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Synergies and potential of hybrid solar photovoltaic-thermal desalination technologies

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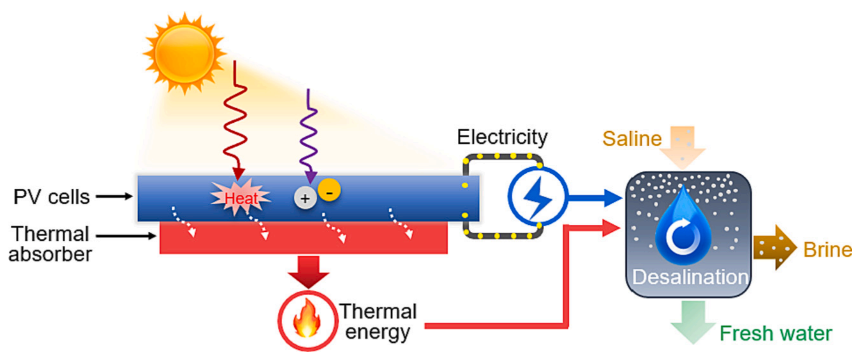
HIGHLIGHTS

- Electrical and thermal operation mapping between PVT and desalination
- Review and discuss opportunities for smart co-use of electricity and heat
- Identified new integration options for PVT-desalination systems
- Preliminarily access PVT-desal with current solar-desal systems

GRAPHICAL ABSTRACT



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ABSTRACT

Solar desalination has emerged as a sustainable solution for addressing global water scarcity in the energy-water nexus, particularly for remote areas in developing countries. How to use the light spectrum through solar devices can profoundly affect the solar energy utilization, desalination rates, off-grid applicability, and water affordability. Solar photovoltaic (PV) and solar thermal (ST) respectively have enabled a variety of interesting solar desalination technologies, but the resulting applications usually limit the integration between solar and desalination to be either electrically or thermally connected. Here this review paper explores smart co-uses of heat and electricity from the sun to improve the efficiency, productivity, and independence of various solar desalination processes. It is found that coupling solar photovoltaic-thermal (PVT) with desalination could be a practical and immediately deployable route for plausibly more sustainable solar desalination than current solutions, because the combined electrical and thermal energy outputs from PVT panels could be used synergistically to catalyze the improvement on the solar energy efficiency, specific energy consumption, and specific water production, as well as the operational independence for off-grid applications. Our preliminary analysis indicated an up to 20 % lower cost of PVT-desalination than current solar PV-desalination and ST-desalination but also with challenges discussed.

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1. Introduction

The sustainable and secure access to energy and other resources, especially water, amid continuing global population and economic growth is progressively impacting societies, leading to significant challenges, particularly in water-stressed areas, which will become home to two-thirds of the world's population by 2025 as water shortages worsen [1,2]. As urbanization, industrialization and population growth progress, the demand for the planet's freshwater resources increases, and the use of alternative water sources is essential [3,4]. Desalination, which involves the separation of salt from saline water (e.g., seawater) to produce freshwater, has become increasingly important in this context. Currently, there are >15,000 operational desalination plants globally, which produce water at a rate of about 95 million m^3/day[5]. However, these desalination plants are disproportionally located; about 71 % of global desalination capacity is sited in high-income countries [5].

High energy consumption is a major hindrance to the widespread deployment of desalination. It leads not only to high costs of desalinated water but also to a requirement for reliable energy infrastructure to ensure production. Most of the energy supplied to current desalination plants comes from the burning of fossil fuels, which leads to significant emissions. Solar-powered desalination has emerged as an affordable, sustainable alternative to conventional plants, as costs are much lower than those of fossil-fuel-powered desalination and solar abundance often occurs in areas of water scarcity. Tremendous interest in the development of solar desalination has emerged in recent years [6], including the development of high-performance materials for photothermal conversion [7,8], high-efficiency system components and designs [9–12], and flexible ways to operate desalination plants via advanced control techniques [13,14].

The wide variety of research efforts to integrate solar energy as the main energy source into desalination technologies have mainly fallen into two categories [15]: electrically-focused desalination, which relies on the use of photovoltaic (PV) cells [16,17], and heat-focused desalination, which relies on the use of solar thermal (ST) collectors [18,19]. Recently, a third approach has emerged, which combines electrically-driven desalination with ST-driven organic Rankine cycles [20], although such systems are still at an early stage of R&D compared to the other two.

While these systems enable solar-to-water conversion, they pay less attention to utilize fully the available solar energy for water desalination. In PV-driven systems, the solar utilization efficiency is about 20 %, with the remaining 80 % rejected to the surroundings [21]. ST-driven systems show higher solar utilization efficiency, but the increased amount of energy required to achieve thermal evaporation leads to lower productivity than that achieved by PV-driven (i.e., electrical) desalination systems. Additionally, many ‘active’ ST-driven desalination systems require electrical power to pump water through the system, so they still require electricity from other sources (e.g., the grid) [22]. The dependence of these systems on electrical power leads to challenges in their use in unelectrified rural areas or adds operational costs in other applications.

Solar photovoltaic-thermal (PVT) technology is a promising solution that hybridizes PV cells and a ST absorber in order to maximize solar utilization (or, harvesting) efficiency. Previous studies on the hybridization of PVT collectors with desalination modules have demonstrated the potential of such systems to increase the utilization of solar energy [23–26]. The overall efficiency of a PVT solar collector can reach 60-80 %, which is typically higher than that of standalone PV or ST collectors, while simultaneously delivering useful electricity and heat as outputs [27]. This available dual-energy output from PVT collectors opens up a wide range of possibilities for their integration within wider solar generation systems [28], including opportunities for improved use of the full solar radiation in desalination processes while enabling operational independence of ‘active’ ST-desalination systems from the grid. The high solar-to-water efficiency potential of these systems also could promise significant reductions to the necessity for capital investment in land and system infrastructure.

Previous studies have shown the benefits of PVT-desalination technologies on improving solar energy utilization [29], which could lead to increased water yield under the same solar conditions [30] and potentially reduced water costs of solar desalination [31]. However, most previous PVT-desalination studies to-date have focused on the development of system integration solutions between conventional PVT collectors and desalination modules, and have not considered opportunities for synergistic electro-thermal coupling mechanisms. Variation in the use of heat and electricity in desalination can improve the performance of the system even when it is operated at similar solar-energy efficiencies. Therefore, the effective use of the combined electrical and thermal outputs from PVT collectors for water desalination requires an in-depth understanding of the fundamental roles that heat and electricity play in different desalination processes.

Therefore, in this perspective review, we focus on the synergies of electricity and heat that occur between the energy generation from custom hybrid PVT solar collectors and the energy requirements of various desalination technologies. We discuss ways in which electricity and heat gained from the sun can be co-used smartly for the effective desalination of saline water, which could create new integration options beyond currently electrically-driven or thermally-driven processes for solar desalination. In Section 2, we begin with an introductory review of various desalination and PVT technologies, in which we aim to show the operational conditions that offer opportunities for matching of energy generation and use. The section may also serve the purpose of facilitating readers who are only familiar with either of the two research topics focused – desalination and solar PVT. For readers who already know well about both research fields, they could skip Section 2. In Section 3, we describe the mechanisms through which the combined use of electricity and heat can reduce entropy generation and improve the performance of desalination. We identify new opportunities for reducing the amount of energy that is consumed during desalination, improving water productivity and ion selectivity, mitigating salt scaling and concentration polarization (CP), and improving operational flexibility. We discuss the challenges of the smart use of PVT collectors for desalination. Lastly, in Section 4, we analyse preliminarily the performance and cost differences between PVT desalination, PV desalination and ST desalination systems, and indicate in which situations PVT-desalination systems may be more affordable than the other two. The discussion shows that PVT desalination with improved performance could be applied to rural and urban water-scarce areas to sustainably cover the water demand while mitigating emissions. A schematic illustration of the paper's structure is shown in Fig. 1.

2. Review of desalination and PVT solar technologies

2.1. Desalination: electrically and thermally driven technologies

Desalination involves a portfolio of technologies that produce low-salinity freshwater from saline water sources, usually brackish water (BW) or seawater (SW). Based on the main form of energy required, desalination is usually performed by electrically driven or heat-driven processes. In electrically driven desalination, the most widely used technologies are reverse osmosis (RO), electrodialysis (ED) and mechanical vapour compression (MVC), while capacitive deionization (CDI) is undergoing rapid development. The most developed processes that use heat as the main form of energy are multiple-stage flash (MSF) and multiple-effect distillation (MED), which have been widely deployed in the Middle East. In the last decade, membrane distillation (MD) has also emerged as a compact, modular, membrane-based thermal desalination technology. Diagrams that illustrate these desalination technologies are shown in Fig. 2.

2.1.1. Electrically driven desalination technologies

RO is based on the physical phenomenon of osmosis, which is the natural movement of water molecules that is driven by chemical potential energy from a solution of low salinity to one of high salinity across a semi-permeable membrane. The 'semi-permeability' of the membrane allows water molecules to pass through while salts are prevented from doing so. In an RO process, hydraulic pressure is applied to the high-salinity solution to create a hydraulic potential across the membrane. If the hydraulic potential is greater than the chemical potential that is caused by the salinity difference across the membrane, water molecules are forced to move from the high-salinity side (i.e., brine) to the low-salinity side (i.e., product), as shown in Fig. 2a. The water permeation is in a direction opposite to that of natural osmosis and leads to the separation of water from saline solutions. An energy recovery device (ERD) is used to recover the hydraulic potential of brine in seawater reverse osmosis (SWRO) processes by transferring the hydraulic potential to the feed before it flows into the RO membrane module. The use of an ERD significantly reduces the energy consumption as it reduces the amount of 'waste' hydraulic energy of the exhaust brine. The most efficient isobaric ERDs (e.g., dual work exchanger energy recovery and pressure exchanger devices) can reduce the specific energy consumption (SEC) of SWRO to 3-5kWh/(m^3) [32]. RO has been widely used to desalinate water that has a wide range of salinities, although its energy consumption and the likelihood of membrane fouling increase when the salinity of feed water is high. Currently, RO accounts for about 34 % and 7 % of the global SW and BW desalination capacity respectively [5]. It has been used to treat wastewater from industries [33].

Whereas RO removes water, ED removes salt to achieve desalination. ED removes ions through the use of an external electric field and selective ion-exchange membranes. In an ED process, saline water flows through an ED stack, which contains a series of alternating anion and cation exchange membranes. Anion exchange membranes allow passage only of anions and the cation versions pass only cations. When an electric field is applied over the ED stack, anions flow towards the anode and cations towards the cathode, as shown in Fig. 2b. Therefore, the placement of the exchange membranes in series selectively controls the ion removal across the membranes and produces alternating channels of diluate (i.e., product) and concentrate (i.e., brine). The energy consumption of ED increases when the system is used to desalinate water of high salinity, potentially leading to an increased cost per cubic metre of water produced. Compared to RO, ED requires less energy to desalinate water of low salinity and is less vulnerable to the production of precipitate and scale through the electrical polarity reversal operation [34]. However, the capital cost of ED is higher than that of RO and accounts for a large part of the total system cost. As a result, ED is mainly used for the desalination of low-salinity water such as BW, and 60 % of current ED applications are for BW desalination [5].

