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Perspective

Large-scale solar-thermal desalination

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SUMMARY

Solar-thermal desalination technologies could provide a sustainable path toward achieving high-volume (millions of gallons per day) desalted water in remote and inland regions. Yet, efficient integration between solar capture and desalination remains a critical challenge. Integration challenges are accentuated when exploring solar-thermal technologies such as concentrating solar, due to the temperature mismatch, which often exists between solar capture and conversion technologies and desalination technologies. Here, we highlight the potential opportunities for large-scale solar-thermal desalination plants. We also identify the critical metrics of success that are necessary for large-scale solar-thermal desalination plants. Furthermore, we evaluate and detail how performance and cost can be agumented through hybridizing desalination systems by using exergy cascade utilization principals.

INTRODUCTION

Water scarcity as a result of drought, overuse, and climate change affects nearly 20% of the world's population.[1] This water scarcity has resulted in a need for widespread adoption of desalination systems. By 2050, the supply of desalinated water could increase to 192 $\times$ 10^6 m^3/day to accommodate growth in population and water demand.[2] Today, nearly all (~99%) desalination plants rely on fossil fuels as the primary energy source for the production of heat or electricity.[3] If this trend continues, carbon emissions from fossil-fuel-powered desalination plants could increase to 400 million tons of CO_2 per year by 2050.[3] The waste brine produced at desalination plants is also projected to increase to 240 km^3 per year by 2050 (half the volume of Lake Erie).[3] This prompts a strong need to explore strategies for developing renewable-energy-driven desalination plants with reduced waste (CO_2 and brine) production.

Coastal regions might be able to meet these needs using seawater reverse-osmosis-based plants driven by grid available renewable electricity (photovoltaics, wind, hydro, or nuclear). Here, waste disposal should be minimized; however, disposal is easier due to the plants' proximity to the ocean. Inland desalination plants in remote regions will face greater challenges with less access to grid-scale renewable electricity.[4,5] Large-scale disposal of waste brine is also geographically limited to regions with deep well injection sites.[6] The water source variability (brackish to hypersaline) also complicates the selection of the desalination technology. Although reverse osmosis is emerging as the obvious choice for seawater desalination, treating high-salinity streams with high recovery ratios will require some degree of thermal separation.[5] For these requirements, solar-thermal desalination with low-cost thermal energy storage might provide avenues for continuous off-grid renewable-powered desalination.

Here, we provide insight into critical energetic, economic, and environmental performance metrics for solar-thermal desalination systems. We highlight the chief

Context & scale

Most of the world uses groundwater as the main source of water for domestic, agriculture, and industrial use. Increasing droughts indicate that regional inland aquifers and rivers will not be able to continue to meet these water demands in the coming decades. With 67% of the global population located away from coastal regions, there is a growing need for inland desalination plants, which treat brackish or wastewater (industrial or municipal) to fill this deficit. Current desalination plants driven by fossil-based energy sources will likely produce water with high economic cost and carbon emissions. In addition, desalination plants designed without a plan for waste (brine) disposal and minimization will not provide a sustainable long-term solution for these communities. Solar-thermal-driven desalination technologies might aid in alleviating many of these social, energy, and economic challenges through minimizing the carbon footprint of desalination plants. Solar-thermal-driven desalination technologies also provide a platform capable of attaining zero-liquid discharge.

bottlenecks and opportunities needed to improve these technologies and emphasize the importance of the exergy cascade utilization principle. Finally, we explore the role water production volume will play on cost and sustainability.

CRITICAL METRICS FOR THERMAL DESALINATION

Thermal desalination technologies rely on phase-change to separate salt from water. This process is inherently energy intensive, resulting in low energy efficiency.[5] The second law efficiency is the critical metric used within the field of desalination to indicate how close a technology is to the minimum least energy as defined by Gibbs free energy[7,8]

$$\eta_{II} = \frac{\Delta G}{\dot{W}_{sep} + \dot{Q}_H\left(1 - \frac{T_0}{T_H}\right)} = \frac{\left(g_p - g_b\right) - \frac{1}{rr}\left(g_f - g_b\right)}{\dot{W}_{sep} + \dot{Q}_H\left(1 - \frac{T_0}{T_H}\right)}, \quad \text{(Equation 1)}$$

where ΔG is the total Gibbs free energy difference between the inlet and outlet fluids, g represents the specific Gibbs energy, and rr is the recovery ratio defined as the ratio between produced water and feed water ($\dot{m}_p/\dot{m}_f$). The subscripts p, f, and b denote the produced water, saline feed water, and effluent concentrated brine, respectively. $\dot{W}_{sep}$ is the power consumed by the separation process (pumping, compression, or direct electricity, depending on the desalination process), and $\dot{Q}_H\left(1 - \frac{T_0}{T_H}\right)$ is the exergy of the heat consumed during the separation process with respect to the ambient temperature (T_0) and heat source temperature (T_H). The use of exergy-based metrics such as second law efficiency, allow one to compare desalination systems independent of the energy required (electricity or heat). The expected second law efficiency for a thermal desalination technology (assuming zero electricity consumption) operating in the range of typical stand-alone multi-effect distillation (MED) technology, requiring between 50 and 67 kWh/m^3 of specific thermal energy, ranges from 7% to 9% for seawater (35 g/kg) when using steam at 100°C.[7] To put this into context, the expected second law efficiency for electricity-driven reverse osmosis (non-thermal) technology is between 10% and 20% for seawater, and the specific energy consumption ranges from 2.5 to 5 kWh/m^3 depending on the system configuration (i.e., energy recovery).[7] Thus, closing the efficiency gap between thermal- and pressure-driven separations, will require thermal desalination technologies make use of high-temperature energy sources (Equation 1). Indirectly using high-temperature heat sources, such as the waste heat from high-temperature power cycles, can also increase the second law efficiency of the overall system (i.e., power block + thermal desalination unit).

