ thickness on the maximum temperature, and showed that the optimal values of the NCZ thickness range from 1 to 1.5 m[52], and Bansal and Kaushik analyzed the SGSP as a steady-state flat plate solar energy collector and investigated the optimization of its geometric and operational parameters[53].

Hull estimated the incoming radiation flux and multiple bottom-surface reflections using universal functions[54]. The Hull model was later used by Srinivasan and Guha and Sezai and Taşdemiroğlu[55,56], and then Husain et al. estimated the radiation flux by 2 simple formulations, reducing the computation time by 10 to 12 times compared to the Hull model[36]. Also in 1982, Lewis et al. used Mach-Zehnder interferometry to understand the physical mechanisms of an SGSP environment[57], and Isaac and Gupta discussed the effect of varying design, operational, and geo-climatic parameters on the SGSP steady state temperatures[58]. Wang and Akbarzadeh suggested that ground temperature beyond 5 m below the SGSP is equal to the annual mean ambient temperature and underground conditions have a strong influence on the SGSP thermal performance[59,60].

In 1984, an implicit finite difference model to solve the equations relating solar radiation input, diffusion, dispersion, and withdrawal of heat within the pond was used[37]. In parallel, Cengel and Ozisik developed an empirical formulation considering multiple reflections[61]. One year later, Beniwal et al. studied the heat losses of an insulated and non-insulated cylindrical flat-bottomed SGSP[62].

Ali presented a mathematical model of SGSP performance using a lumped parameter model of the three pond zones[63]. Ho-Ming et al. simplified the equations of the LCZ time-temperature variations[64]. Then, Ali showed that the SGSP temperature could reach the boiling point, in hot climate regions[65] and Muñoz et al. showed that the SGSP thermal behavior strongly depends on its layers thicknesses, in particular the NCZ[66]. Later, Al-Nimr presented closed-form expressions for the useful heat extraction rate and for the SGSP efficiency[67] and Al-Jamal and Khashan showed that thermal efficiency depends on the layer thicknesses and the heat extracted[68].

Tahat et al. studied the performance of a mini portable solar pond[69], Jaefarzadeh studied the thermal behavior of a small solar pond and reported an energy efficiency of 10%[23], Ramadan et al. studied the thermal performance of a shallow solar pond under an open-cycle mode of heat extraction[24], then Andrews and Akbarzadeh developed new relationships for heat extraction from the NCZ[70].

In 2006, Karakilcik et al. showed that the sunny area and LCZ temperature are very sensitive to wall shading and that the LCZ efficiency increases when the reflection, the areas shading in the NCZ and LCZ, and the bottom, sidewalls, and UCZ heat losses decrease[71]. Then a second study, investigated the temperature distributions in an isolated SGSP, during day and night[2]. Moreover, Karakilcik and Dincer studied the exergy performance of a 4 m^2 SGSP[72]. Then applications rolled on, so Sakhrieh and Al-Salaymeh studied the temperature distribution in a Jordanian-isolated SGSP and recorded a 47 °C LCZ temperature[73], and Bernard et al. modeled the performance of a pilot solar pond plant in Martorell, Spain, and a future pre-industrial SGSP in Granada, Spain[74].

In 2013, Date et al. compared the transient thermal performance of an SGSP with NCZ heat extraction alone, LCZ heat extraction alone, and combined LCZ and NCZ heat extraction[75], Karakilcik et al. studied SGSP performance with and without shading effect[76], and Dehghan et al. investigated the energy and exergy performance of two 3 m^2 prototype solar ponds, built in Bafgh, Iran, with square and circular cross-sections and demonstrated that the circular solar pond has superior thermal performance[77]. Bozkurt and Karakilcik studied the effect of sunny area ratios on the SGSP thermal efficiency[78]. Liu et al. showed that the temperature of a mini SGSP increases with time, roughly from its sunk day, and it will be stable in about 30 days[79].