CDI involves the use of pairs of oppositely placed, porous carbon electrodes, which store ions when an electrical voltage difference is applied. When saline water flows through the flow channel between the two electrodes, ions move towards the electrodes due to the external electric field, as shown on the left-hand side of Fig. 2c. Electrical double layers form inside the intra-particle pores and cause the ions to become immobilized in the pores of the carbon material. To desalinate water, ions are absorbed by the porous electrode until the accessible intra-particle pore volume is saturated with electrosorbed ions and the storage capacity of the device is reached [35]. Then, the absorbed ions are released from the electrode to the brine by reducing or even reversing the cell voltage and thus the electrodes are regenerated, as shown on the right-hand side of Fig. 2c. A variation of CDI is membrane capacitive deionization (MCDI), in which ion-selective membranes are placed next to the electrodes to reduce co-ions in the electrodes. CDI is suitable for the desalination of low-salinity water.

MVC is a well-established desalination technology that has been widely deployed to treat SW and high-salinity feeds at a variety of scales. It is based on a heat engine. The MVC desalination process uses electrical work to realize a thermodynamic cycle of water evaporation and

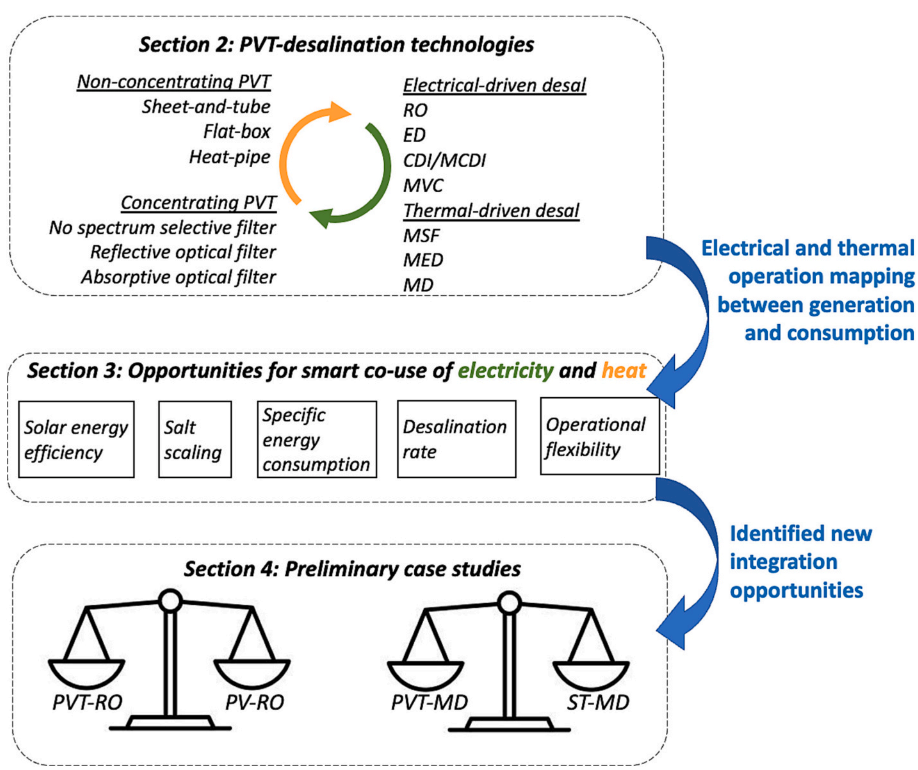

Fig. 1. Diagram of this paper's structure. RO is reverse osmosis. ED is electrodialysis. CDI/MCDI is (membrane) capacitive deionization. MVC is mechanical vapour compression. MSF is multi-stage flash. MED is multi-effect distillation. MD is membrane distillation. PV is photovoltaic. ST is solar thermal. PVT is photovoltaic thermal.

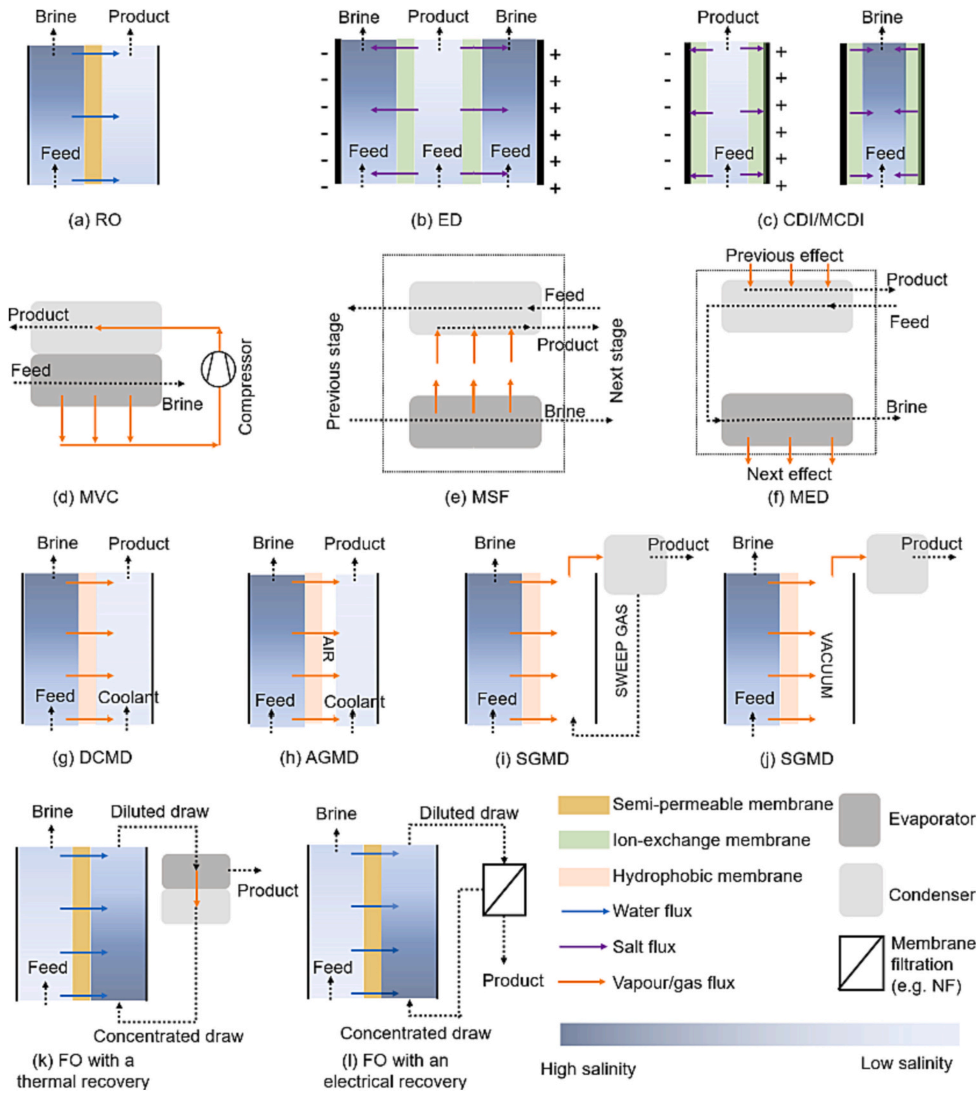

Fig. 2. Illustration of various desalination technologies. The simplified diagrams only show the working principles of desalination processes, but do not represent real system configurations or operations.

condensation, as shown in Fig. 2d. The saline water (usually SW) is heated in a combined evaporator and condenser: the feed is heated by the product water and the compressed vapour to evaporate; in turn, the produced vapour is compressed to increase its temperature and is used to heat the feed. Therefore, the primary energy required in the MVC system is mainly the compressor work. MVC is usually considered to be less energy efficient than RO in the desalination of SW. However, as the energy consumption of MVC does not rely on the salinity of the feed water, it may have higher efficiency than other electrically driven desalination processes to desalinate water at high salinities [36].

2.1.2. *Thermally driven desalination technologies*

Passive distillation uses thermal energy (e.g., solar heat) to heat water directly, which leads to enhanced evaporation and water production. One example of passive distillation is the solar still, which employs simple system designs that have low capital costs, but the water productivity and energy efficiency are usually very low. The low energy efficiency of conventional solar stills and the high SEC of thermal evaporation are mainly caused by high heat losses. Researchers have tried to reduce energy losses by optimizing the designs of solar stills [37]. Another research direction is the recovery and reuse of the heat to enhance energy efficiency. As there is a finite volume of thermal energy available, either from solar or from other sources, efficient use of thermal energy through the repeated recovery of the latent heat of vaporization is critical to the enhancement of the desalination system's performance [19].

Recent studies of passive ST-driven desalination have mainly focused on novel material and device designs to increase water productivity and reduce water cost. New nanomaterials that promote heat localization have been developed to concentrate solar thermal energy where it is needed in order to evaporate water with minimal energy losses [38]. Several studies have displayed device designs that used and recovered latent heat of water evaporation in an efficient manner in order to enhance water production in ST-driven systems. Multi-stage device designs have enabled these passive ST-driven distillation systems to achieve an ST-to-vapour efficiency of 138-385 % with production rates of 1.8-5.8 L/(m^2h) [10,11,39].

In contrast with passive processes, active thermal distillation involves control of pressure and temperature to force the occurrence of the water-vapour phase change. MSF is an active thermally driven desalination process that relies on a flash distillation of the heated brine at low temperature and pressure. At each stage, two processes occur: the water evaporates from the brine and the distilled water condenses. The feed saline water (usually SW) flows across the condenser as a cold stream before subsequently flowing sequentially through the process stages, where it is continuously heated. Therefore, the distilled water vapour produced in the evaporator is condensed due to the cold feed water passing over it. Before the feed water enters the first stage as the 'top brine', its temperature is further increased to 90-120 °C by an external heating source. Subsequently, the heated brine flows through the stages as water is flash distilled at each stage.

MED is another active thermally driven desalination technology in which heat evaporates water through multiple effects in series. As illustrated in Fig. 2f, each effect has a condensation compartment in which water is heated by the vapour produced in the previous effect to the boiling point, usually at reduced pressure (i.e., vacuum); an evaporation compartment then produces water vapour for the next effect. In MED, each effect operates at a lower pressure than the one before it, in order to reduce the boiling temperature.

MD is an emerging, heat-driven separation process. It involves the use of porous hydrophobic membranes that allow only water vapour molecules to pass through. The vapour pressure differences that are induced by the temperature differences across the membranes form the driving force for the vapour transport. The water vapour is collected through additional condensation. Four MD technologies are usually classified based on the configuration of water vapour condensation [40]: direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD) and vacuum membrane distillation (VMD). In DCMD, as illustrated in Fig. 2g, the water vapour directly condenses in the membrane module, where it is cooled by the low-temperature permeate. However, due to the flow on the low-temperature side, the energy loss due to heat convection is high. In AGMD, this heat loss is reduced as the permeate flow is replaced by an air gap, as illustrated in Fig. 2h. The water vapour is condensed on the cold surface on the low-temperature side. The drawback of AGMD is that the driving force is reduced due to the enhanced mass transfer resistance caused by the air gap. To reduce this mass transfer resistance, in SGMD, a sweep gas flows on the low-temperature side. As illustrated in Fig. 2i, the gas flow with water vapour enters a separate condenser to produce freshwater, but the size of the condenser must be increased from that used in the previous two designs due to the introduction of non-water vapour. In VMD, these factors are balanced by the creation of a vacuum on the low-temperature side, which minimizes the heat loss and avoids the introduction of additional gas to the condenser, as illustrated in Fig. 2j.

The main advantages of MD over conventional thermally driven desalination processes are: 1) MD can operate at temperatures in the range of 40-80 °C, so low-grade waste heat might be suitable; and 2) the membranes provide a high contact area per unit of equipment volume, so enabling the production of very compact installations with reduced footprint. MD is at a development phase. Its performance varies significantly between different lab-scale and pilot systems [41] and the robustness of the membranes requires improvement [42]. MD is less energy efficient than RO; however, in many circumstances, it is advantageous for companies to utilize low-grade thermal energy (e.g., waste heat from industries) rather than electricity and to treat high-salinity brines, both of which can be achieved through the use of MD but not RO.