In addition to the second law efficiency, the gained output ratio (GOR):

$$GOR = \frac{\dot{m}_p h_{fg}}{\dot{Q}_{desal,in}}, \quad \text{(Equation 2)}$$

which is the ratio between the latent heat of the produced freshwater (h_{fg}) and the input thermal energy ($\dot{Q}_{desal,in}$) is an important performance metric.[9] The GOR measures how many times the latent heat is captured in condensation and reused in a subsequent evaporation process at lower operating pressures and boiling temperatures.[7] A plant GOR is typically between 6 and 9 for a commercial stand-alone multi-stage flash (MSF) system and between 10 and 13 for a MED system.[7] Strategies to improve the thermodynamic efficiency and GOR of thermal desalination plants center on re-utilization of latent heat within the system. The use of multi-effects (or stages) is one approach used to reuse waste heat from a separation

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process in a new sub-process. Each sequential stage has a minimum temperature difference to maximize the thermodynamic efficiency and GOR while increasing the heat transfer. However, there are also practical limitations associated with increasing the number of system components and stages, which constrain the maximum attainable GOR and thermodynamic efficiency. Adding more effects increases the cost of the system but also decreases the temperature difference between each stage, which is the main driving force in these systems.

Conventional thermal desalination systems (MED, MSF, humidification-dehumidification) also require energy in the form of electricity for compression and pumping. This results in a further reduction in the maximum second law efficiency to less than 7%.[7] Thus, to compare the capacity of thermal desalination technologies, it is necessary to account for both forms of energy (electricity and heat) because of the differences in the quality of the energy source.[8] Second law efficiency and the universal performance ratio (UPR) proposed in recent years[10] are metrics that allow comparison between technologies considering the quality of the energy source. However, both require a detailed exergy analysis to convert thermal energy consumption into equivalent work.[8] Because of the lack of reported data for heat source temperature in open literature, it is necessary to account for an equivalent conversion of thermal energy into electricity when Carnot efficiency cannot be estimated. In these cases, we propose an adapted form of the UPR called equivalent universal performance ratio (UPRequiv), which considers the reference latent heat of evaporation and specific equivalent electricity consumption as follows

$$UPR_{equiv} = \frac{h_{ref}}{CF_{kJ,kWh} SEC_{equiv}}, \quad \text{(Equation 3)}$$

where h_{ref} is a constant benchmark value representing the specific enthalpy of evaporation at 73° (2,326 kJ/kg), $CF_{kJ,kWh}$ is a conversion factor for kJ/kg to kWh/m^3 equal to 3.6. SEC_{equiv}, the specific equivalent electricity consumption of the desalination system in kWh/m^3, is defined as

$$SEC_{equiv} = SEEC + STEC \times \eta_{cdt}, \quad \text{(Equation 4)}$$

where specific electric energy consumption (SEEC) (k_{Whelec}/m^3) and specific thermal energy consumption (STEC) (kWh/m^3) are the specific electricity and thermal energy consumption, and η_{cdt} is the average electricity generation, distribution, and transmission efficiency (33% in the United States) used for obtaining the electrical equivalent of thermal energy.[11] A high UPR_{equiv} indicates an improved performance. UPR_{equiv} represents an alternative for comparing technologies, but it lacks precision when comparing systems driven by different primary energy sources.[8] However, to the authors' knowledge, there is a lack of a solid universal metric allowing comparison of desalination systems when driven by different primary energy sources, especially when considering renewable energy sources.

GOR is inversely proportional to STEC and function of latent heat of evaporation (h_{ref}). Therefore, the limitations outlined for GOR also constrain the UPR_{equiv}. With the rapid pace of renewable thermal energy, these chief considerations associated with traditional thermal desalination systems (high thermodynamic efficiency, GOR, and UPR_{equiv}) are less likely to solely guide decision makers. This is because with solar-thermal desalination systems, heat is produced through renewable energy rather than fossil fuels. Thus, the value proposition of the lost energy is less significant. Later, we highlight alternative metrics that might drive decision makers.

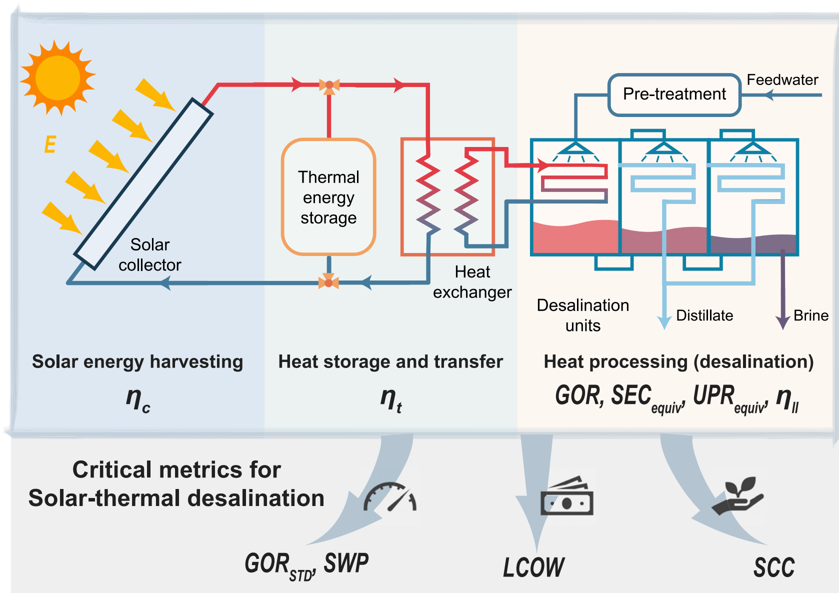

Figure 1. Critical system metrics to evaluate the energy, economic, and social benefits of solar-thermal desalination systems

CRITICAL METRICS FOR SOLAR-THERMAL DESALINATION

Solar-thermal desalination technologies rely on the capture of solar radiation to drive water phase-change to separate salt from water. Efficient capture and conversion of thermal energy is still important for solar-thermal desalination, as inefficient use will increase footprint and capital cost. Thus, decreasing the energy consumption to reduce the capital investment is critical to enable widespread adoption of solar-thermal desalination systems and technologies. The GOR of solar-thermal desalination (GOR_{STD}) is defined as the ratio of the latent heat of produced water to the input solar energy ($\dot{Q}_{c,in}$). Fundamentally, GOR_{STD} is a function of the thermal efficiency of the solar collector (η_c), the heat transfer efficiency (η_t) from collector to desalination systems (η_t is 1 for direct solar-thermal desalination technologies such as solar still and photothermal membrane distillation), and the GOR (Figure 1).