In 2016, Sayer et al. presented a model to calculate the temperature in the three zones of an SGSP in Kuwait, which reached around 90 °C in July[80]. On the other hand, Monjezi and Campbell developed a transient model to predict brine temperature in any layer on an hourly basis, from the start of operation[81], and Alcaraz et al. defined energy efficiency as the ratio of the instantaneous energy change of the LCZ to the total amount of solar energy penetrating the pond surface during a defined period. It was dimensionally incorrect[82]. Then Aramesh et al. developed a model to predict the thermal behavior of a rectangular solar pond during the heat extraction process with less than 3% uncertainty[83], Njoku et al. studied the energy and exergy performance of an SGSP by incorporating the thermal extraction of the LCZ[84], Khalilian developed a model to analyze transient energy behavior in each pond area, incorporating many processes that affect performance[85], and Torkmahalleh et al. examined the performance of a small-scale circular SGSP built and operated at the Middle East Technical University, Cyprus[86]. Later, Khalilian et al. analyzed energetically and exegetically the SGSP transient thermal performance under different heat extraction modes[87], and Amigo et al. showed that when the water table below the pond is deep, the soil acts as an additional heat storage volume[88].

Alcaraz et al. exposed a 500 m^2 industrial solar pond in Granada, Spain, to snowfall, and showed that the LCZ temperature remained constant, the salinity gradient and the LCZ were not affected, and the weekly efficiency reached 10%[89]. Anagnostopoulos et al. developed a model to assess the heat loss to the environment, the irradiance absorbed by the pond, and the yearly thermal performance[90].

2.2. Stability and double-diffusivity studies

Many researchers have studied SGSP stability, such as Zangrando, Huppert and Moore, and Leshuk et al., who reported the stability of a potassium nitrate SGSP under a solar simulator[16,91,92].

Meyer et al. predicted the behavior of the interface between convective and non-convective zones[29,93]. Panahi et al. simulated the SGSP dynamic performance, using a finite element technique[94]. Akbarzadeh showed that sloping walls increase the concentration gradient at the NCZ bottom and decrease it at the top. However, this effect is weak in large ponds[95].

In 1985, Zangrando and Bertram showed that NCZ perturbations can lead to oscillations, i.e., to local mixing, and they specified a stability condition to prevent these oscillations[96]. Later, Akbarzadeh and Manins and Akbarzadeh studied at the laboratory scale the instabilities induced by sunlight absorption on the sun-facing wall[97,98]. Hull et al. introduced two models to explain the Nielsen equilibrium condition: the Hull and Mehta micro-convection model and the Witte thermal burst model[99]. Furthermore, Al-Jamal and Khashan developed a mathematical model to determine the various parameters affecting the performance of an SGSP under Irbid, Jordan meteorological conditions[100], then Giestas et al. studied the linear stability of the NCZ as a confined layer or an infinite extensive layer[101,102].

Jayaprakash and Perumal compared the density profile of an unstained SGSP with a 1D model[103]. Two years later, Kurt et al. modeled the NCZ as a series of flat layers, and the UCZ and LCZ as a single, homogeneous layer of fixed thickness[12]. Abdeljabbar and Safi studied the growth mechanisms of the lower mixed layer[104]. Jubran et al. studied the effects of wall inclination angle and salt concentration on convective layers[105].

In 2005, Angeli and Leonardi introduced the thermos-diffusion effect into the salt diffusion equation and solved numerically the 1D mathematical model[13]. One year later, Angeli et al. studied salt diffusion and heat extraction in solar ponds[106], Rebai et al. studied the linear stability of a 2D thermo-solutal system in the NCZ[107] and Mansour et al. studied the problem of transient heat and mass transfer and the long-term stability of an SGSP[108]. Then, Hammami et al. studied the transient natural convection in an enclosure[109]. Later, Giestas et al. developed a 2D model for SGSPs using Hammami et al. equations[110].

Suárez et al. represented the short- and medium-term functioning of the SGSP[111]. Choubani et al. analyzed transparent tank convection, specified the cause for which SGSPs had only 10–15 years of work, and proposed the use of a grid on the NCZ boundary[112].