2.1.3. Forward osmosis with thermally or electrically driven draw regeneration

Forward osmosis (FO) is a promising technology for the remediation of produced water [43]. FO uses natural osmosis to move water from low-salinity to high-salinity water. This water reclamation process requires negligible energy input because of the spontaneous nature of osmosis; however, energy is required to recover the extracted water and regenerate the draw solution. The high-salinity draw solution is regenerated as the water is extracted from it. Potential draw solutions that have lower flash points than water could be recovered through the use of waste heat. McCutcheon et al. used a highly soluble ammonium bicarbonate draw solution that yielded high water fluxes, which was demonstrated to be recoverable at a moderate temperature (~50 °C) [44]. Alternatively, the regeneration of the draw solution can be achieved through the electrical separation process [45]. Therefore, FO and its integrated systems could be used in either thermally or electrically driven desalination systems, as illustrated in Fig. 2k and Fig. 2l respectively. Compared to RO, FO has advantageous performance: 1) FO with an electrically driven draw regeneration can have improved energy efficiencies [46]; 2) FO potentially can operate with hypersaline solutions beyond the reach of RO [47]; and 3) FO exhibits more easily reversible fouling due to the low applied pressure [48].

2.1.4. Comparison of desalination technologies: energy consumption, operating temperatures and system modularities/scales

Different mechanisms that underline the electrically and thermally driven desalination technologies set different theoretical limits. The energy that is consumed in RO, ED and CDI systems is used primarily to transport water molecules or ionic charges and to overcome parasitic resistances to mass transfer. Conversely, the energy that is consumed in thermally driven desalination processes such as MD, MSF and MED is used primarily to enable the phase change from water to vapour. SEC is commonly used as a key metric to quantify the efficiency of the conversion of energy to water in kWh/m^3. The latent heat of water from liquid to gas is about 2400 kJ/kg (667 kWh/m^3) [3]. The minimum energy consumption required for electrical separation processes is determined by the specific Gibbs free energy of separation, which depends on the feed salinity and water recovery rate. For example, the specific Gibbs free energy of separation is about 1.06 kWh/m^3 for 50 % recovery with a feed (SW) salinity of 35 g/kg [49], which is about two to three orders of magnitude lower than the enthalpy of vaporization [50]. These energy consumption figures reflect different fundamental phenomena in these desalination processes. At a molecular level, thermal separation must break the hydrogen bonds between water molecules to produce water vapour; electrical separation only moves water and salt molecules and maintain the non-equilibrium against their inherent propensity to mix to reach equilibrium [50]. Consequently, although ST-driven desalination processes utilize solar energy at much higher efficiencies (3-4 times) than PV- driven desalination processes, the water production rates are usually lower in ST-driven systems relative to corresponding PV-driven systems at similar system scales.

Table 1 lists typical SECs of various desalination technologies that are reviewed and summarized in this paper. The energy consumption of each technology is divided into electrical and thermal SECs to indicate the requirement for electricity and thermal energy respectively. Table 1 also lists common operating temperature ranges for different desalination technologies. Thermal-based desalination processes usually operate at higher temperatures (but usually <100 °C) than electrical ones, which usually operate at the ambient temperature. Furthermore, MSF and MED are particularly suitable for large-scale desalination applications, as they can produce water at rates close to 10,000 m^3/day. MVC systems are usually employed for medium-scale desalination systems, i.e., up to 5000 m^3/day. RO and ED, due to their membrane modularity, can be used across a range of deployments, from very small-scale to very large-scale. In contrast, emerging technologies such as MD, CDI and FO are focused on relatively small-scale demonstrations, but which potentially can provide water at scales similar to RO and ED, due to their modularity. As the main energy consumption in FO is caused by the draw regeneration through either a thermally or electrically driven desalination technology, FO is not specifically reviewed or discussed further in this study.

2.2. Hybrid PVT solar technology development and performance

The current solar market remains dominated by PV, which converts solar energy directly into electricity without moving parts or noise [66]. The global installed capacity of PV reached 630 GW in 2019 and is still growing fast [67]. The 'first generation' silicon PV panels (usually with 15-20 % electrical efficiency) occupy over 90 % of the current global PV market. The main motivation for the development of PVT technology is

Table 1
Typical operating conditions and performance of various desalination technologies.

	MSF	MED	MD	RO	ED	CDI/MCDI	MVC	FO
Form of main energy	Thermal	Thermal	Thermal	Electrical	Electrical	Electrical	Electrical	Thermal or electrical
SEC_e [kWh/m^3]	3-5 [51]	1.5-2.5 [51]	0.3-1.5 [52–54]	0.5-3 [51]; (BW) 2.5-7 [51] (SW)	0.2-3 [34,55] 3-7 [56] (BW); 2-6[a] [57]; 17 [56] (SW)	0.1-1.5[b] [58]; 0.02-1[b] [59] 1.1-1.2[c] [60] (BW)	8-14 [61]	0.24 [46] (thermal); 2.4-3.3 [46] (electrical)
SEC_{th} [kWh/m^3]	250-330 [51]	145-390 [51]	55-200 [50]	Negligible	Negligible	Negligible	Negligible	25-150 [36] (thermal)
Operating temperature [°C]	<120 [61]	<70 [61]	<80 [40]	~20	~20	~20	<70 [61]	~20 (electrical); 40-50 [44] (thermal)
Typical system capacity [m^3/day]	5000-70000 [61]	500-12000 [61]	1-1000 [50]	>100,000	Up to ~10000 [62]	~5 [60], 3785 [63] 60000 [64]	3000-5000 [61]	Up to ~1000 [65]

[a] Considering the stack power only, i.e., the direct current energy consumption due to the applied electrical field in the stack without the pumping power.
[b] Considering the energy consumption for the capacitive process only, without the pumping power.
[c] 558-917 mg/L water.

not only to cool PV cells in order to improve electrical efficiency [68], but also to collect additional thermal energy so that the full spectrum of solar radiation can be utilized. The overall efficiency of PVT collectors can reach 60-80% [27], which is significantly higher than that of standalone PV panels.

2.2.1. *Introduction to PVT technologies*

The concept of PVT technology is shown in Fig. 3. To use the full spectrum of solar radiation (Fig. 3a), PVT collectors usually consist of PV cells and thermal absorbers (Fig. 3b). The PV cells are able to convert ~90 % of the incident solar energy to electricity and heat, while the thermal absorbers harvest the heat generated in the PV cells to produce useful thermal energy. Therefore, PVT collectors simultaneously generate electricity and thermal energy. PVT collectors usually employ commercially available PV cells. Therefore, current PVT studies mainly focus on the design of high-efficiency thermal absorbers, including the structure and heat transfer fluid of the thermal absorber. At the end of 2018, the cumulative global PVT collector area exceeded 1.07 million m^2, according to a report by the International Energy Agency (IEA) [69].

PVT collectors contain either gas- or liquid-based heat transfer fluids. Gas-based PVT collectors usually employ cooler air as the coolant to remove the heat generated in the PV cells and to produce hot air [68,71]. These systems usually supply end-users that have demands for hot air for use in space heating or agriculture drying [72,73]. Zondag summarized the performance of different gas-based PVT collectors [27]. Liquid-based PVT collectors utilize liquids such as water to absorb heat. They are considered to be more effective than gas-based PVT collectors. The thermal output of liquid-based PVT collectors can be used to heat buildings, domestic water and swimming pools, and in desalination plants. In the next section, we review liquid-based PVT research/designs which are of greater potential for integration into desalination modules than gas-based designs.

2.2.2. *Designs and development of PVT collectors*

Liquid-based PVT collectors take around 80 % of the current PVT market [69]. Fig. 4 illustrates several common types of PVT designs that are both on the market and shown in the literature. Typically, liquid-based PVT has the thermal absorber attached to the back of the PV cells to absorb the heat generated in the PV. A transparent glass layer above the PV cells can be used to suppress heat losses, thereby increasing the thermal efficiency; however, this typically compromises the electrical efficiency as the glass layer reflects part of the sunlight (~10 % for normal low-iron glass). There is a trade-off between electrical and thermal efficiencies. Thus, the glass layer is optional, dependent on the demands of end-users. Approximately 60 % of commercial liquid-based PVT collectors do not incorporate the glass, while 35 % do, and 5 % are encapsulated in a vacuum tube to further reduce heat losses [69]. The thermal insulation layer on the back is used to reduce the heat losses from the back of the thermal absorber.

The sheet-and-tube structure is the most common type of thermal absorber in liquid-based PVT collectors [74–76,77]. In this design, a metal tube array is welded to a flat-plate metal sheet, as shown in Fig. 4a. The metal sheet collects and conducts heat from all the PV cells to the tube array, in order to enhance the thermal efficiency. The tube may be straight [79] or twisted [80], while the cross-section of the tube may be of different shapes [81,82], such as the round, flat-sided oval, rectangular or semi-circular. Sheet-and-tube thermal absorbers are standard products in the solar thermal industry that are made according to mature manufacturing methods and are low cost [74], so most commercial PVT products [83–86] employ them. They also offer high heat transfer efficiency [87] and high-pressure bearing capacity [88]. The fin performance of the sheet-and-tube structure is a crucial factor that affects the overall efficiency of the PVT collectors [89]. The thermal efficiency of sheet-and-tube PVT collectors typically varies from 30 % to 60% [27,90], depending on the structure and operating temperature.

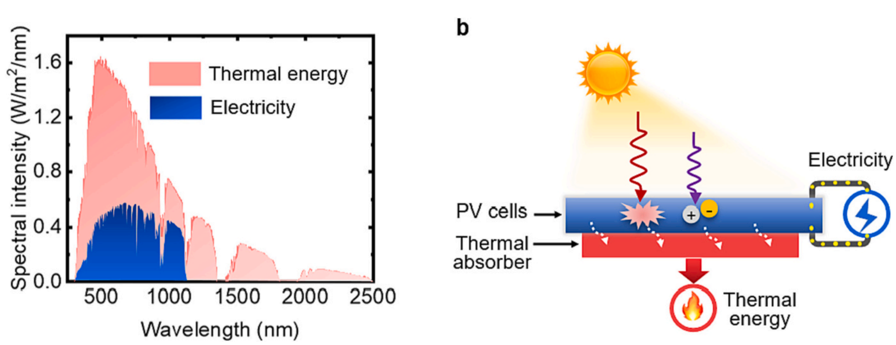

Fig. 3. Hybrid PVT solar collector concept. (a) Solar spectrum for generating electricity and thermal energy, and (b) diagram of a typical PVT collector.