$$GOR_{STD} = \frac{\dot{m}_p h_{fg}}{\dot{Q}_{c,in}} = \eta_c \eta_t \frac{\dot{m}_p h_{fg}}{\dot{Q}_{desal,in}} = \eta_c \eta_t GOR. \quad \text{(Equation 5)}$$

For solar-thermal desalination, GOR takes into account all of the thermal energy entering the desalination device,[8] whereas GOR_{STD} is the metric evaluating the solar energy input. Although the efficiencies of the solar collector and collector-to-desalination heat transfer efficiency are always less than one, deploying a well-designed multi-stage desalination system with latent heat recovery might increase GOR to greater than 10.[11]

The specific water productivity (SWP),[12] defined as the mass of water produced per solar radiation area per time, is a key solar-to-water metric for measuring the overall performance of a solar-thermal desalination system in experiments. SWP is useful for making techno-economic considerations because it combines both the environmental factor (solar radiation) and overall system performance.

$$SWP = \frac{E}{h_{fg}} GOR_{STD} = \frac{E}{h_{fg}} \eta_c \eta_t GOR, \quad \text{(Equation 6)}$$

where E is the solar irradiance (kW/m^2), h_{fg} is the latent heat of evaporation, η_c is the efficiency of solar collector system for converting solar energy into thermal, and η_t is the heat transfer efficiency for evaporating water by using thermal energy. SWP compares how efficiently solar radiation is used to produce freshwater. When this metric cannot be measured or calculated, the UPR_{equiv} is suitable as an alternative. However, as mentioned earlier, UPR_{equiv} cannot be used as a sole comparison tool, but as a complement for a detailed analysis, because it lacks precision when considering different energy sources.

A techno-economic evaluation of solar-thermal desalination is most closely tied to the solar field capital cost and plant economic performance. The levelized cost of water (LCOW) in the unit of $\$/m^3$ evaluates the cost of each cubic meter of produced water over the entire life. This is a suitable economic measure that can be easily compared with other desalination technologies (Figure 1). LCOW is expressed as the ratio of the total annualized cost of the solar desalination system over the annual freshwater production. The total annualized cost considers capital, operation and maintenance ($C_{O\&M}$), and fuel (C_{fuel}) annualized costs, and the latter considers electrical and thermal energy consumption cost.[13] The annual freshwater production depends on the capacity factor of the plant and the nominal water production.

$$LCOW = \frac{CRF \times CC + C_{O\&M} + C_{fuel}}{CF_{STD} V_{STD}}, \quad \text{(Equation 7)}$$

$$CRF = \frac{k_d (1 + k_d)^{yrs}}{(1 + k_d)^{yrs} - 1}, \quad \text{(Equation 8)}$$

where CRF is the capital recovery factor applied for annualizing in equal parts the total capital cost (CC) expenditures of the system, with the discount rate (k_d) and the lifetime of the system (years).[14] The use of solar energy reduces fuel costs (C_{fuel}) to even zero for systems without fossil backup[15]; yet, solar-driven desalination systems traditionally have higher CCs, which more strongly influences the LCOW.[16] CF_{STD} is the capacity factor of the solar desalination plant defined as the ratio between the current annual production and the nominal freshwater production (V_{STD}). Thermal energy storage enables a larger capacity factor for solar-thermal desalination while maintaining the capacity cost of the desalination sub-system. Meanwhile, as the solar collector size increases for a larger amount of water production, the unit capital cost (per energy capacity) decreases.[17] Therefore, deploying low-cost thermal energy storage can reduce the LCOW (Equation 7).

It is important to take environmental implications and social costs into account as indicators for solar-thermal desalination systems. This is accomplished through estimation of CO_2 emission abatement, defined as the difference between carbon emissions of a solar-thermal desalination system with the hypothetical same system operated with fossil fuels.

CO_2 emission abatement benefits population through the reduction of carbon levels in the air. The social cost of carbon (SCC) represents the long-term damage of emitting one additional ton of CO_2 and has been quantified to be 42 \$/tonCO_2 (Figure 1).[18] By multiplying the CO_2 emission abatement by the SCC, the social economic benefit per cubic meter of freshwater produced can be added into the techno-economic model. Thus, a full evaluation of a solar-thermal desalination system must evaluate not only the system performance (GOR_{STD}, SWP, and UPR_{equiv}) but also the technoeconomics (LCOW) and environmental benefits (CO_2 emission abatement and social benefit).

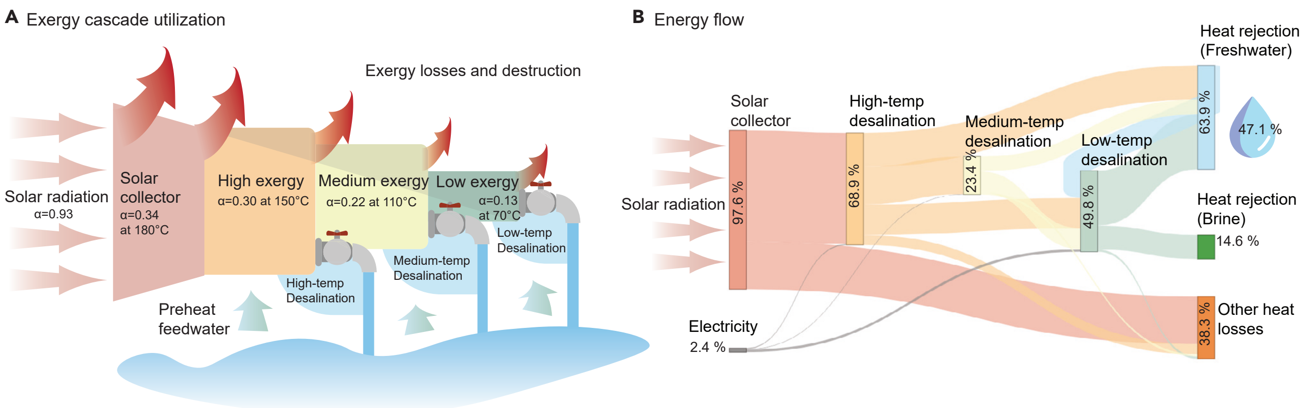

Figure 2. Exergy and energy flow through a solar hybrid desalination system consistingof high (150°C), medium (110°C), and low (70°C) temperature desalination technologies

(A) Exergy.