Wang et al. used Giestas et al.'s formulation for linear and nonlinear stability studies[113]. In 2012, Boudhiaf et al. revealed that the buoyancy ratio is important in reducing the UCZ temperature and maintaining the LCZ temperature[114], Busquets et al. found that mass diffusion and convection in the LCZ accelerate the NCZ[115] and Husain et al. investigated the inclusion of an additional 50 mm salt-gradient zone between the NCZ and UCZ[116].

In 2014, Giestas et al. developed a comprehensive numerical model to simulate the SGSP dynamics[117], Boudhiaf and Baccar analyzed the complex velocity, temperature, and concentration distributions of the transient flow structure[118], and Suárez et al. compared temperature sensing observations from a small-scale SGSP experiment to numerical simulations of a full-scale SGSP[28]. El-Mansouri et al. developed a 2D numerical model to simulate a small-scale SGSP, which combines different physical phenomena[119]. Sayer et al. estimated the evolution of the convective zone concentrations over time in ponds with vertical and inclined walls, and of different volumes[120]. Furthermore, Sleiman et al. presented a simple 1D approach to the concentration distribution of NaCl in an SGSP[121].

In order to maintain the stable, long-term operation of an SGSP, it may be essential to suppress interface erosion. Thus, Tian et al. developed a 2D transient model using an external magnetic field to suppress the intense convection region, then improve its stability, delay the concentration homogenization, and improve the LCZ heat storage performance[122].

In the open literature, the circulation of heat was treated in a vertical direction only. For this reason, the modeling of SGSPs was one-dimensional in most investigations except for a few studies that dealt with the behavior of the SGSP in 2D and 3D[123–125].

By comparing the literature, we see that: (i) the SGSP performance is profoundly affected by the LCZ temperature, which increases with depth; unlike the amplitude of temperature fluctuations due to climate changes, which decreases with depth, since the SGSP is characterized by a large thermal storage capacity; (ii) to minimize these fluctuations, the LCZ thickness should be increased, leading to an intact temperature and salinity gradient regardless of climatic variations; (iii) a UCZ a few centimeters thick increases the amount of solar energy reaching the LCZ; (iv) the reduction of heat losses from the various walls of the pond and superficial zone, in particular by evaporation of the latter, increases the LCZ efficiency; (v) an increase in the perimeter of the pond will also increase its effectiveness; (vi) convective mixing has a strong impact on the SGSP stability, so it must be managed to maintain pond stability and isolate the NCZ; (vii) SGSP lifetime depends on the behavior of the gradient zone, in which instabilities occur and lead to destroyed linearity, thus leading to a mixed layer; (viii) NCZ thickness reduces upward heat loss; (ix) NCZ erosion is accelerated by mass diffusion and convection in the LCZ.

3. Operation, management, and performance enhancement studies

3.1. Salt criteria and establishment

Akbarzadeh and Macdonald proposed a protection system based on the natural circulation of water by density difference[126]. Kanayama et al. and Kho et al. analyzed the performance of sodium chloride SGSP[127,128]. Subhakar and Murthy studied the magnesium chloride and potassium nitrate SGSPs[129–131]. Banat et al. predicted the temperature and concentration profiles of a carnallite SGSP[132]. Pawar and Chapgaon compared two 1 m^2 urea SGSPs to NaCl and $MgCl_2$ ponds[25]. Alagao simulated a closed-cycle SGSP through three salt recycling modes[133]. Murthy and Pandey showed that muriate of potash, a potassium fertilizer, can generate energy more cheaply than urea[133,134]. Ouni et al. reported that a successful SGSP operation relies on NCZ maintenance, surface washing, and salt-stratification initial design[35]. Murthy and Pandey compared KCl, NaCl, and unsalted solar ponds[135]. Angeli and Leonardi simulated the transient behavior of SGSP with brine injection and analyzed the development of instability[37]. Agha et al. discussed the daily variations of brine concentration in the experimental Tajoura SGSP and those based on different designs under different scenarios[136]. Kurt et al. investigated the feasibility of sodium carbonate to suppress global convection inside a small-scale laboratory pond[27]. Valderrama et al. designed a diffuser to establish the salinity gradient, which increases the flow rate and completes the injection process with a recalculated Froude number of 11[137]. Bozkurt et al. analyzed an experimental 0.72 m^2 magnesium chloride SGSP[138]. Berkani et al. compared the thermal behavior of 3 different salts (NaCl, Na_2CO_3, and $CaCl_2$) with identical small SGSPs[1].