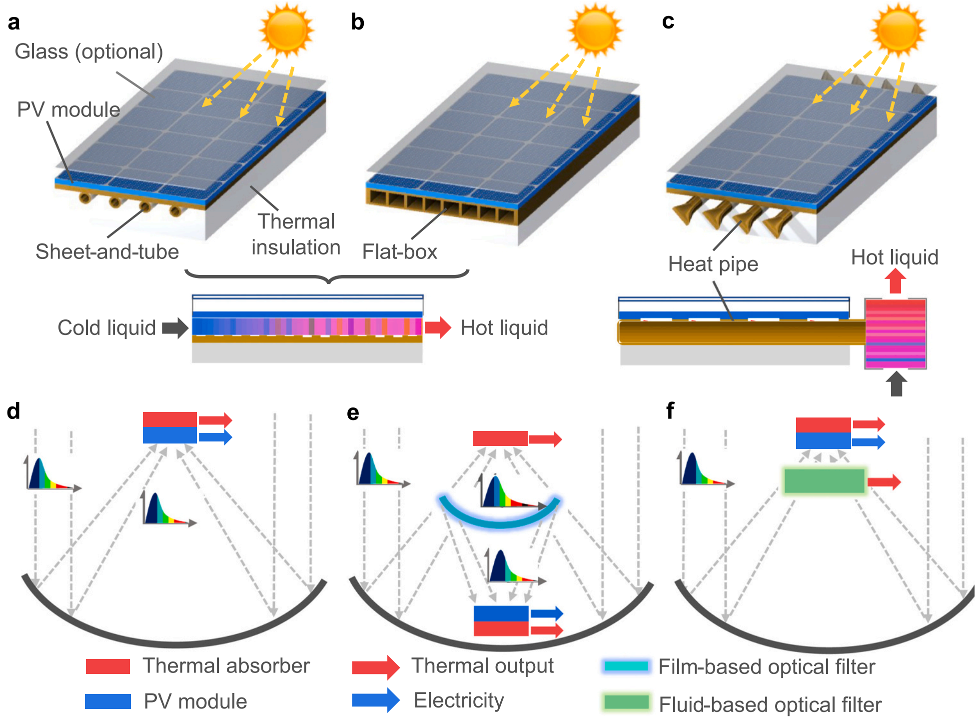

Fig. 4. Designs of liquid-based PVT collectors with: (a) sheet-and-tube thermal absorber, (b) flat-box channel thermal absorber, and (c) heat pipe thermal absorber. Concentrating PVT collector designs: (d) normal-type design, (e) spectral-splitting design with a selectively-reflective optical filter, and (f) spectral splitting design with a selectively-absorptive optical filter.

The electrical efficiency of sheet-and-tube PVT collectors is similar to that of standalone PV panels, i.e., around 15-20 %, depending on the material and manufacture of the solar cells.

The flat-box structure is another common type of thermal absorber in liquid-based PVT collectors [91], as shown in Fig. 4b. It has excellent heat transfer performance owing to the large heat transfer area between the flowing liquid and the PV cells. Of note is that the flowing channel structure inside the flat-box thermal absorber is not limited to the structure shown in Fig. 4b. The flowing channel can be straight [78] or twisted [92], multi-path [78] or single-path [93]. Researchers have also integrated elements that enhance heat transfer into the flat-box flowing channel, such as micro-fins [94], honeycomb structures [95] and grooves [27], in order to improve further the heat transfer efficiency of the thermal absorber. The thermal efficiency of flat-box PVT collectors is slightly higher (by ~2 %) than that of sheet-and-tube PVT collectors [96], while their electrical efficiencies are similar.

Heat pipes are heat-transfer elements that offer advantages of high heat-transfer efficiency, no moving parts, no energy consumption and long service life. They have been applied to PVT collectors [97–101] to recover the heat in PV cells, as shown in Fig. 4c. The heat pipe can be considered as a heat-transfer medium that has ultra-high thermal conductivity. The heat effectively transfers from the PV cells to the heads of the heat pipes, and then is recovered by the flowing fluid around the heat pipes. Researchers have applied flat [97,98] and cylindrical heat pipes [99–101] to PVT collectors to enable retention of the temperature of the PV cells in a uniform distribution. Heat-pipe PVT collectors have been shown not to freeze and to work well in cold regions [99,102]. The thermal efficiency of heat-pipe PVT collectors typically varies from 40 % [97,102] to 60% [102,103], depending on the structure and working fluid arrangements of the heat-pipe array.

The output heat of non-concentrating PVT collectors is typically limited to ~80 °C [27,69,90]. The output temperature and thermal efficiency of PVT collectors can be improved further by using an optical concentrator and a tracking system [104–107]. The output heat of some concentrating PVT collectors is above 80 °C. Fig. 4d shows the normal design of concentrating PVT collectors: a liquid-based PVT collector is mounted at the focus of an optical concentrator. Concentrating PVT systems harvest sunlight effectively and generate both electricity and high-temperature heat that are suitable to meet the demands of different desalination modules. However, the thermal absorber is thermally coupled with the PV cells; thus, the PV cells face the challenge of overheating and efficiency reduction as they deliver high-temperature thermal output. The maximum temperature of the thermal output is limited due to the temperature limit of the PV cells.

Spectral splitting is a promising methodology that can lead to the breakage of the temperature limitation of the normal type of concentrating PVT collectors [108–111]. There are two main types of spectral-splitting PVT collectors, which employ selectively-reflective or -absorptive optical filters. As shown in Fig. 4e, the selectively-reflective optical filter separates the solar spectrum into two spectral parts. It sends one part to the PV cells for electricity generation and the other part, which cannot be electrically utilized by the PV cells, is directed to a separate thermal absorber to generate high-temperature thermal energy [112–116]. Alternatively, as shown in Fig. 4f, the selectively-absorptive filter absorbs this part of the incident solar spectrum and generates high-temperature thermal energy. The rest of the spectrum is transmitted through the fluid-based filter to the PV cells for electricity generation [117–119]. Spectral-splitting PVT collectors can produce 100-400 °C thermal energy, without compromising the electrical efficiency [120]. Although it has been shown that spectral-splitting PVT collectors display excellent performance, there are challenges of cost, reliability and optical properties to be overcome [110]. Spectral-splitting PVT technology is under development and there is no product available on the market.

3. Integration of desalination with PVT collectors for full solar spectrum utilization

Conventional solar desalination systems, either PV-desalination or ST-desalination, only use one form of energy from the sun, as the amount of energy required for desalination varies significantly among different (electrical-driven and thermal-driven) desalination processes. As shown in Table 1, thermal-driven desalination processes such as MSF, MED, and MD consume about 100 times more thermal energy (in kWh_{th}) than electrical energy (in kWh_e); while conventional electrical-driven desalination processes such as RO, ED, CDI/MCDI, and MVC barely need heat in their conventional operations. Compared to PV and ST systems, although alternative PVT systems may have varied energy efficiencies, which could lead to different water production performance for desalination, these non-synergistically integrated PVT-desalination systems (in which only one form of energy, either electricity or heat, is used, and let the other energy form for other purposes) use solar energy in the same way as PV-desalination using PV power or ST-desalination using ST.

Integration mechanisms of these non-synergistically integrated PVT-desalination systems are the same to existing PV-desalination or ST-desalination systems, which are not the focus of this study. This paper aims to explore new mechanisms that potentially smartly co-use electricity and heat for advancing the PVT-desalination integration. This section starts with a review of prior studies on PVT-powered desalination processes. Then we discuss how electricity and heat may reduce entropy generation during desalination, and consider several new opportunities and challenges of smart co-use of electricity and heat that may catalyse the production of efficient and usefully integrated PVT-desalination systems.

3.1. Improved solar energy utilization with PVT-assisted desalination

Optimization of heat and electricity flow between energy generation and desalination processes has been studied. Combined power and heat-power plants have been integrated with desalination systems to reduce capital investment costs. Such integration represents a possibility to transform an electrical power plant from its usual position as a water consumer to a freshwater producer [121,122]. If a fossil-fuel power plant is switched to a solar plant, the co-generation of water, power and/or heat could be used to increase the efficiency of utilization of solar energy. Previous studies of solar desalination have focused on their coupling with thermally driven [19] or electrically driven desalination [123], and few studies have concentrated on the integration of PVT collectors with desalination modules.

In two studies, solar stills were integrated with PVT collectors to enable active heat-driven evaporation with recirculating flows to increase the rates of evaporation and the water yield (to rates possibly three to five times higher than those found in passive solar stills) [124,125]. Xu et al. demonstrated a monolithic tandem solar electricity-water generator with a power output of 204 W/m^2 that purified water at a rate of 0.80 kg/m^2h under one sun illumination. This represented an overall solar energy utilization efficiency of 75 [126]. The PVT-desalination device showed mutually enhanced electricity and water generation, with 8 % and 170 % greater electricity generation efficiency and evaporation efficiency respectively, compared to those of an alternative system in which PV and the desalination system were separated [126]. Wang et al. demonstrated a PVT-MD device that could stably produce clean water (> 1.6 kg/m^2h) from SW while simultaneously showing uncompromised electricity generation performance (> 11 %) under one sun irradiation [39]. The water production rate was three times higher than that of conventional solar stills [39].

PVT desalination has been used beyond small-scale systems. Mittelman et al. (analysed a hybrid concentrated PVT (CPVT) and MED system through the use of simulations [23]. The study indicated how the efficiency of the CPVT collector was improved, to 37 % electrical efficiency and 80 % overall efficiency, by holding heat in over 100 °C hot water. The hot water was then used to run a 10,000 m^3/day MED plant [23]. Ong et al. (experimentally investigated a hybrid CPVT and MED system [24]. The CPVT collector co-generated electricity and thermal energy at high efficiencies: 30 % electrical and 85 % overall efficiency [24]. The heat in a temperature range of 75-80 °C was stored in a 13.5 m^3 thermal storage tank to enable desalination over a 24-h period that used MED [24]. Kelly et al. (investigated a PVT system both mathematically and experimentally by using the feed water to cool down the solar panel before it flowed to the RO module [25]. The experimental demonstration showed a 59 % increase in water production through the combination of the PV panel cooling, feed water heating and the solar concentration [25].

3.2. Fundamental impacts of the co-use of additional electricity and heat

From theoretical perspective, all solar desalination technologies could be assessed via two energy conversion processes: the solar-to-energy (kWh/kWh) process that transfers solar radiation (in kWh) to usable energy output (in kWh); and the energy-to-water (kWh/m^3) process that transfers the usable energy (in kWh) to water production (in m^3). Previous published studies of PVT-desalination focused on replacing PV or ST collectors with PVT collectors and integrating them with desalination processes to offer incremental energy provision (in the form of either heat or electricity). These PVT systems can increase efficiency of the solar-to-energy conversion. As a result, the added usable energy output in kWh could increase the water production. However, less attention has been paid to the improvement of the energy efficiency of desalination, namely the energy-to-water efficiency. If improvements can be achieved in both conversions, potentially, the overall solar-to-water conversion in “smart” PVT-desalination can be higher than current PVT-desalination systems, as well as PV-desalination or ST-desalination systems. The improved solar-to-water efficiency can reduce capital investment, land use, energy and water system infrastructure costs.

3.2.1. Reduced entropy generation via the co-use of electricity and heat

To explore practical opportunities for “smart” use of electricity and heat for desalination, in this section we aim to understand fundamental mechanisms to minimize irreversible energy losses.

The least work/heat of separation that is required is a theoretical energy limit to separate water from a saline solution, which is determined by the thermodynamic conditions of feed, product and brine [58]. In practical desalination processes, entropy is generated during the thermal, hydraulic and electrical processes. The total entropy generation is usually much higher than the least work/heat of separation. For example, RO has the highest efficiency in terms of the second law of thermodynamics, which is about 30% [127], so 70 % of energy consumption becomes irreversible energy losses. The second-law efficiency of other desalination processes is usually lower than 10% [127]. Therefore, reduction of the entropy is critical to reducing the energy consumption of desalination. Main mechanisms of irreversible entropy generation that occur in various desalination processes are summarized in Table *2*.

As listed in Table 2, among these irreversible energy losses, chemical, hydraulic and thermal disequilibrium of discharge streams are exhaust losses, which can be minimized through improvement of the part of the system design that minimizes disequilibrium of the exhaust. For example, ERDs in RO are used to recover the hydraulic waste energy; the thermal exhaust is recovered by multi-stage/effect design; and even the chemical disequilibrium (i.e., as a result of desalination) can be recovered to equilibrium by use of salinity power generation techniques [128,129]. Except for the disequilibrium in the exhaust, other major exergetic losses mainly occur in the processes of heat transfer, transport, and pumping.