(B) Energy.

APPROACHES TO OVERCOME CHIEF LIMITATIONS

Concentrated solar (CS) technologies produce high-quality thermal energy above 200°C by adopting a series of reflective surfaces to redirect a solar beam onto tubular (e.g., compound parabolic concentrator, linear Fresnel reflector, and parabolic through concentrator) or focal point absorbers (e.g., parabolic dish and solar tower).[19] However, the state-of-the-art thermal desalination technologies operate at a much lower temperature range (e.g., 70°C of MED and 110°C of multi-stage flash[20]) to avoid the soft scale components (such as magnesium, calcium, and sulfate ions) from degrading the system. Thus, direct integration of high-quality heat sources from CS technologies with a low-temperature desalination system result in substantial exergy losses.[21] The solar-thermal desalination technologies operating within restricted temperature range exhibit low energy performance (GOR_{STD}) due to insufficient latent heat recovery, and the thermodynamic and economic challenges are exacerbated. Finally, coupling a thermal desalination plant with a solar system introduces additional losses (η_c and η_t) in the solar collector and the heat transfer process (Equation 5).

Exergy cascade utilization approach plays a significant role in engineering next-generation CS desalination systems that overcome these known thermal and economic limitations. Exergy cascade utilization enables an effective integration of low-temperature thermal desalination systems with high-temperature CS collectors by cascading and distributing the harvested high-quality thermal energy to thermal applications at varied temperature ranges (Figure 2A). Exergy cascade utilization for integrating high-temperature CS technologies with desalination systems can be mainly categorized into (1) electricity + heat, (2) heat + heat, and (3) boosting stage/effect-level exergy cascade utilization with pretreatment according to the purposes of the cascaded energy applications at varied temperature ranges (Figure 3).

Electricity + heat

A concentrated solar power (CSP) cogeneration plant, which produces electricity and waste heat, is a system-level exergy cascade utilization approach that avoids large exergy losses associated with CS desalination systems.[22–24] This electricity + heat exergy cascade is especially applicable for the high concentration ratio CS technologies (e.g., solar tower), which efficiently produce electricity (Figure 3). The

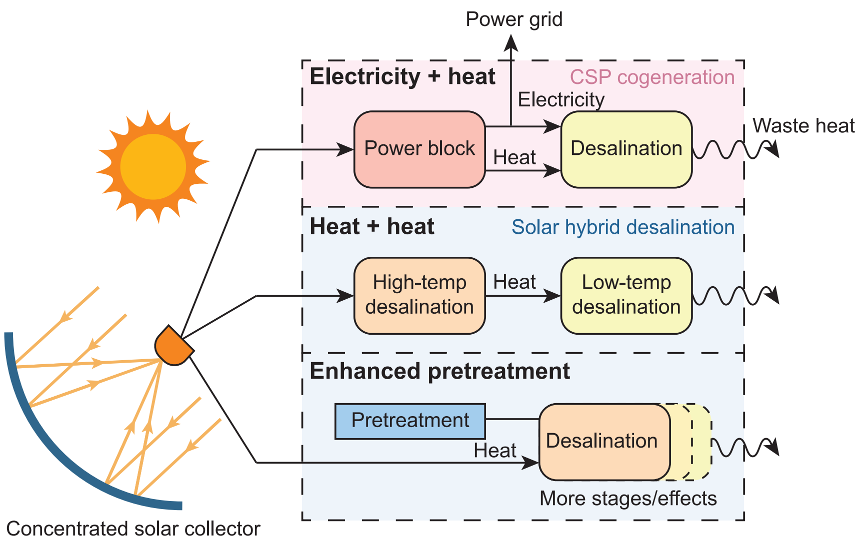

Figure 3. Achieving effective exergy cascade utilization in solar-thermal desalination systems occurs through simultatneously producing electricity (power) + heat, heat (heating) + heat, or through novel enhanced pretreatment processes

low-temperature waste heat from the power cycle drives the desalination system with the matching energy quality requirement. The CSP cogeneration plant benefits from the perspectives of economy and synergy. The integrated low-temperature desalination system might replace the cooling condenser (accounts for approximately 3% of plant investment cost[25]) of the CSP power plant and the desalination system shares the CC of the solar field with the power block. Furthermore, in such a system, the desalination system produces the freshwater to meet the power block water demand onsite, and the power block can effectively deliver electricity to desalination auxiliary components (pumps and control system).

The CSP cogeneration scheme does not necessarily improve the energy-related performance metrics associated with the desalination system (GOR, SWP, and UPR_{equiv}). However, the high production volumes allow for improvements in economic-related performance metrics (LCOW). There is a growing number of studies that have examined various power cycles (e.g., Rankine cycle sCO_2 Brayton cycle,[26,27] steam Rankine cycle,[28] and regenerative Rankine cycle[29]) and the integration points of low-temperature desalination[30] for enhancing overall thermal-economic performance of CSP cogeneration plant. Other than cogeneration plant (electricity + desalination), the electricity + heat exergy cascade utilization approach can also be deployed for freshwater production. The power produced by high-temperature CS technologies might drive desalination systems that consume electricity (e.g., reverse osmosis[24] and mechanical vapor compression[31]). The power can also drive heat pumps to raise the energy quality of waste heat or ambient so as to match the operating temperature of thermal desalination process.[21,32]

Heat + heat

The high-temperature CS technologies (>600°C) require costly high-accuracy reflector tracking systems and more complex (e.g., molten salt) pipeline designs for reducing optical losses and maintaining continuous operation.[33] Therefore, it is worth exploring the solar desalination design schemes for CS systems with a lower operating temperature range (<300°C), which produce electricity less efficiently.

The CS technologies might cascade the collected heat to multiple thermal desalination systems (i.e., heat + heat hybrid desalination) (Figure 2A). In this work, hybrid refers to systems that take advantage of the exergy cascade utilization principle combining multiple desalination or water treatment (i.e., enhanced pretreatment) technologies. The hybridization scheme expands the operating temperature range of the desalination system by combining different desalination technologies on the basis of the high operational temperature (Figure 3), increasing the level of latent heat recovery, and making use of high-temperature energy sources from CS technologies.

