



Solar thermal utilizations revived by advanced solar evaporation

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Recent advances in the development of advanced solar evaporation have opened up new possibilities for the revived explorations of solar thermal utilization. Among them, microstructure-enabled solar evaporation received the most attention due to its unique capability of solar energy harvesting and localized heating effects, which are beneficial for an enhanced vapor production rate, a fast-responsive high-temperature steam generation, and so on. Here we review the primary photothermal properties of interfacial solar evaporators and the recent progress in potential point-of-use applications of solar desalination, solar sterilization as well as enthalpy-recycled power generation. A brief summary and prospective analysis have been discussed as well.

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Energy and water are two of the most threatening global challenges for human society. The solar thermal utilization for water and/or power generation is regarded as a promising roadmap toward renewable energy-water nexus, which has garnered revived interest due to the emerging development of interfacial solar vapor generation (ISVG). Unlike conventional liquid-to-gas phase transition of water, ISVG is triggered mainly by solar energy and featured by its thermodynamic localization nearby interfaces [1^{*}], leading to a pronounced energy transfer efficiency and promising applications for the water-energy nexus (Figure 1). The ISVG process

is reckoned as a dynamic equilibrium of different energy flows, which reads:

$$P_{\text{eva}} + P_{\text{ref}} + P_{\text{rd}} + P_{\text{cv}} + P_{\text{cd}} = P_{\text{solar}} \quad (1)$$

where P_{solar} is the solar radiation, P_{eva} is the energy transferred for water evaporation; P_{ref} , P_{rd} , P_{cv} , and P_{cd} refer to reflection, radiation, convection, and conduction loss, respectively. The energy transfer efficiency is defined as