The heat-transfer process exists mostly in heat-driven desalination processes, which include both phase-change evaporation/condensation and non-phase-changing heat exchanges. Flashing and evaporation are closely related to the vapour pressure and surface tension. The equilibrium vapour pressure for a water molecule that escapes from a saline solution into the saturated vapour is an indication of a liquid's evaporation rate. When the feed temperature increases in thermal

Table 2
Entropy generation mechanisms in desalination processes.

Desalination process	Entropy generation processes
MSF	Pumping, heat transfer (flash, evaporation, condensation and other heat exchanges), thermal and chemical disequilibrium of discharge streams
MED	Pumping, heat transfer (evaporation, condensation and other heat exchanges), thermal and chemical disequilibrium of discharge streams
MD	Transport (diffusion and thermal resistance, and heat conduction), pumping, heat transfer, thermal and chemical disequilibrium of discharge streams
RO	Transport (diffusion resistance), pumping, chemical and hydraulic disequilibrium of discharge streams
ED	Transport (electrical resistance), pumping, chemical and hydraulic disequilibrium of discharge streams
CDI/MCDI	Transport (electrical resistance), pumping, chemical and hydraulic disequilibrium of discharge streams
MVC	Compression, pumping, heat transfer, chemical and thermal disequilibrium of discharge streams

desalination, vapour pressure increases due to weakening of the intermolecular forces; surface tension decreases, and thus more molecules escape. If additional heat is available at a higher temperature than the operating temperature, the enhanced temperature imparts kinetic energy to the feed, so the molecules become more agitated and tend to become vapour at the same pressure gradient. Warsinger et al. studied the theoretical entropy generation of several desalination processes that were powered by variable temperature waste heat at 50 °C, 70 °C, 90 °C, and 120 °C [130]. They found that entropy generation was reduced in thermal desalination processes that occurred at higher heat temperatures, due to improved water recovery with an increased allowable stage/effect number for the thermal system design [130]. In other words, if heat with higher temperature than conventional operating conditions is available, more water may be produced with generation of less entropy in heat-driven desalination processes (i.e., MSF, MED and MD).

Entropy is generated in pumping mainly because of the friction that is caused by liquid as it flows through pipes, valves, heat exchangers and flow channels in membrane modules. This friction increases the pressure head that is required to ensure that the liquid continues to flow at the required rate through the entire desalination process, and this is compensated by the pumping power. For a given velocity of fluid, if the hydraulic flow path is fixed, the friction is proportional to the fluid's density and viscosity, both of which decrease with an increase in temperature. Thus, a higher fluid temperature can reduce the pressure loss and the consumption of pump energy. As pumping contributes to entropy generation, a reduction in consumption of pump energy through the use of additional heat from PVT collectors may have a wide impact.

For membrane processes, a major part of entropy generation occurs in the transport of water or salt species. The controlled mass transport across the membranes (e.g., in RO and ED) or to electrodes (e.g., CDI/MCDI) to overcome natural mixing results in irreversibility, which can be shown in the loss of pressure during conversion of feed to product water in RO, energy losses that occur due to electrical resistance in ED and CDI/MCDI, and the CP in boundary layers (i.e., diffusion resistance) that occurs in all membrane processes. The use of dual-form energy from PVT collectors could help to reduce these entropies. In RO, CP decreases with temperature, while membrane permeability to water and salt increases with temperature [130]. In electrochemical desalination processes, the electrical resistance of the solution is reduced with temperature as the conductivity of the solution increases. The membrane resistances also tend to decrease with temperature [131]. For all membrane processes, the enhanced back diffusions at higher temperatures that mitigate the CP also reduce the diffusion resistance and entropy that are generated in polarized concentration boundary layers.

3.3. Opportunities and challenges of improved electro-thermal coupling for efficient desalination

With the knowledge gained in the previous section, we review and discuss several opportunities to improve specific energy efficiency, scaling, water productivity and operational flexibility. Fig. 5 summarizes identified opportunities for smart co-use of electricity and heat, which will be discussed in detail in this Section.

3.3.1. Improved energy efficiency and water productivity at enhanced operating temperatures

Use of higher operating temperatures in desalination is usually seen as detrimental because achievement of high temperatures requires a heat source of high quality; however, if heat at an enhanced temperature is available free of charge or at very low cost, the elevated operating temperature may enable achievement of improved energy efficiency in the thermal process [132]. Ortega-Delgado et al. investigated the use of a high operating temperature in the first effect of MED [133]. The simulation results indicated a significant improvement in the gain output ratio (GOR) by 70 % and a reduction of the specific heat consumption by 45 % when the heating steam temperature was increased from 70 °C to 120 °C in the first effect. Increased operating temperatures may also lead to higher water vapour fluxes in MD processes. Common polymer-based membranes may not be applicable at temperatures above 90 °C [134], but the use of the temperature-tolerant polymer polytetrafluoroethylene enabled Luo et al. to increase the feed inlet temperature from 80 °C to 180 °C [134]. They evaluated the performance in numerical simulations, which indicated that the SEC was decreased 2.9-fold [134]. Using a similar material, Singh et al. experimentally studied the performance in DCMD systems of microporous films of polytetrafluoroethylene that were subjected to aqueous feeds at temperatures in the range of 80-130 °C [135]. They found that the water vapour flux increased by six times when the temperature increased from 80 °C to 130 °C. The water flux that was achieved at 195 kg/m^2h was also higher than that which was usually achieved in SWRO [135].

High operating temperatures could help to improve water production in heat-driven desalination processes. Compared to ST systems, use of high-temperature PVT collectors such as CPVT or spectrum-splitting PVT collectors could provide the heat at enhanced temperature to enable MSF, MED or MD to operate at temperatures potentially higher than 100 °C. Integration of PVT and heat-driven desalination systems could increase water production rates in standalone systems by increasing the operating temperature in areas where electricity is available for pumping. However, the solubility of potential foulants (such as calcium carbonate, magnesium hydroxide and calcium phosphate) decreases as the temperature increases [136]. Therefore, raising the temperature of thermally driven desalination processes makes them increasingly vulnerable to scaling by salts that tend to precipitate (e.g., calcium carbonate) if they are present in the feed water. Mitigation of salt precipitation and scaling, as well as the consequent membrane fouling, challenges the sustainability of desalination processes that are operated at enhanced temperatures.

In electrically driven desalination systems, a high feed water temperature leads to reduced viscosity, which may result in production of less hydraulic friction in pipes and improved transport across membranes. This suggests that high-temperature operation of RO desalination could enable higher recovery rates and lower energy consumption [137]. Valenzuela et al. studied the thermal uniformity of the PVT panel and its effects on the performance of a coupled brackish water reverse osmosis (BWRO) system [138]. Among the scenarios they studied, the lowest SEC of the PVT-powered BWRO system was about 20 % less than that of the same BWRO system powered by PV, due to the cooling of PV panels and the heating of the BWRO feed [138]. Koutsou et al. investigated the effect of temperature on the performance of RO systems [139]. They studied feed water temperatures that ranged from 15 °C to 40 °C. They found that the supply of feed water at the highest temperature

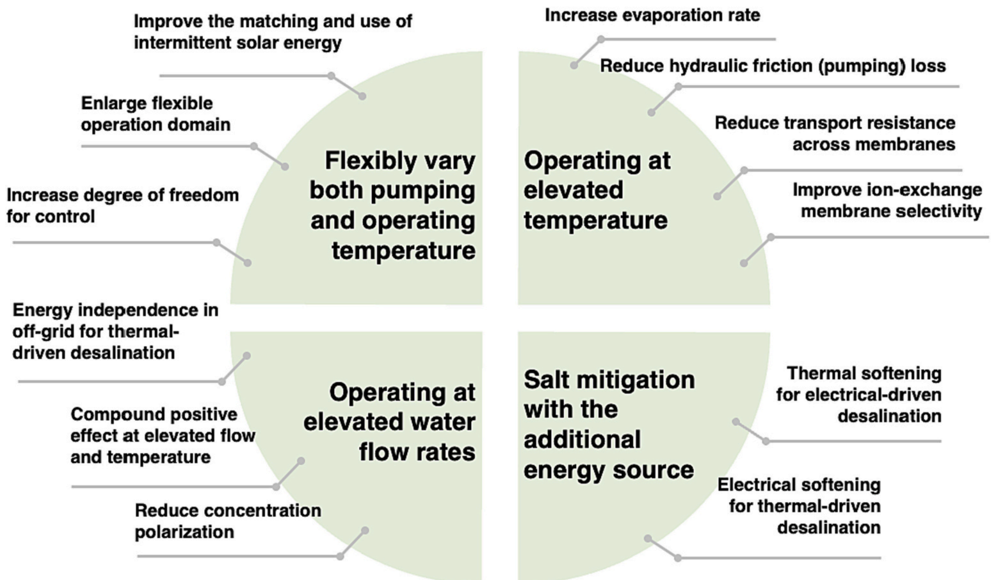

Fig. 5. Illustrated identified opportunities for smart co-use of electricity and heat from PVT for desalination systems.

reduced the SEC of the BWRO system by 40 %. By contrast, during desalination of SW, the increased osmotic pressure that occurred at enhanced temperature required greater energy consumption to transport water molecules across the membrane, and this increased energy use neutralized the temperature-induced positive energetic impact. This trade-off meant that the SEC reached a minimum at about 30 °C during SWRO, and this SEC was about 8 % less than that found during SWRO operated at 15 °C [139]. Monjezi et al. compared the performance of two 5 m^3/day SWRO systems, one that employed PV-RO and the other PVT-RO [140]. Their simulation results indicated a reduction of 0.12 kWh/m^3 (3%) in SEC and a 6 % reduction in the required solar panel area for PVT compared to the PV system [137]. These findings indicate that SEC is less significantly improved with temperature in SWRO than in BWRO. This aligns with the observations from operational datasets of SWRO plants, in which the feed temperature has been shown to have a negligible effect on the SEC of SWRO systems [32].

The SEC reduction due to increased operational temperature is also observed in ED systems. Benneker et al. reported that the energy required for ED processes could be reduced by 15 % if the temperature of both feed streams was increased from 20 °C to 40 °C while the charge-selectivity of the membranes was maintained, and by 9 % if the temperature of one feed stream was increased by 20 °C [141]. This reduction in energy use was explained in terms of the increased diffusivity and reduced resistance of the membranes to ions at elevated temperatures [131,141]. The increased diffusivity led to enhanced conductivity of the solution, and thus the resistance of the total stack was reduced. The conductivity of the solution increased by 27 % as the temperature increased from 15 °C to 40 °C [142], and this conductivity change resulted in a reduction of the voltage that was necessary to maintain the same current. Their calculations accounted only for the stack power consumption and not for the hydraulic pumping energy [141], although the pumping energy probably also decreases at an increased operating temperature.

High operational temperature may also increase the selectivity of ED between monovalent ions (e.g., K^+ and Cl^-) and divalent ions (e.g., Ca^{2+} and CO_3^{2-}). The temperature impact on the diffusivity is slightly different for ions and can influence the ED membrane's selectivity for mono- and divalent ions. At higher temperatures, this difference in ion diffusivity is enlarged [143], leading to different transport characteristics. This selectivity is important and useful, as the separation of divalent from monovalent ions is of interest in desalination [144] and is deemed beneficial for irrigation purposes [145] and in industries such as direct lithium extraction [146]. Benneker et al. found that the separation favoured the selectivity of divalent ions when the dilute stream was heated, due to their different responses to temperature [147]. Zhao et al. studied the temperature effect on lithium extraction from brine during ED that employed monovalent ion-exchange membranes [146]. Their experiment demonstrated that the recovery rate increased from 21 % to 39 % when temperature was increased from 10 °C to 30 °C [146].