The exergy flow within the heat + heat hybridization scheme (Figure 2A) illustrates the exergy cascade utilization principle. Losses and destruction occur as the exergy flow from solar radiation (exergy factor α of ~ 0.93[34]) crossing the solar system and temperature-cascade desalination sub-systems (exergy factor defined by Carnot efficiency[34]). Each desalination sub-system utilizes energy according to its energy quality requirement (temperature boundary conditions). In principle, high-grade energy from a CS collector can be integrated with a high-temperature desalination unit, and waste heat from that unit can be recovered to initiate rapid vaporization in a low-temperature desalination sub-system (Figure 2B). Furthermore, the sensible heat of produced freshwater can be recycled to preheat the feedwater.

Boosting stage/effect-level exergy cascade utilization with pretreatment

Hybridizing pretreatment prior to thermal desalination systems can also extend the operating temperature window (Figure 3). Pretreatment methods can remove mineral components, alleviating the scaling formation in the concentrated brine at high temperatures.[35] The higher top brine temperature (temperature of the preheated feedwater entering the first stage) of the desalination systems can improve the stage/effect-level exergy cascade utilization (i.e., more latent heat recuperation times) and utilize higher quality thermal energy from CS technologies. Hybridizing nanofiltration (NF) into MED as a pretreatment method can extend the top brine temperature from 65°C to 125°C, enabling more number of effects for recovering latent heat.[3] A lab-scale solar-NF-MSF demonstrate water production rates nearing 1 m^3/day and a GOR of 15. These values are nearly double of the state-of-the-art MSF systems.[36] The exergy cascade utilization design method makes use of high-temperature CS technologies, fully utilizes varying quality energy, and increases the latent heat recovery and recovery ratio. The three approaches mentioned earlier can collaborate to further improve water production volume and cope with dynamic water and power demands. Despite the promise of exergy cascade utilization design principles, there are only a limited number of theoretical and experimental studies (especially for heat + heat approach) that apply these principles to solar desalination.[37]

CURRENT STATE OF SOLAR-THERMAL HYBRID SYSTEMS

We evaluated the current state of solar-thermal hybrid systems on the basis of LCOW, UPR, carbon emissions, and SCC through a literature review and compared solar-thermal hybrid systems with non-hybrid desalination technologies. Non-hybrid refers to a sole thermal desalination technology driven by solar energy, whereas hybrid refers to the same thermal desalination technology operating in combination with other desalination or water technologies. Reported production values range from very small demonstrations to large scale (Figure 4). Very small systems produce less than 1 m^3/day (suitable for lab scale, pilots, or a family use), small-scale plants produce less than 10 m^3/day (suitable for small villages), medium scale plants

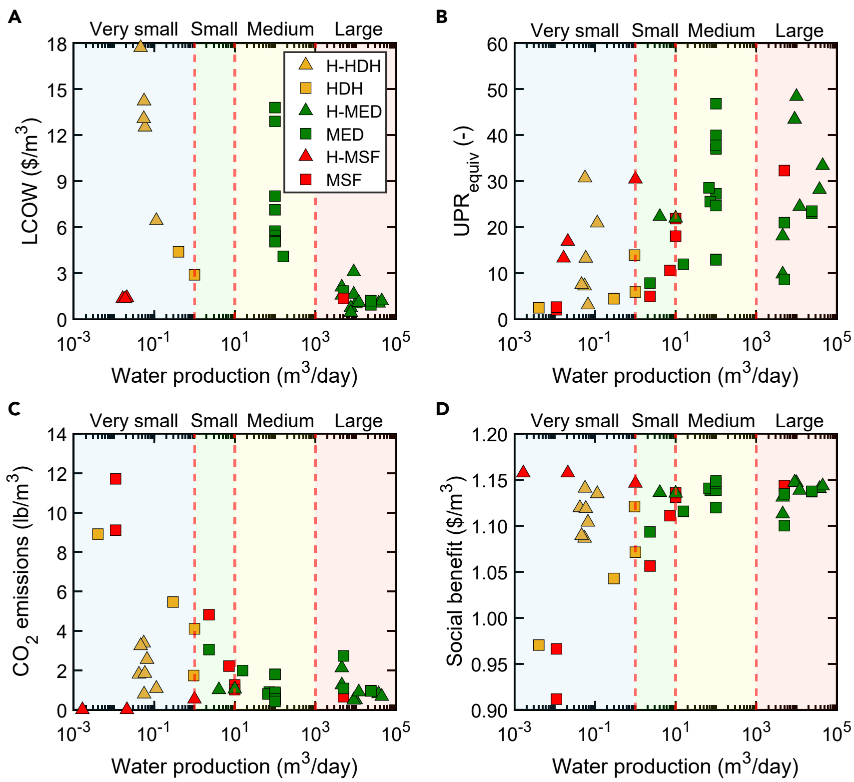

Figure 4. A performance comparison between solar-driven thermal desalination systems operating in a hybrid (prefix H) and non-hybrid manner (Table 1).

(A–D) LCOW (A), universal performance ratio equivalent (UPR_{equiv}) (B), carbon emissions associated with thermal energy consumption (C), and social benefit from CO_2 emissions abatement (D). The thermal desalination technologies considered were humidification-dehumidification (HDH), multi-effect distillation (MED), and multi-stage flash (MSF).[37–39] We assume low energy intensity values for current typical desalination[11] when electricity consumption is not reported in the literature (1.5 kWh_{elect}/m^3 for MED, 2.5 kWh_{elect}/m^3 for MSF, 0.09–0.4 kWh_{elect}/m^3).[11,42,74]

produce less than 1,000 m^3/day (suitable for towns or villages), and large-scale plants produce more than 1,000 m^3/day (suitable for municipal applications).[38] The economic benefit of solar-thermal desalination systems depends on the desalination technology (hybrid or non-hybrid) and the plant capacity. There is greater benefit for solar hybrid desalination at large-scale systems (≥1,000 m^3/day).[37–39] At this scale, theoretical studies on solar hybridized MED-based plants suggest that the LCOW might range from 3.09 to 0.45 $/$m^3$. This is a lower LCOW than non-hybrid solar-MED systems (Figure 4A)[38] and fossil-fueled MED systems (0.52–1.5 $/$m^3$ for MED).[11] The hybrid system with the lowest LCOW reported is a CSP cogeneration system producing power with high-quality energy to drive a reverse osmosis (RO) and releasing low-quality waste heat to drive a hybrid MED-thermal vapor compression (TVC). The TVC enables the sensible heat recovery from the produced steam, acting as a high-temperature heat source for the MED system at a lower energy consumption.[31] This multi-system hybrid plant (combining electricity + heat and heat + heat approaches) produces 7,600 m^3/day at a cost of 0.45 $/$m^3$.[40]