3.2. Turbidity and bottom reflectivity

Wang and Seyed-Yagoobi studied the water turbidity effect on the SGSP thermal performance[139]. Gasulla et al. and Malik et al. studied the maintenance of brine clarity in an SGSP[140,141]. Atiz et al. investigated the effect of turbidity on the SGSP exergy performance[142].

3.3. Erosion effect and liners

Li et al. examined the erosion phenomenon on the NCZ of a small-scale SGSP, under a solar simulator incident radiation[143,144]. Silva and Almanza analyzed the physical, chemical, and hydraulic properties of different soils as compacted clay liners[145].

3.4. Wind mixing and evaporation effects

Atkinson and Harleman developed a 1D mixed wind model for large-scale SGSPs and showed that wind effects can be managed by floating grids[30]. Jaefarzadeh and Akbarzadeh found that floating rings and continuous surface flushing can maintain a thin UCZ, introduced the salt charger as a salt replenishment system, and described the brine shrimp method to improve transparency[146]. Bézir et al. used 2 collapsible covers to reduce heat energy losses from the surface of an experimental 3.5 × 3.5 m^2 SGSP[147]. Ruskowitz et al. studied the suppression of evaporative losses with a continuous transparent cover and two transparent floating elements (discs and hemispheres)[148].

3.5. Geographical and meteorological conditions

Hawlader compared the performance of different latitudes operating SGSPs and showed that at higher latitudes (significant seasonal variations); SGSP must be deeper than a pond operating near the equator, so it acts as an inter-seasonal storage device[149].

3.6. Heat extraction

Sabetta et al. proposed an in-pond heat exchanger made of reinforced polyethylene pipe[150]. Jaefarzadeh studied heat extraction from a 4 m^2 SGSP, using in-pond heat exchangers with water as the working fluid[151]. Dah et al. evaluated a new method of heat extraction from the NCZ that improves the efficiency of a 0.64 m^2 SGSP[152]. Tundee et al. modeled SGSP heat extraction via thermosyphons[3]. Leblanc et al. introduced heat extraction from the NCZ of a small-scale solar pond and observed a 55% increase in efficiency compared to heat extraction from the LCZ[153]. Singh et al. showed that the combination of thermosiphon and thermoelectric cells allows the realization of a fully passive and simple power system[154]. Abdullah et al. designed a heat extraction system from a 113 m^2 solar pond at Umm Al-Qura University, Saudi Arabia, demonstrating the technical viability of SGSPs in the Middle East[155,156]. Ziapour et al. simulated a large-scale SGSP power plant using closed two-phase thermosyphons[157]. Ziapour et al. simulated an SGSP system combined with a thermoelectric generator, instead of an ORC condenser[158]. Khodabandeh et al. investigated the water graphene nanoplatelet/platinum hybrid nanofluid efficiency in a horizontal spiral tube with 4 cross-sections used at the bottom of SGSP[159]. Verma et al. found that extracting heat from the ground has significant effects on SGSP stability, entropy production, and NCZ thickness[160].