$$\eta = P_{\text{eva}}/P_{\text{solar}} \quad (2)$$

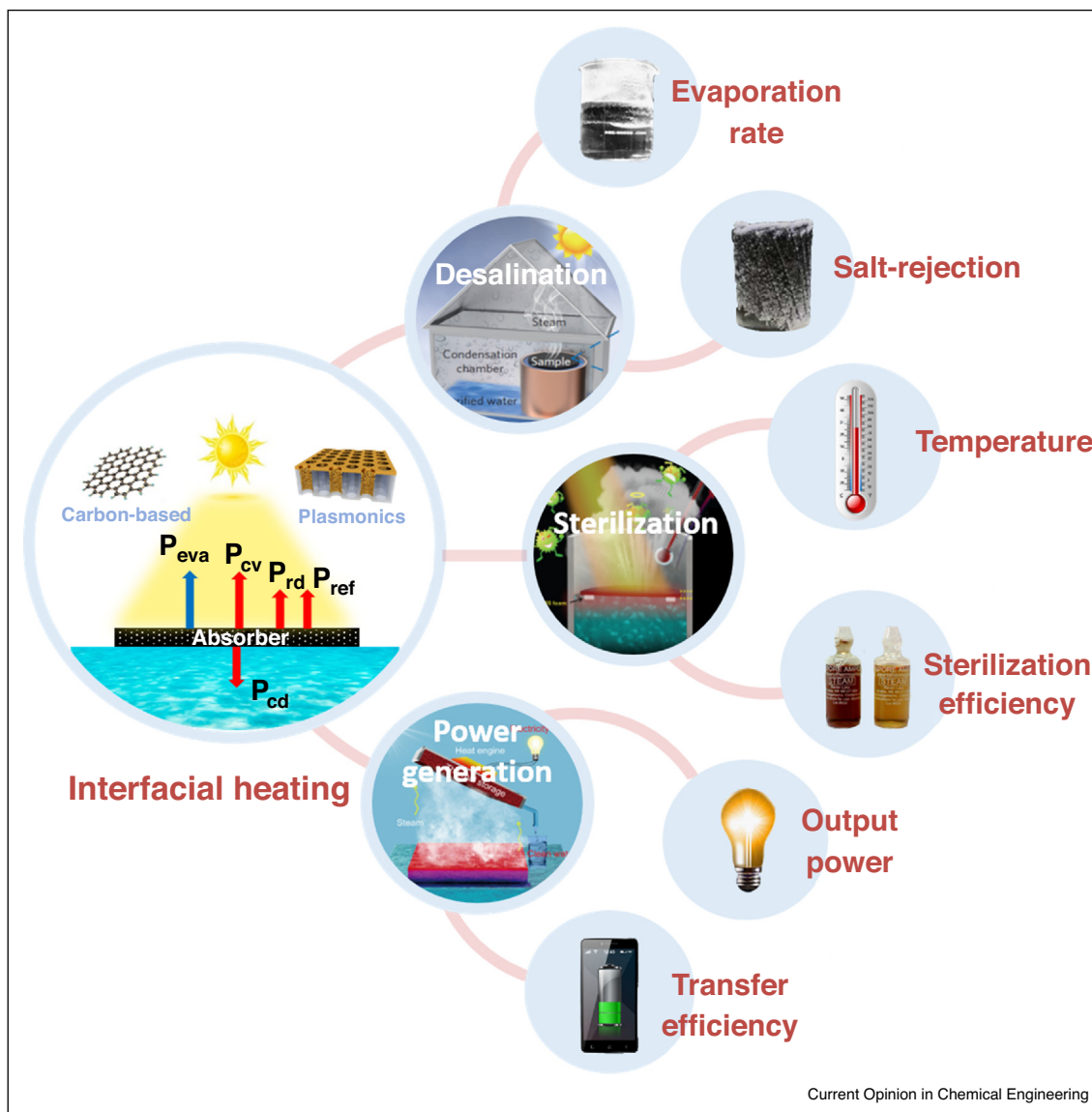
In order to maximize the efficiency, multiple strategies have been developed to minimize the optical loss (P_{ref}) and thermal loss (P_{rd} , P_{cv} , P_{cd}), including nanophotonic designs for perfect solar absorbers [2^{*}], thermal management of minimal or even negative temperature increment [3] as well as water path engineering [4]. Two widely employed photothermal materials are plasmonic and carbon-based nanomaterials, both of which are claimed capable of reaching an average absorptivity of >95% over the solar spectrum [5,6]. By optimizing material properties, thermal management, water supplement, and structural design, efficient and rapid solar steam generation is gradually being realized [7–15]. So far, the maximum reported energy conversion efficiency has exceeded 90% [16]. This high efficiency, despite the risk of being compromised in industrial large-scale applications, still promotes intensive researches into various fields related to environment, sanitation or energy production. In this review, we mainly focus on ISVG-enabled solar thermal utilizations such as desalination, sterilization and power generation (Figure 1), in which crucial issues toward point-of-use applications are highlighted (energy transfer efficiency, evaporation rate, salt rejection, vapor temperature, etc.).

Solar evaporation enabled point-of-use solar thermal utilizations

Solar thermal-based desalination

Solar thermal-based desalination, which is one of the most promising solar thermal applications, aims at water purification from seawater by exclusively consuming solar energy. By essentially increasing the vapor production rate as well as energy transfer efficiency via concentrated heating process, ISVG has inspired new progresses in the field of solar desalination. In the past few years, two kinds of photothermal materials, plasmon-based and carbon-based materials, have been intensively explored as solar evaporators in various desalination devices [5,21].

Figure 1



An overview of interfacial solar vapor generation.

A dynamic equilibrium of energy flow, as well as major applications of SVG: desalination, sterilization, and power generation, with respective figure of merits [3,17,18**,19,5,20].

As a complimentary off-grid water purification technology compared to the large scale filtration-based desalination or multiple effect distillation [22], the solar evaporation-based desalination is advantageous for the ubiquity of available renewable energy and water supply, the portability of the entire devices, as well as the cost effectiveness for both infrastructure and maintenance [23]. Two of the most crucial components for point-of-use off-grid solar desalination are considerable water production and long-term stability of the systems. There are a couple of review papers that systematically overviewed recent advances in solar evaporation with photothermal

materials, structures engineering strategies and system optimization toward water production [1*,24]. On the basis of the fast progresses during the past few years, the water production rate together with the energy transfer efficiency have enabled considerable improvements via enhanced sunlight absorption and heat localization, which reaches $76.8 \text{ L/m}^2/\text{day}$ reported by Zhao *et al.* in 2018 through a well-designed nano-porous gel [25]. Its unique molecular mesh can successfully reduce the latent heat for highly efficient water production which can meet the requirements of drinking water for more than four adults a day.