For very small-scale capacity (≤1 m^3/day), a humidification-dehumidification (HDH) system (yellow points on Figure 4A) achieves a LCOW reduction as production increases without accountable benefit for hybridization. The hybrid method (integrated with single water flash[41] or solar still[42]) is not able to increase water production enough to

Table 1. Summary of solar hybrid desalination systems

Main desalination technology	Hybridization possibilities	Solar integration	TBT (°C)	BBT (°C)	Production ($\frac{m^3}{day}$)	Cost of water ($\frac{\$}{m^3}$)	GOR	SEEC ($\frac{kWh}{m^3}$)	STEC ($\frac{kWh}{m^3}$)	CO_2 ($\frac{lb_{CO2}}{m^3}$)	Ref
MED	AD	collector	60	10	10	–	–	1.63	84.13	1.05	Son et al.[65]
MED	MVC	CSP	46.8–57.28	–	4,545	2.10	3.8	9.68	169.87	2.13	Sharaf et al.[31]
MED	TVC	PTC	46.9–57.53	–	4,545	1.57	6.4	2.44	100.76	1.26	Sharaf et al.[31]
MED	TVC	CSP	–	–	10,000	1.00	16.0	1.50	40.56	0.51	Kouta et al.[44,66]
MED	TVC	CSP	–	–	37,336[a]	1.05	10.0	1.50	64.89	0.81	Palenzuela et al.[67]
MED	TVC	CSP	–	–	44,672[a]	1.20	12.0	1.50	54.07	0.68	Palenzuela et al.[67]
MED	TVC	CSP	70	35	7,600	0.75	–	1.20	–	–	Weiner, et al.[40]
MED	TVC	SLF	62	37	9,000	1.63	16.7	1.50	38.86	0.49	Askari and Ameri[45]
MED	TVC	SLF	62	37	9,000	3.09	16.7	1.50	38.86	0.49	Askari and Ameri[45]
MED	TVC	SLF	65	38	4	–	8.3	2.10	81.30	1.02	Alhaj and Al-Ghamdi[68]
MED	TVC-RO	CSP	70	35	7,600	0.45	–	1.20	–	–	Weiner, et al.[40]
MED	RO	CSP	70	38	12,012	1.10	9.0	–	72.29	0.90	Iaquaniello et al.[24]
HDH	WF	Solar collector	70	–	0.042	–	4.5	–	144.20	1.80	Kabeel and El-Said[69]
HDH	WF	Solar collector	–	–	0.113	6.43	7.5	2.32	86.52	1.08	El-Said et al.[70]
HDH	WF	Solar collector	–	–	0.059	12.53	4.4	0.03	147.47	1.85	Kabeel and El-Said[41]
HDH	WF	Solar collector	–	–	0.055	13.08	2.4	0.03	270.37	3.38	Kabeel and El-Said[41]
HDH	WF	Solar collector	–	–	0.046	17.71	2.5	0.04	259.56	3.25	Kabeel and El-Said[41]
HDH	WF	Solar collector	–	–	0.056	14.23	10.2	0.04	63.62	0.80	Kabeel and El-Said[41]
HDH	stills	evacuated heater	87	65	0.066	34	3.2	140.00	204.05	2.55	Sharshir et al.[42]
MD	stills	solar still	55	23	0.010[b]	–	–	–	–	–	Banat et al.[71]
MD	AD	collector	80	32	4.100	–	–	–	–	–	Kim et al.[72]
MSF	RO	PV	<100	45	0.017–0.021[b]	1.35		0.95	0.36	0.005	Heidary et al.[73]
MSF	RO	PV-collector	74	50	0.019[b]	1.35	–	–	–	–	Heidary et al.[43]
MSF	NF	PTC	100	–	1.000	–	15.0	7.00	43.26	0.54	Mabrouk and Fath[36]

Abbreviations are as follows: TBT, top brine temperature; BBT, bottom brine temperature; GOR, gain output ratio; SEEC, specific electric energy consumption; STEC, specific thermal energy consumption; CO_2, carbon emissions; MED, multi-effect distillation; HDH, humidification-dehumidification; MD, membrane distillation; MSF, multi-stage flash; AD, adsorption; MVC, mechanical vapor compression; TVC, thermal vapor compression; RO, reverse osmosis; WF, water flashing; NF, nanofiltration; CSP, concentrated solar power; PTC, parabolic trough collector; SLF, solar linear Fresnel; PV, photovoltaic panel array.

[a]Averaged value from three different configurations.

[b]Daily production estimated assuming 7.5 h of operation per day.

decrease LCOW when compared with non-hybrid solar HDH systems (Figure 4A). Solar hybrid MSF systems achieve an LCOW comparable with a theoretical model for solar non-hybrid MSF, but on a much smaller scale. These experimental systems combine MSF with RO (electricity + heat approach)[43] and offer promising results that have potential economic benefits for modularization of solar desalination.

The system configuration, capacity, and specific electricity and thermal energy consumption (SEEC and STEC) all affect the UPR_{equiv} (Figure 4B). There is a slight increase in UPR_{equiv} with the plant size. At a large scale and assuming a low SEEC consumption of 1.5 kWh_{elect}/m^3,[3,11] CS-MED hybridized with a TVC sub-system (heat + heat approach) can achieve a higher UPR_{equiv} compared with non-hybrid MED systems.[44,45] Although the use of hybrid HDH or MSF systems do not noticeably decrease LCOW compared with their non-hybrid counterparts in low scale systems (Figure 4A), their UPR_{equiv} values reach approximately 30, which are higher than any other non-hybrid solar-thermal system (Figure 4B).