After presenting these studies, we can summarize that: (i) a successful SGSP requires a good first design of the establishment of the salt gradient to avoid instabilities, surface flushing, and temperature maintenance of the LCZ via brine injection at the bottom of the pond and heat extraction; (ii) water turbidity, caused by the growth of algal and microbial populations, dust, impurities, etc., has a crucial impact on the thermal performance of the SGSP, as it decreases the amount of solar radiation that reaches the bottom of the pond. Various treatments can improve water clarity, such as chemical treatments with a well-maintained pH (4.5) to prevent corrosion and, with the aim of maintaining low turbidity, the introduction of brine shrimp; (iii) clay soils are a well-cost option for SGSP liner; (iv) non-opaque floating rings and continuous covers reduce surface evaporation, as well as surface flushing; and (v) two proven methods of extracting heat from the LCZ: hot brine circulates through an external heat exchanger and heat transfer fluid circulates through an in-pond heat exchanger. Heat extraction from the NCZ also increases the overall energy efficiency of the SGSP. Heat extraction from NCZ and LCZ can also be effective.

3.7. Performance and efficiency

Various methods have been presented by many other researchers, such as Ibrahim and El-Reidy, Arulanantham et al., El-Sebaii, Tundee et al., Bozkurt and Karakilcik, to increase the temperature of the storage zone[161–165].

Jubran et al. investigated the effects of using a solar augmentation system on carnalite SGSPs[166]. Rivera et al. used single-stage and advanced absorption heat transformers to increase the temperature of heat obtained from solar ponds[167]. Aboul-Einein et al. used an external reflector to reflect additional solar radiation in the pond[168]. Akbarzadeh et al. examined the combination of a chimney with an SGSP[169]. Bozkurt and Karakilcik proposed the integration of a solar pond with flat solar collectors[170]. Al-Nimr and Al-Dafaie used nanofluids to improve the SGSP's thermal efficiency and storage capacity[171]. Wang et al. increased the LCZ temperature by adding coal cinder to its bottom[172]. Wang et al. used the cheap porous medium material of slag (coal combustion residues in the boiler) at the bottom of a small-scale SGSP[173]. Assari et al. have also investigated porous-medium solar ponds as a way to improve thermal performance[174,175]. Ganguly et al. limited the SGSP heat loss by using a flow controller with a temperature sensor[176]. Ganguly et al. transferred solar heat collected by evacuated tube solar collectors to the LCZ by circulating fluid from the LCZ, to improve its thermal performance[177]. Ganguly et al. suggested increasing the LCZ depth to increase thermal mass[178]. Ali et al. showed that the combination of photovoltaic/thermal collectors with an SGSP leads to an increase in thermal efficiency[179].

Simic and George reported remote data acquisition (DAQ) and then control of solar pond power generation. The SGSP control center could be located anywhere, while the pond sites are selected at the best solar locations[180].

4. Economic studies

Edesses et al. stated that SGSP is an economical device for generating low-temperature thermal energy. Its design depends on the site and the application. However, its total initial investment is strongly linked to the local availability and price of salt, since it takes between half and several tons of salt per square meter of SGSP. Subsequently, a NaCl pond may require 30–60% of that investment for the initial NaCl charge. Additionally, the economics of SGSPs include excavation and blackened coating costs[181].

Many studies also dealt with the SGSP economic aspect in different applications: Szacsvay et al. presented the technical and economic aspects of small-scale solar-pond-powered seawater desalination systems[182]. Agha analyzed the economics of a solar pond coupled low-temperature multi-stage desalination plant[183]. Parsa et al. conducted an economic analysis of an SGSP integrated with a low-temperature multi-effect desalination[184].

Cao et al. conducted a thermo-economic evaluation of a combined Kalina cycle and humidification-dehumidification desalination system integrated with SGSP[185].

An SGSP can provide industrial heat at a cost competitive with natural gas or coal. This was the case for a 23,240 m^2 SGSP, designed to preheat water used for washing copper cathodes in Sierra Gorda, Chile[186]. The use of heat from SGSP in power generation is economically less satisfactory because the cost of organic Rankine cycle production equipment is relatively high[187]. This economy can be improved by the design of large-scale SGSPs (more than 100,000 m^2).

5. Applications

5.1. Desalination

Many researchers have studied the use of SGSPs for water desalination, such as Garman and Muntasser, Agha, Liu et al., and Rahaoui et al.[183,188–190].