Here we intend to focus exclusively on long-term stability, the bottleneck for the overall performance of a device in its lifecycle, which mostly depends on the salt rejection capability of the evaporator. Accumulation of salt tends to block water transfer and steam evaporation, decrease solar absorption, and therefore compromise the overall performance of SVG evaporators.

With the development of ISVG for solar desalination, the energy transfer efficiency and salt clogging issue are always inextricably linked. Researchers have been trying to enable a balance from both material and system levels. In 2016, Zhou *et al.* reported the first aluminum-plasmon-based solar desalination with an energy transfer efficiency of $\sim 90\%$ under four sun illumination (Figure 2a) [26]. No significant decrease of evaporation rates ($<10\%$) was observed after 25 cycles (Figure 2b), which is probably due to the self-limiting aluminum oxide layers as well as the relative hydrophobicity of metals.

A more comprehensive design from the material level was presented by Xu *et al.* in 2017 with fine interfacial hydrophilicity design [27]. As shown in Figure 2c, a Janus structure with hydrophobic carbon black nanoparticles (CB) coated the polymethylmethacrylate (PMMA) upper layer for light absorption, and an extra hydrophilic polyacrylonitrile (PAN) lower layer was employed for water transport and salt rejection. The hydrophilicity of water paths and different layers in the artificial evaporators were well controlled, preventing the brine from reaching the top of the structure (Figure 2c). A strong salt resistance can be clearly suggested from the negligible degradation in evaporation rates, which strongly contrasted with the control experiment with a mere CB-PAN layer (Figure 2d).

In the meantime, a system level design for salt rejecting solar desalination device was reported by Ni *et al.* in 2018. They proposed a salt-rejection evaporation structure through alternating layers of insulating polystyrene foam and white cellulose fabric (Figure 2e) [28]. The porosity and hydrophilicity of the fabric enabled wicking of water to the absorber, while concentrated salt could be back into the underneath bulk water via diffusion and/or advection processes. The as-fabricated structure is reported to be considerably anti-fouling in salts, and a stable evaporation rate of $2.5 \text{ L m}^{-2} \text{ day}^{-1}$ is achieved (Figure 2f).

The purification efficiency and the water production rate are two points to evaluate the performance of seawater treatment. Compares to commercial desalination methods such as reverse osmosis, solar vapor desalination technique has as-high salinity removal performance ($>99\%$) but low water production rate. In order to enhance its water output under the premise of maintaining high purification efficiency, manipulation

of micro-structures appears to be an effective way. A water generation rate of $3.2 \text{ kg m}^{-2} \text{ h}^{-1}$ was reported by Zhao *et al.* in 2018 through a well-designed nanoporous gel [25]. Its unique molecular mesh can successfully reduce the latent heat for highly efficient water production which can meet the requirements of drinking water for more than four adults a day. With the research of solar-driven evaporation on molecular level gets further development, an even higher water production rate can be expected and the applications' field will be expanded.