The high UPR_{equiv} and water production rate of CS hybrid MEDs reduces carbon emissions. A solar hybrid HDH system has higher opportunities with low CO_2 emissions, comparable with hybrid MED because of the low electrical pump work requirement (SEEC). However, this technology is still in the pilot or lab scale phase; thus, it is only suitable for very small-scale water demand (Figure 4C). The difference between carbon emissions from these solar hybrid systems with the current estimated environmental impact of desalination systems (25 kg CO_2/m^3)[46] allows one to estimate the CO_2 abatement social benefit through the SCC. CO_2 emissions for a concentrate solar heat system are ≈ 5.98 g $CO_2/kWh_{thermal}$. Multiplying carbon emissions savings by the SCC provides the social economic benefit per cubic meter of freshwater produced (Figure 4D). Allocating the social benefit to LCOW provides a possible reduction of the produced water. Under this point of comparison, small-scale solar hybrid desalination systems offer the higher social benefit (1.15 $/m^3) when compared with non-hybrid systems, and equal benefits to large-scale solar hybrid MED plants. This indicates that solar hybrid desalination systems that design around the exergy cascade utilization principle will produce freshwater with a lower environmental and social impact, independent of the capacity. Some desalination technologies have not yet been integrated in hybrid systems such as directional solvent extraction (DSE). DSE is a thermal desalination process without phase change[47] and offers significant opportunities for energy savings. The all-liquid-phase process utilizes solvents to extract freshwater out of saline water and release it as the solvents cool down. DSE operates at low temperature (45°C), presenting the potential to integrate DSE in the heat + heat exergy cascade utilization approach (Figures 2A and 2B). In addition, the high-temperature heat source for future hybridization designs will not be limited to concentrating solar collectors. Both solar thermochemical processing[48] and thermal industrial process heat[49] might integrate with hybrid thermal desalination technologies of large-temperature windows.

FROM THEORY TO REALITY

The principle of exergy cascade utilization implies that each sub-system (e.g., desalination unit) operates at a different temperature. Combining multiple desalination systems that operate at high and low temperatures enables the integration of high-quality CS thermal energy and energy performance improvement of the water production. Although simple in theory, hybridizing systems with various operating temperatures is challenging. There are four types of streams to consider in designing the CS hybrid desalination system (with heat + heat exergy cascade utilization approach). The heat transfer fluid transmits the thermal energy collected by the solar system to the desalination device. Fluids at different parts of the desalination plant can be categorized as freshwater (product), feedwater (initial), and brine (product). Brine at high temperature is prone to scale formation, which might degrade system performance and increase maintenance costs.[3] Sending the brine to the desalination unit that is less prone to scaling (i.e., operate at a lower temperature) is one strategy to mitigate this dynamic. High-temperature freshwater from higher temperature units can either perform as a heat source to the other desalination units or help preheat saline water to lower the energy consumption. The waste heat in the effluent brine from one desalination unit can initiate the other unit's desalination process. Therefore, it is necessary to consider the function of various streams to design a CS hybrid desalination system. Different fluid streams form a topological network. Figure 5 demonstrates an example of a hybrid desalination system engineered with exergy cascade utilization principles. A parabolic trough collector (PTC) operates around 200°C and drives a desalination plant comprising three sub-units. The three sub-units include: (1) an adsorption

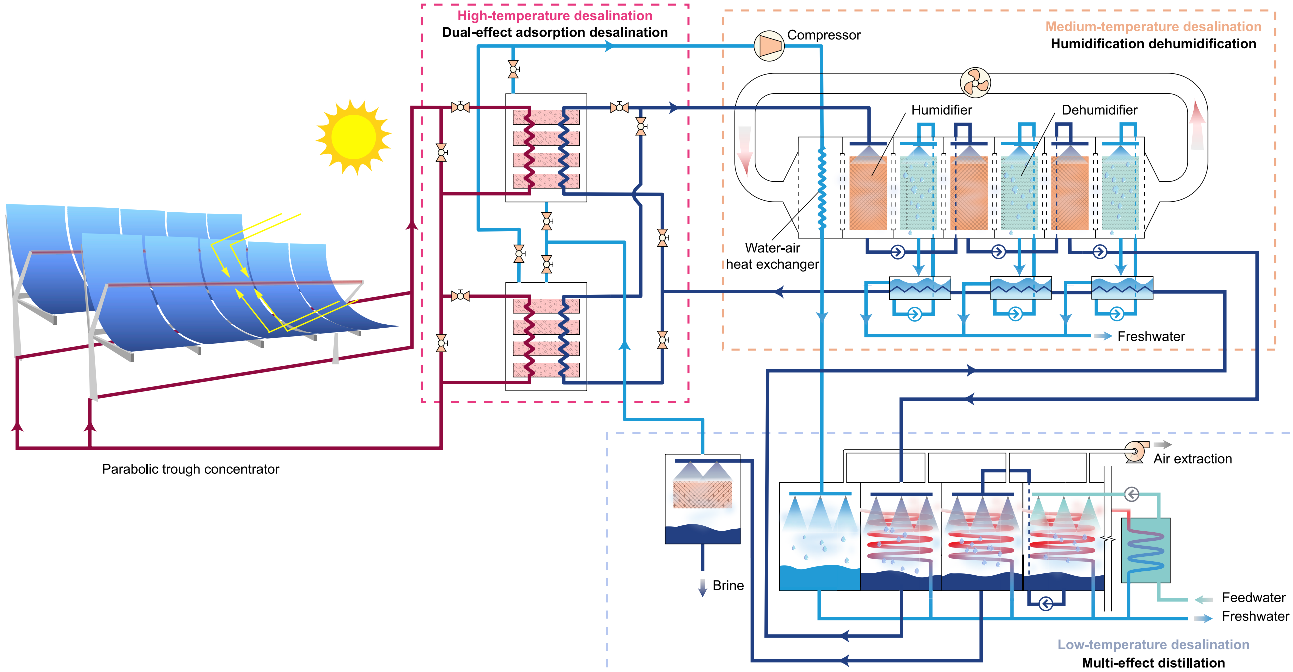

Figure 5. Schematic of a topological solar-thermal desalination system that consists of a concentrating solar collector (parabolic trough concentrator) with high- (adsorption desalination), medium- (multi-effect humidification, dehumidification), and low- (multi-effect distillation) temperature-based desalination technologies