The University of Texas at El Paso studied SGSP technology from 1983 to 2003, and the El Paso Solar Pond was a long research, development, and demonstration project that improved the feasibility of SGSPs[115]. Since 1987, the project has focused on thermal desalination[191].

Saleh et al. studied an SGSP coupled to a Jordanian desalination plant[191]. Salata and Coppi demonstrated the possibility of producing desalinated water by taking advantage of solar energy stored in solar ponds and absorption heat transformer technology[192]. Suárez et al. and Nakoa et al. presented a coupled direct contact membrane distillation (DCMD)/SGSP system, for freshwater production and reducing the environmental footprint of brine[193–195].

5.2. Space/greenhouse heating and air conditioning

Rabl and Nielsen studied the use of SGSPs for space heating[47]. Shah et al. used an SGSP to provide heat to a greenhouse[196]. Brown and Cambel analyzed the energy of 3 different residential solar pond scenarios: a detached house, a 20-house complex, and a community system with district heating, in Ohio and Massachusetts[197]. Tsilingiris studied SGSP coupling to an absorption chiller[198,199]. Badran et al. studied an SGSP greenhouse heating system under Jordanian climatic conditions[22,200]. Jabri and Rasheed investigated the ability of SGSP to provide space heating for residential buildings[201]. Badran and Hamdan studied an under-floor heating system using solar collectors and solar ponds[202]. Kanan et al. showed that a 400 m^2 SGSP can provide cooling for a 125 m^2 house in Baghdad, Iraq[203]. Salata et al. and Saleh also applied SGSP stored energy for conditioning, via absorption chillers[204,205].

5.3. Salt production

In China, SGSP technology has been applied in aquaculture, Glauber's salt production, and lithium carbonate production from Zabuye salt lake. Nie et al. studied a natural brine solar pond in Tibet and showed that SGSPs can be used to produce minerals[206].

5.4. Power generation

Electricity generation satisfying an energy-efficient household electricity demand (2–5 kWh/day), from a few hundred square meters of SGSP, has been demonstrated since 1984[154]. The current total has been estimated at 160 GW[116]. Haj Khalil et al. analyzed a Rankine cycle using an environmentally friendly working fluid (refrigerant 134a) for electricity generation in Jordan[207]. Singh et al. and Ding et al. showed the possibility for thermoelectric generators (TEGs) to generate electricity via the stored heat of SGSPs[208–210]. Ding et al. explored the capability of SGSP in power generation, using a plate-type power generating unit (PTPGU)[211]. Kumar et al. proposed an inverse optimization method to predict the different dimensions of

SGSP zones feeding a thermoelectric generator[212].

5.5. Industrial process heating

Kumar and Kishore built a 6000 m^2 SGSP for an Indian dairy to provide process heat[213]. Andrews and Akbarzadeh also investigated the use of SGSP for industrial process heating[214]. Garrido and Vergara designed a 23,240 m^2 SGSP for preheating water used in washing copper cathodes in a mining operation in Sierra Gorda[186]. Zhang et al. tested a solar pond and an AD reactor system for the digestion of activated sludge waste[215]. Karakilcik et al. examined the hydrogen production performance of a reactor assisted by a solar pond[216].

6. Conclusion

In this paper, we presented a detailed review of the various stages that solar pond technology went through, starting with its discovery naturally, to its re-enactment in artificial ponds. In a sequential and detailed manner, we mentioned the various studies that dealt with their thermal behavior and stability, then studies that focused on their operation, management, performance enhancement, and economic savings, and later, their famous applications. Thus, this paper aims to highlight various studies related to solar ponds in an attempt to stimulate research into the hidden or neglected aspects of this technology and to work on developing and benefiting from them in light of the accumulated environmental crises and the effectiveness of SGSPs at this level. Further research should focus on methods to extend the lifetime of SGSPs, develop the idea of operating ponds remotely, and improve their economic outputs.

Conflict of interest

The authors declare no conflict of interest.

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