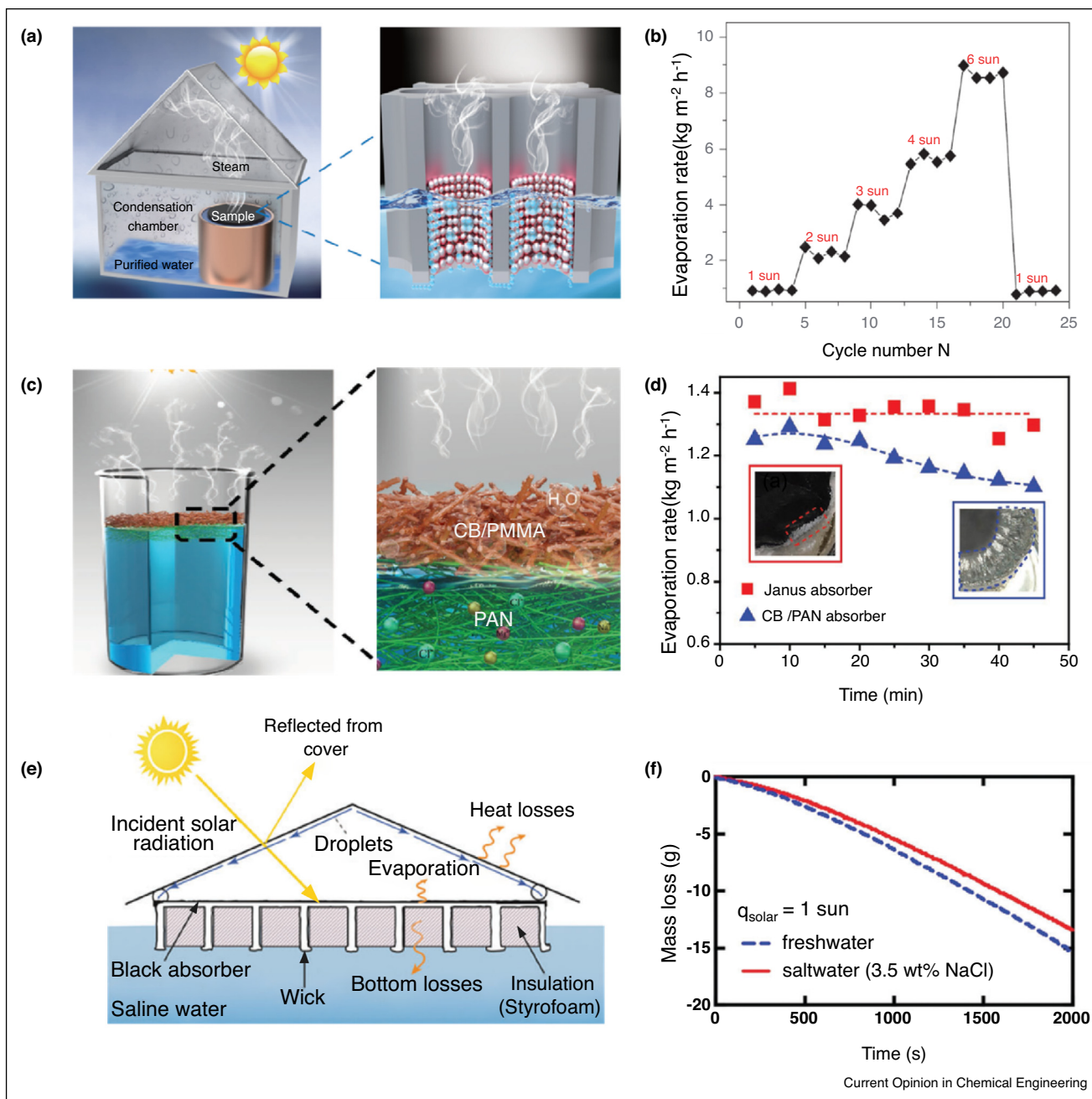
Solar sterilization

Solar sterilization enabled by solar steam is another promising application of off-grid solar thermal utilization. To effectively neutralize the bacteria, higher temperature steam is required with respect to solar desalination, which is commonly guided into a sealed container to transfer heat to surrounding bacteria under high-pressure conditions. In addition, each sterilization cycle should be established within minutes, allowing the entire procedure to be time-efficient. Hence, two of the most crucial issues of solar sterilization are the temperature and response time of the solar steam.

The steam temperature, as an indicator of sterilization efficiency, should be above the tolerance threshold of the bacteria. Nanostructured solar absorbers, through near-perfect absorption of the incoming solar power, provide a new pathway for much shorter rising time in steam temperature. In 2013, by dispersing Au nanofluids randomly into water, Neumann *et al.* designed both a closed-loop and open-loop solar autoclave aimed at passive sterilization (Figure 3a) [29]. In an operation cycle, they respectively achieved an exposure period of 115°C for 20 min, and 132°C for 4.6 min (Figure 3b), which are in accordance with the Food and Drug Administration sterilization requirements (Figure 3c). Zhang *et al.* fabricated a reduced graphene oxide/polytetrafluoroethylene composite membrane with an average absorptivity of $\sim 90\%$ which, combined with localized heating effects, realized a localized temperature of $>140^\circ\text{C}$ without the introduction of an autoclave [19].