PVT collectors could provide additional thermal energy to improve the desalination performance of electrically driven desalination technologies compared to PV-powered or grid-powered systems. The increased temperature of feed water through application of heat from PVT collectors could reduce the SEC of electrically driven processes and increase the efficiency of ED in the selection of mono- and divalent-ions. These benefits are usually not feasible for traditional RO or ED systems, either PV- or grid-powered. However, the temperature must be controlled carefully to balance the trade-off between increased performance and potentially reduced membrane lifetime, and this challenge may mitigate positive effects of an increased operating temperature. Typically, to prevent membrane degradation, the feed-water temperature must be limited to a maximum of 45 °C [25]. In addition, increasing the feed water temperature in RO tends to impact negatively on membrane salt rejection and scaling [139], which also decreases the product water quality.

3.3.2. *Salt scaling mitigation by pre-treatment*

Pre-treatment may mitigate the detrimental occurrence of salt precipitation and scaling. Use of pre-treatments can enable the operation of desalination processes at enhanced temperatures and water production rates. Thermal softening is widely used in high-temperature systems to cause salts such as calcium carbonate to precipitate out [136]. Thermal softening also reduces the concentration of carbon dioxide in feed water, which reduces the chance of formation of bicarbonate ions and mitigates further the amount of salt scaling during desalination [136].

Electrically driven pre-treatments such as NF [148] can lead to rejection of organic matter and removal of hardness from feed water, which enable the operation of desalination processes at high fluxes or temperatures. Use of NF as the pre-treatment in MED and MD can enable their operation at temperatures of 120-130 °C and in RO at temperatures of 15-40 °C [149]. Hamed et al. used NF as the pre-treatment to remove scaling ions (e.g., sulphate) and to increase the top brine temperature of MSF to over 130 °C [150].

Heat- and electricity-based pre-treatments could use energy from

PVT collectors. The additional heat produced in PVT-powered electrically driven processes (compared to PV- or grid-powered systems) could be used for thermal softening. Thermal softening – which may require boiling of the feed water - is energy expensive; however, the marginal cost of heat from PVT collectors is relatively low compared to that involved in other methods. Additionally, in thermally driven desalination processes, the additional electricity could be used to drive filtration processes such as NF in order to remove divalent ions that tend to precipitate and scale. The energy consumption of NF is much lower than that of RO [151], so it is an efficient option for integration with a PVT-powered, thermally driven desalination process.

3.3.3. Increased water productivity at increased flow rates

In membrane-based processes, CP occurs naturally due to the finite water/salt/vapour permeation rates through membranes. One phenomenon that results from occurrence of CP in flow channels is that the concentration of solutions in boundary layers is different from that in the bulk. This difference means that the driving force to maintain the flow is smaller than that expected if it is calculated using the bulk concentrations. If flow rates are increased to enhance shear stress next to membranes, the mixing that is promoted in boundary layers can mitigate the concentration difference between the boundary layer and the bulk, and this enhances the driving force and increases water production rates. This improvement has been demonstrated in various membrane-based desalination processes, including RO [152], ED [14] and MD [153].

In particular, Luo et al. studied the coupled effect of the temperature and the flow rate in an MD process [129]. By comparing the performance of MD when operated in a range of Reynolds numbers at two operating temperatures, they concluded that raising the Reynolds number (which led to more electrical power for pumping) provided more benefits in high-temperature DCMD at 180 °C than in conventional temperature DCMD at 80 °C [134]. This indicated that there was a positive compound effect on the desalination performance through the combined use of additional electricity and heat, which aligned with the co-generation feature of PVT. In addition, the enhanced flow rate could also mitigate the potential occurrence of fouling in membrane-based desalination processes, because the increased shear stress would help to remove the precipitated salts or matter that aggregated on membranes [154].

Desalination performance through additional electrical energy consumption could be improved through hybridization of PVT with MD, RO or ED processes. In MD, the additional electricity supply (relative to traditional ST-driven processes) can enable operation of the system in off-grid areas, even at enhanced flow rates. In RO and ED, since a PVT collector is likely to show higher electrical efficiency than a standalone PV panel with the same solar irradiance, the greater power generation from PVT collectors could enable operation of the membrane process at high flow rates to improve water production rates and to reduce the scaling tendency.

3.3.4. Enhanced operational flexibility to meet varying water demands

With the coupling mechanisms discussed above, the co-use of electricity and heat from PVT collectors potentially can increase the energy efficiency and water production rates while mitigating the salt scaling in various desalination technologies. However, solar energy is intermittent and varies on timescales from seconds to years; and water consumption significantly depends on the weather conditions, particularly the ambient temperature. This mismatch between the energy available and the demand for water requires the use of storage (of energy and/or water) to balance the intermittent energy supply with the varying demand. Hot water tanks are the most commonly used form of thermal energy storage that can be integrated with thermally driven desalination processes [24], and electrically driven processes usually employ electrical battery storage [155]. However, battery storage is usually expensive and contributes to a large fraction of the total system cost [55]. The requirement for regular maintenance of batteries also restricts their deployment or reduces their lifetimes in rural areas, due to the lack of technical and economic resources to conduct this maintenance. This limits the use of solar-powered desalination or increases the water cost. To mitigate this issue in electrically driven desalination processes, flexible operation of desalination with storage of the water produced has been demonstrated to be a less expensive and easily maintained solution [156]. Richards et al. developed a flexible BWRO technology by investigating the boundaries for the creation of a safe operating window [157]. This flexible RO theory was later demonstrated experimentally to produce water under wind power at various speeds [158] and solar power at several irradiance levels [159]. A highly flexible ED technology was developed recently and demonstrated experimentally. The coupled hydraulic flow in the channel and mass transfer across the membrane were investigated. The voltage and flow rates were optimized smartly to match the solar PV power on the timescale of seconds and to maximize water production at every power level [14]. The significantly enhanced operational flexibility of ED was able to reduce substantially the water desalination cost and could enable production of solar-powered ED systems that are competitive in cost with grid-powered RO systems [160], making the sustainable technology particularly suitable to off-grid areas.

No study in the literature has considered the control and flexible use of electricity and heat from PVT collectors on a refined timescale (e.g., seconds or minutes). However, PVT-powered desalination systems could offer greater flexibility than PV or ST desalination systems. This could include increased degrees of freedom (e.g., operating temperature, flow rate and the hydraulic/electrical/thermal driving force) for the control and optimization of the desalination and the enlarged operational range (e.g., wider ranges of operations with higher flow rates and temperatures). Depending on the type of PVT collector, either electricity coupled with heat generation (e.g., conventional PVT collectors without spectrum splitting) or electricity decoupled from heat generation (e.g., spectrum-splitting PVT collectors) offers different operational constraints in terms of the control variables and variations in operational flexibility.

These benefits – increased degree of freedom for control, enlarged flexible operational range, and flexibly distributed electricity and heat generation – could significantly improve the coupling between intermittent solar energy and desalination by reducing the response time and increasing the ramping rate of desalination to instant solar fluctuations, covering a wider range of (daily and seasonal) solar energy variations, and providing bespoke (electrical and thermal) energy supplies for different desalination processes. Ultimately, all of these could lead to water cost reductions of solar desalination, which potentially would benefit people in off-grid areas. However, flexible co-use of electricity and heat would increase the complexity for the controller design and implementation, which will require smart solutions/algorithms that aim to balance the computational cost and (near) real-time operation constraints (e.g., refined control timesteps over seconds). Prior studies indicated promising potential of machine learning algorithms in managing this trade-off, such as generation and demand forecast using artificial neutral networks [161] and support vector machines [162], optimization using k-nearest neighbors [163], and real-time optimal control using reinforcement learning [164,165]. Further research is needed on these topics.

4. Discussion

A preliminary techno-economic analysis of potential PVT-desalination integrated systems is developed using performance and cost metrics, in comparisons with the alternative PV- and ST-desalination system, respectively.

4.1. Performance of PVT-desalination systems

The aim of this paper was to discover the potential of synergistically integrated PVT technology with different desalination processes. Here, we reference the working temperatures required by desalination technologies for PVT collectors to indicate their thermal and electrical efficiencies, as shown in Fig. 6. Generally, the thermal efficiency of a PVT collector decreases as the delivery temperature (i.e., output temperature of the PVT collector) increases due the increased convection and radiation heat losses, based on the energy balance law. The electrical efficiency also decreases as the delivery temperature increases, caused by the increased PV cell temperature [166]. Commercial PVT collectors – the solid red and blue lines in Fig. 6 – usually can produce thermal energy in a temperature range from 20 °C to 80 °C and can meet water demand through the use of electrically driven desalination processes and some thermally driven desalination processes. With advanced designs that mitigate heat losses and employ high-performance solar cells, both thermal and electrical efficiencies of PVT collectors can be improved (the dashed red and blue lines in Fig. 6) [90]. CPVT collectors can produce heat at higher delivery temperatures than 80 °C, which is suitable for thermally driven desalination processes. However, fewer CPVT collectors than non-concentrating PVT collectors are available in the current market.

Since PVT collectors combine the use of electricity and heat, their use can increase the overall solar utilization efficiency to 70-90 %, which is higher than the figures for conventional PV and ST collectors. Particularly in electrically driven desalination, the increased electrical efficiency of PVT collectors due to the cooling effect can lead to the production of more electricity than can be achieved in standalone PV panels operated at a higher temperature without cooling, so PVT collectors can provide more electricity for desalination than PV collectors. In addition, the availability of the additional electricity or heat from PVT collectors can be used as a "catalyst" to improve the energy-to-water efficiency (i.e., SEC in m^3/kWh) and the water productivity. The smart use of additional heat or electricity from PVT collectors can reduce the SEC by increasing the operational temperature (Section 3.3.1) or reducing the salt concentration via pre-treatment (Section 3.3.2), increase water productivity by removing ions that are liable to precipitate in pre-treatment (Section 3.3.2) and enhancing the mixing in boundaries (Section 3.3.3), and improve the flexibility for effective use of variable, intermittent solar energy (Section 3.3.4).

Two metrics are used to indicate the potential improvement offered by PVT-desalination systems. These are solar utilization efficiency and specific water production (SWP). The solar utilization efficiency represents the electrical, thermal and overall energy efficiencies of solar energy used for desalination. The SWP indicates the amount of water production per unit area of used solar panel. The SWP is a compound result of the SEC and solar utilization efficiency. Fig. 7 illustrates potential performance improvements through use of PVT-desalination systems in comparison with PV desalination and ST desalination systems respectively. For electrically driven desalination, the electricity generation by PVT collectors tends to increase due to the cooling effect of the feed water on the solar panels; in turn the heated feed water tends to reduce the SECs of various electrically driven desalination processes (Section 3.2.1). Thus, PVT-electro-desalination shows higher solar utilization efficiency and lower SEC than alternative PV desalination systems (Fig. 7). The improved solar-to-energy and energy-to-water efficiencies also could lead to improved water productivity per panel area under the same solar radiation conditions.

In contrast, PVT-thermo-desalination systems usually show slightly reduced thermal efficiencies compared to ST-driven desalination systems. The SEC of thermally driven desalination processes is mostly determined by the latent heat of water and the system's efficiency in the recycling and reuse of latent heat (namely GOR), so the variation in SEC is negligible if the ST collector is replaced by a PVT collector. Therefore, the reduced thermal efficiency and almost unchanged SEC lead to lower water production rates by PVT-thermo-desalination than those of ST-thermo-desalination at the same solar radiation levels and GORs in either single-stage or multi-stage systems. However, thermally driven desalination processes except for solar stills also require electricity to pump water, and most therefore rely currently on grid power or diesel generators in off-grid areas. This increases the operational energy costs and negative environmental impacts (e.g., carbon emissions and air pollution). The use of PVT collectors could mitigate these economic and environmental costs by enabling energy independence with the dual energy form of electricity and heat from PVT collectors.