desalination (AD) unit, (2) a multi-effect humidification-dehumidification unit (MEH), and (3) an MED system. The PTC supplies the high-temperature thermal energy to the AD unit with absorbent material of a high regeneration temperature (e.g., active Alumina of 120°C–260°C[50]). Therefore, the absorbed water turns into superheated steam exchanges heat with dry air within the MEH unit. A compressor might be required to ensure the vapor temperature above ~ 110°C so that it can release both the sensible and condensation heat at the water-air heat exchanger. The liquid with remaining sensible heat (approximately 70°C) performs as the motive steam to the MED unit. Although the vapor flows from high-temperature to low-temperature units, the overall design of brine flow presents a trend of low temperature corresponding to high salinity. The detailed design should consider the salinity tolerance and operating temperature of each desalination technology (and even specify into each evaporation effect). For example, the high-temperature adsorbent beds of AD are separated from the low-temperature brine tank. As the low-temperature brine runs through the coil within the adsorbent bed, cooled adsorbent becomes hydrophilic and starts to adsorb vapor from the low-temperature (approximately 50°C) brine tank. Therefore, it can process the brine effluent with high salinity from the MED unit. Meanwhile, the design of brine flow might take advantage of the waste heat from the concentrated brine. For instance, the brine flow from the lower temperature effect of MEH can be directly introduced to the MED unit to reduce the energy consumption. The proposed topological system that consists of different desalination units makes use of exergy in a cascading manner. It provides a potential route to improve energy performance (GOR_{STD}) drastically. Introducing more distillate stages or effects by sacrificing driving potential or/and a pretreatment method (e.g., nanofiltration[51]) to broaden the temperature window can further improve the performance.

Optimization methodologies

After designing a novel CS hybrid desalination system based on the exergy cascade utilization principles, it is necessary for future plant designers to carry out optimization methodologies to improve the energy, exergy, economic, and environmental performance. To elevate the energy performance (GOR_{STD}), designers might deploy a solar tracking system, strengthened insulation, and high optical efficiency concentrator for increasing solar collector efficiency. Hybridizing desalination technologies with different temperature operation range, enlarging heat transfer coefficient,[52] or heat and mass transfer (evaporation-condensation) area[53] can improve desalination performance (UPR_{equiv}). These approaches might also effectively mitigate exergy losses and elevate the second law efficiency, although they could increase capital costs. Hence, for solar hybrid desalination systems, taking the economic factors into the analysis of energy or exergy can make optimization more objective.

Exergy-economy analysis allocates the water production cost to exergy streams and the sources of thermodynamic irreversibility as exergy costs.[54] Exergy cost allows to understand the freshwater production cost formation process within the hybrid system. As a conservative magnitude, it increases as the stream goes through components of the system and irreversibility involved.[55] By analyzing the process of exergy cost formation, future plant designers can determine the key components with the potential of economic saving and design improvement.[56]

Energy-economy analysis is more suitable for the optimization of the overall system. The analysis includes considerations of both costs and benefits. Capital costs (for equipment, pre- and post-treatment, land cost, and installation, and so on) and operating costs (such as operation and maintenance fees, brine management, and amortization charges) constitute systems' investment.[57] The overall water production depends on energy (GOR_{STD}) and environmental factors (e.g., local solar irradiance level and feedwater temperature and salinity[6]). LCOW is the most common objective function for energy-economy analysis (Equation 7). For a solar desalination plant that takes into account the market factors (i.e., water selling price), government subsidy for eliminating CO_2 emission and income from valuable byproduct,[58] considering payback period[57] or self-defined non-dimensional index[23] would be a preferable objective function for energy-economy optimization.

Environmental tools that can quantify and evaluate the emission abatement and other environmental benefits or risks are helpful for further optimizing sustainability and promoting CS desalination. Life cycle assessment (LCA) is a "cradle to grave" approach for assessing the environmental impact of all processes and materials involved in a technology.[59] Because of intensive energy consumption, the environmental load (carbon footprint and pollutant gas emissions) of conventional desalination plants has a much higher share (88.6%–99%) in operation stage than assembly and final disposal processes (1%–11.4%).[60] Utilization of solar energy can significantly lighten lifetime emission footprint because it almost eliminates the operational emissions. An accurate emission footprint comparison between renewable and conventional desalination methods using LCA can help policy/decision makers formulate reasonable local incentives or subsidies, elevating the economics of solar hybrid desalination. LCA also helps select materials and manufacturing processes that have a milder impact on the environment.[60] Environmental risk assessment can help identify possible deleterious effects of hypersaline concentrate effluent of solar desalination plants on marine ecosystems and species.[61] It would prompt designers to adopt an appropriate brine disposal scheme or redesign the desalination system for zero-liquid discharge.[62]

The topological hybrid structure increases and complicates the design and operating parameters. Aiming at the energy, exergy, economy, and environmental optimization goals, future researchers can use sensitivity analysis[63] or machine learning tools (e.g., artificial neural networks, particle swarm optimization, and genetic algorithms)[64] for multi-objective optimization reducing computational cost.

CONCLUSIONS

Solar-thermal desalination might begin to play an increasingly important role in meeting inland water demands. The ability of these systems to respond to variable feed streams could be valuable for the industrial, municipal, and agricultural sectors. However, solar-thermal desalination systems exhibit low energy performance (GOR_{STD}, SWP, and UPR_{equiv}), often resulting in high LCOW when compared with fossil-driven alternatives. This perspective suggests that future researchers must address these challenges by holistically considering energy, economic, and environmental considerations. Designing novel hybrid desalination structures, which emphasize the exergy cascade utilization principle, with a broader temperature range is a recommended strategy for enhancing the performance of these systems. The current CS hybrid desalination research has proven the potential energy, economic, and environmental benefits, which can be realized when compared with the non-hybrid counterparts. Finally, we propose a topological solar-thermal desalination model, which exploits the exergy cascade utilization principle.

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