Different desalination processes lead to significantly different SECs between electrically driven and thermally driven processes. The performance of electrically driven membrane processes depends on the material's permeability and transport selectivity, which have been improved with research and development. For example, use of highly permeable RO membranes has enabled operation of the membrane process at close to the thermodynamic transfer limit, which has

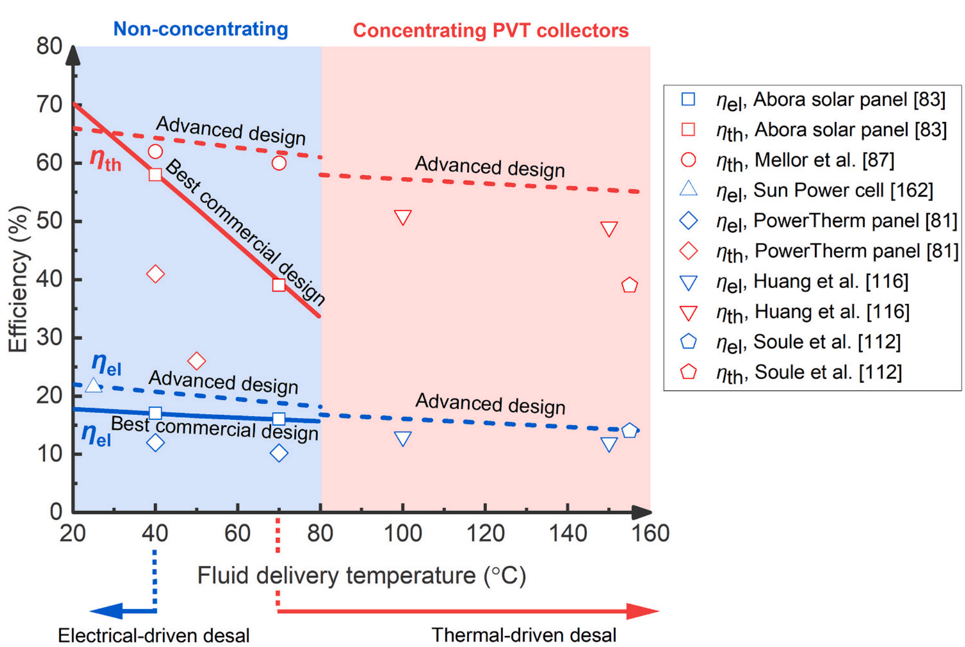

Fig. 6. Thermal and electrical efficiencies of PVT collectors (solid curves: today's best commercially available PVT collectors; dashed curves: advanced PVT designs).

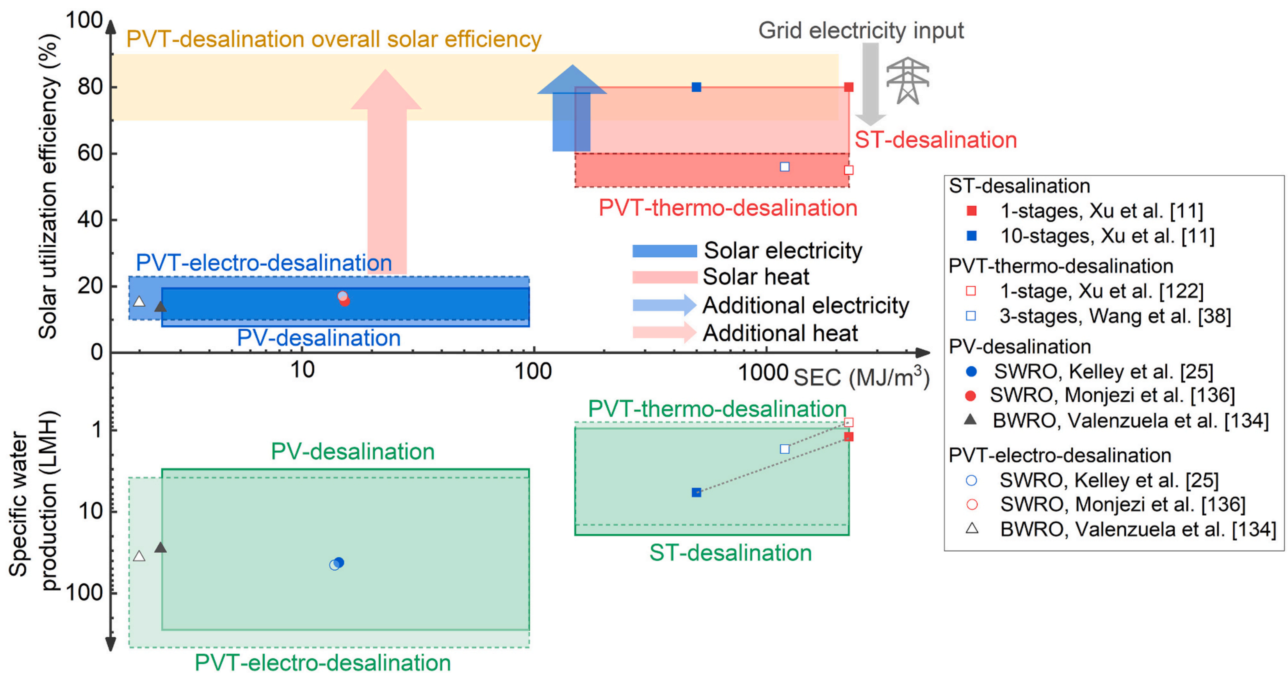

Fig. 7. Comparison of PVT, PV and ST desalination system performance. The *y*-axis of the upper part of the figure indicates the solar utilization efficiency, and the y-axis of the lower part indicates the specific water productivity, both of which are linked by the SEC (*x*-axis). The rectangular areas represent either PV or ST desalination systems; the blue and red rectangles represent electrically driven and thermally driven desalination systems, respectively.

substantially reduced SEC and increased the water productivity [167]; by contrast, the SEC of thermally driven processes is significantly affected by the latent heat of water in its vaporization. Thermodynamically, the latent heat of water shows negligible variation among different operating conditions, but higher thermal efficiencies and operating temperatures may enable introduction of more stages during the desalination in order to recycle and reuse the latent heat to reduce the SEC (Fig. 7). Nevertheless, as the SEC required for thermally driven desalination processes is usually one to three orders of magnitude higher than that required for electrically driven desalination processes, solar-powered electrically driven desalination (i.e., PV desalination and PVT electro-desalination) usually have increased specific water production (by one to two orders of magnitude) than the SEC of solar-powered thermally driven desalination (i.e., ST-desalination and PVT thermo-desalination).

4.2. Costs of PVT desalination systems

Through consideration of two cost comparisons that are published in the literature for state-of-the-art PV-RO and ST-MD systems, we aim to understand and identify an opportunity window for PVT desalination systems to be preferred economically over alternative solar desalination systems.

We develop a preliminary techno-economic analysis method (see Appendix) by use of relative cost and performance ratios to compare the relative levelized cost of desalinated water (RLCOW) among PVT desalination, PV desalination and ST desalination systems. Two recent pilot systems (see Appendix), i.e., PV-RO [168] and PV-MD [169], are used as the reference to indicate potential cost variations if PV and ST are replaced by PVT respectively. Although the reported costs of these early-stage systems may not reflect the costs when they are massively produced, the analysis method used in this study investigates the cost difference between current solar systems and alternative PVT systems. In this way, the cost reduction through the scale of economy likely will benefit all PV-, ST-, and PVT-systems if the production scales are similar.

In the cost analysis and comparison, it is assumed that the capital and operational costs of desalination systems, accessory equipment (e.g., electronics and cables), and hydraulic systems are same between PV-RO and ST-MD systems and alternative PVT systems. However, the two variables considered are: 1) the water productivity of PVT-desalination relative to PV desalination and ST desalination; and 2) the capital costs of PVT systems relative to PV and ST systems. Currently, the cost of a commercially available PVT system is usually 1.5-2 times that of an equivalent PV system [170] due to the more complicated structure and the requirement for additional accessories (e.g., pipes, pumps, tanks etc.) of PVT systems. The cost of a PVT system is usually 1-1.5 times that of an equivalent ST system [170].

As shown in Fig. 8, PVT electro-desalination systems tend to exhibit higher water productivity than PV electro-desalination systems, due to the additional heat that may reduce the SEC; while the water productivity of PVT thermo-desalination systems may be lower than that of ST thermo-desalination systems, due to their low thermal efficiency in the conversion of solar radiation to heat. Therefore, in the two considered cost comparisons, i.e., PVT-RO vs. PV-RO and PVT-MD vs. ST-MD, the relative water productivity is set to be 1-1.5 and 0.5-1 respectively, which represents the possible performance increase and decrease in PVT electro-desalination and PVT thermo-desalination systems, respectively.

The preliminary results are plotted in Fig. 8. The estimated cost range of current PVT systems is represented by the grey area. The result indicates an opportunity window for PVT desalination within the relative cost and performance ratios considered. The studies in the literature indicate possible SEC reductions of 8 % or 40 % by increasing the temperature in SWRO or BWRO respectively (Section 3.2.1). Compared to the PV-RO system for desalination [168], the 8-40 % SEC cost reduction is plausible and may lead to up to ~20 % cost reduction if the RO system uses PVT as the energy system. Furthermore, depending on the operating temperature, current PVT collectors with good glazing cavities and emissivity-control coatings exhibit reduced thermal efficiency of about 10-20 % compared to ST collectors [90]. Due to the saved operational electricity cost, the PVT-MD system may display a lower overall cost by up to ~20 % than the ST-MD system [169] if the water production decrease is small. The cost reduction of PVT-MD is mainly due to the saving of the operational cost in pumping water, as the additional electrical power is supplied by the PVT collector.

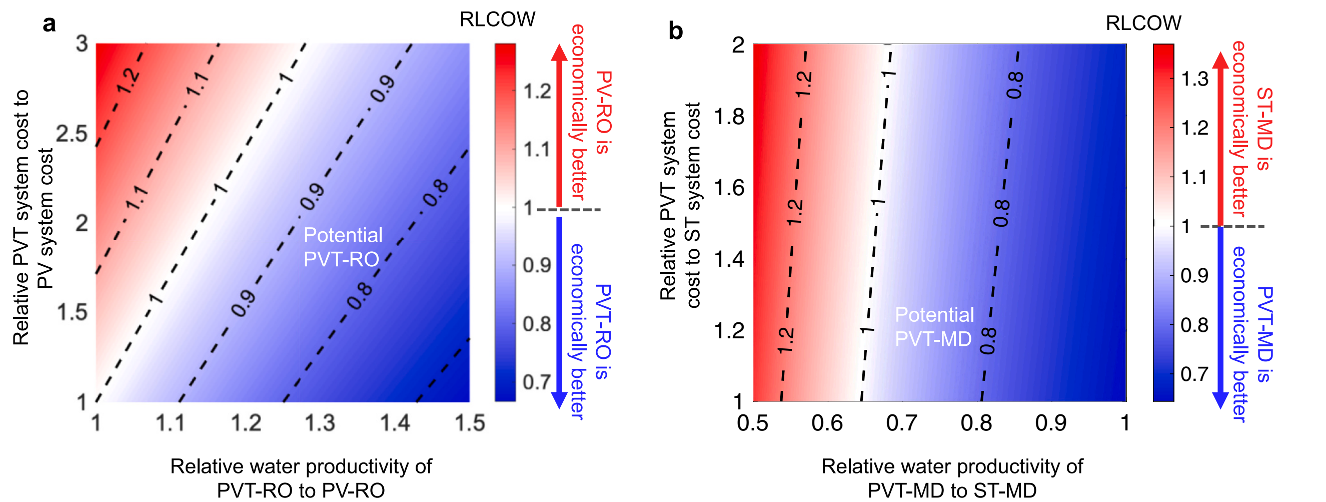

Fig. 8. (a) Ratio of the RLCOW of the PVT-RO system to that of the ST-RO system, and (b) ratio of the RLCOW of the PVT-MD system to that of the PV-MD system for different solar system costs and water production rates of the PVT system relative to PV and ST systems, respectively.

The opportunity window shows a promise for future implementation of PVT-desalination systems, if both electricity and heat could be co-used. Given the dominance of RO in newly installed desalination capacity and the prominent scalability of MD as a thermally driven desalination process, the potential water cost saving indicates opportunities for immediate positive impact, which could help address water challenges in off-grid areas.

Table 3 lists a high-level comparison between PV desalination, ST desalination and PVT desalination systems. This review and the preliminary techno-economic analysis indicates that PVT desalination systems have the potential to achieve higher solar utilization efficiencies, higher water production rates in electrically driven desalination processes, energy independence through use of solar power, lower lifetime water cost, and improved tolerance to deal with high-salinity water, in comparison with PV desalination and ST desalination systems. However, these potential technical and economic benefits rely on the efficient generation of electricity and heat by PVT collectors, the effective use of the dual-energy outputs in desalination processes, and the long-term robust performance subject to negative impacts (e.g., fouling). To achieve these, the system designs and operation of PVT desalination systems are complicated, and this scenario leads to higher capital costs compared to those of PV desalination and ST desalination systems. Particularly, there is a lack of systematic analysis in the literature to investigate the trade-offs between various ways of co-using electricity and heat to improve the system performance. For example, the energy balance of additional electricity and heat from PVT collectors to increase the operating temperature and to mitigate scaling via a designed pre-treatment has not been considered. Also, the technology readiness level (TRL) of smart use of electro-thermal coupling in PVT desalination systems is low (TRL 1-3), and a significant amount of fundamental research is required to understand the limits of the performance improvement and the long-term performance of PVT desalination. Laboratory-scale experimental studies and pilot-scale system demonstrations are also needed to verify the developed theory and the technology's performance.

Table 3
Comparison of desalination performances driven by PV, ST, and PVT solar-powered systems. A higher star level indicates better performance.

	PV desalination	ST desalination	PVT desalination
Solar utilization efficiency	★★★☆☆	★★★★☆	★★★★★
Water productivity	★★★★☆	★★★☆☆	★★★★★
Energy independence	★★★★★	★★★★☆	★★★★★
Adaptability to varied water salinity	★★★★☆	★★★★★	★★★★★
Capital cost	★★★★★	★★★★☆	★★★☆☆
Levelized cost of water	★★★★☆	★★★★☆	★★★★★
System complexity	★★★★★	★★★★☆	★★★☆☆
Technology maturity	★★★★☆	★★★★☆	★★☆☆☆

5. Conclusion

Global water scarcity negatively impacts billions of people across the world. The desalination of saline water (e.g., seawater and brackish water) to produce drinkable water is a promising solution to this problem, with a potentially endless feed water resource. However, the high energy consumption of conventional desalination systems has limited their use to affluent global regions with well-developed power infrastructure, and also meant that most of the energy supplied to current desalination plants comes from the burning of fossil fuels, which leads to significant emissions. Solar desalination has therefore emerged as a promising solution to the provision of water to rural and low-income areas, and its use has started to show positive impacts in the context of addressing growing global water shortages by using various solar desalination systems. However, conventional PV and ST solar technologies cannot fully utilize the solar radiation; solar-powered PVT systems have a much higher overall solar utilization efficiency potential via full solar spectrum to produce dual electrical and thermal energy outputs.

In this paper, we reviewed and analysed synergies between the electrical and thermal energy generation from solar PVT collectors and the energy consumption characteristics of various desalination processes. It has been found that the required amounts of energy are different between electrically-driven and thermally-driven desalination processes, and that between one to three times more thermal energy is required in thermal desalination processes than is required in electrical desalination ones. Non-concentrating PVT collectors can provide heat at temperatures up to about 80 °C, at most, which is suitable for electrically-driven, but also some thermally-driven desalination processes. Concentrating solar PVT collectors could deliver thermal energy at higher temperatures, and these could be used in high-temperature thermal desalination processes.

PVT collectors can provide additional energy from the same area, thereby unlocking performance improvements of the wider solar desalination system at a reduced cost. From theoretical perspectives, opportunities to use electricity and heat for reducing entropy generation are first discussed. Then, in practical applications, the additional heat or electricity from PVT collectors could be used to reduce the SEC in various desalination processes, increase the separation selectivity in ion exchange processes, remove via pre-treatment the salts that are liable to precipitate, improve the mixing in boundary layers, and enhance the operational flexibility for use of variable solar energy. In particular, compared to ST-desalination systems that generally required external (electrical grid) power to pump the water around the plant, PVT desalination systems can provide both electricity and heat to enable entire energy independence from energy infrastructure or external (diesel) fuel sources. This energy independence also may alleviate the burden of the total energy costs and mitigate the lifetime environmental impacts of desalination. By contrast, the smart use of the dual outputs of PVT collectors in electrical desalination processes could lead to both increased solar energy utilization efficiencies and higher water productivity. These two technical benefits could contribute to cost reductions in the solar-powered and desalination systems respectively. Our preliminary cost analysis also quantitatively supports the potential capital and operational cost reductions, indicating a promising opportunity window of PVT desalination systems with up to ~20 % lower lifetime water costs that those of PV and ST desalination systems.

Although technical and economic benefits are indicated through the literature review, theoretical and preliminary techno-economic analysis, challenges over wider performance and cost aspects such as high upfront costs, complex system design and operation, and relatively low technology maturity, may limit the usage of PVT desalination systems in the real world. More research should be conducted to elucidate the electro-thermal coupling mechanism and to develop parametric theories/models for the co-use of electricity and heat in different desalination processes. Armed with this new knowledge, advanced optimization and control can be developed to improve the performance of scaled-up systems, and to prepare for pilot and realistic scale-system demonstrations. With the continuous development and cost reductions in PVT and desalination technologies, PVT desalination systems could be an important and complementary low-carbon option with high efficiency in the use of solar energy and high productivity in the production of freshwater.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Techno-economic analysis method

We developed a preliminary techno-economic analysis framework by using relative cost and performance ratios to compare PVT desalination, PV desalination and ST desalination systems. The cost of a commercially available PVT system is usually 1.5-2 times that of an equivalent PV system [170] due to the more complicated structure of PVT systems and their requirement for additional accessories (e.g., pipes, pumps, tanks, etc.). The cost of a PVT system is usually 1-1.5 times that of an equivalent ST system [170]. PVT systems generate electricity and useful heat simultaneously from the same area, with much higher overall efficiencies than separate, standalone PV and ST systems. Although the cost of PVT systems is usually higher than that of PV or ST systems, the payback time and levelized costs of energies of PVT systems have been proved to be lower than those of standalone PV and ST systems in domestic combined heating and power applications.

We developed a preliminary tech-economic framework to analyse the tech-economic performance of PVT desalination systems compared to conventional PV- and ST-driven desalination systems. Here, we use the levelized cost of desalinated water (*LCOW*) as a tech-economic indicator, i.e., the sum of system costs over the system's lifetime divided by the sum of freshwater production over lifetime. Of note is that *SEC* is usually used to quantify the conversion efficiency of energy-to-water in kWh/m^3, while the *LCOW* is used to quantify the economic performance of water productivity.

$$LCOW = \frac{CRF \bullet (SSC + DSC + AC) + OMC + EC}{Q} \tag{1}$$

where *SSC*, *DSC*, *AC*, *OMC*, and *EC* are, respectively: solar-power system cost (i.e., the capital cost of the PVT, PV or ST system); desalination system cost (i.e., the capital cost of the MD or RO system etc.); accessory costs (i.e., electronics and cables); operating & maintenance cost per annum (assumed to be 10 % of the capital cost per year); and electricity cost per annum (i.e., additional electricity taken from the grid). *Q* is the annual water production rate in m^3.

Based on Eq. (1), converting the *LCOW*s to the ratio of the *LCOW*s of PVT-desalination systems to ST-desalination or PV-desalination systems is done by:

$$r_{LCOW} = \frac{CRF \bullet (r_{SSC} \bullet SSC + r_{DSC} \bullet DSC + r_{AC} \bullet AC) + r_{OMC} \bullet OMC + r_{EC} \bullet EC}{CRF \bullet (SSC + DSC + AC) + OMC + EC} \bullet \frac{1}{r_{WP}} \tag{2}$$

where r_{SSC}, r_{DSC}, r_{AC}, r_{OMC}, r_{EC} and r_{WP} are the ratios of *SSC*, *DSC*, *AC*, *OMC*, *EC* and *WP* of PVT desalination systems to those of conventional PV or ST desalination systems. The ratio of *LOCW*, r_{LCOW}, is the key indicator to compare the tech-economic performance between PVT-desalination systems and PV- and ST-desalination systems. An $r_{LCOW} < 1$ indicates that the PVT-desalination system has a lower LCOW and a better performance than the PV- or ST-desalination system, or vice versa.

Here, we firstly select a typical electrically driven desalination technology, i.e., RO, integrated with a liquid-based PVT collector, and then compare it with a conventional PV-RO system as published previously [168]. The values of r_{DSC}, r_{AC} and r_{OMC} are assumed to be equal to 1. Fig. 6a shows the LOCW ratio of the PVT-RO system to that of the conventional PV-RO system for different r_{SSC} and r_{WP}. PVT collectors produce electricity at higher efficiency than do PV panels, and they produce additional heat output. Thus, r_{WP} is usually >1. The cost of a PVT system is usually 1.5-2 times that of an equivalent PV system [170] (i.e., r_{SSC} usually falls in the range of 1.5-2).

A typical thermally driven desalination technology, i.e., MD, integrated with a PVT collector, is studied and then compare it with a conventional ST-MD system as published previously [169]. The r_{DSC} and r_{OMC} are assumed to be equal to 1. The electricity output of the PVT collector is taken to cover fully the pump electricity demand of the MD system [169]. Thus, the value of r_{EC} is assumed to be zero.

Fig. 6b shows the ratio of the LCOW of the PVT-MD system to that of the ST-MD system for different r_{SSC} and r_{WP}. The thermal efficiency of PVT collectors is usually 0.7-1 times that of ST collectors, depending on the designs of PVT collectors, as shown in Fig. 5. Thus, r_{WP} usually falls to a lower value in the range of 0.5-0.8. The cost of PVT systems is usually 1-1.5 times that of equivalent ST systems [170] (i.e., r_{SSC} usually falls in the range of 1-1.5). The value of r_{LCOW} is not sensitive to r_{SSC}, as the cost of the solar collector occupies a minor percentage of the total cost of the ST-MD system (<10 % according to published data [169]). The value of r_{LCOW} decreases as r_{WP} increases. Thus, the LCOW of the PVT-MD system can be reduced by improving the thermal efficiency of the PVT collector, although this may increase the capital cost of the PVT collector. Fig. 6 has shown the great potential of PVT-desalination systems compared to conventional PV or ST desalination systems. The LCOWs of PVT desalination systems have been shown to be lower than those of PV or ST desalination systems. However, more effort is required to further reduce the value of r_{LCOW}.

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