In pursuit of a faster response time and a stronger stability, Li *et al.* designed a biochar-based solar vapor generation system (Figure 3d), which in average takes $\approx 122 \text{ s}$ to complete the heating phase, as opposed to 1040 s for bulk evaporators (Figure 3e) [30]. One typical sterilization cycle is accomplished in 17.3 min (at 121°C) or 8.4 min (at 132°C), one order of magnitude quicker than that of a typical volumetric-heating-based sterilization cycle. Stability of the steam is also guaranteed from the device, since an interval of over 15 min is witnessed for the steam to go beyond 121°C , during which time the temperature is maintained at 132°C for 5 min (Figure 3f).

Figure 2



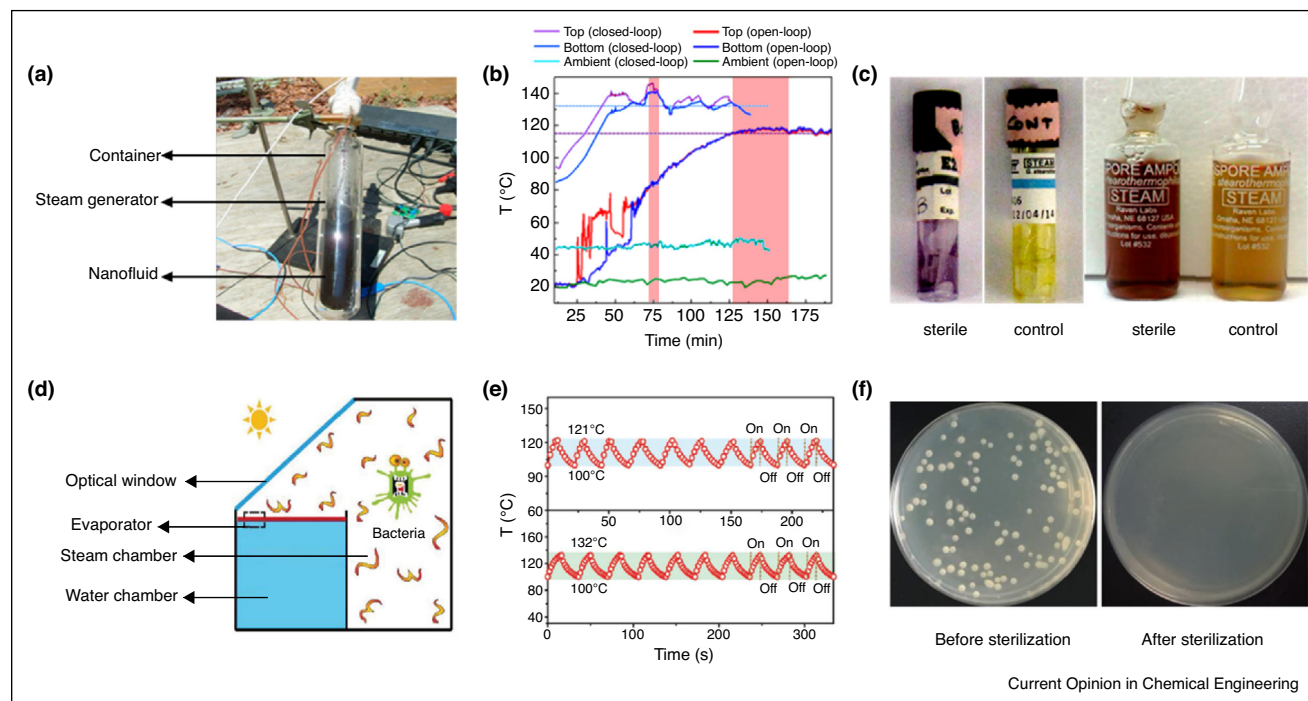
Emergent interfacial solar evaporation toward point-of-use seawater desalination.

(a, b) 3D self-assembly of aluminum nanoparticles into an anodic aluminum oxide membrane (a), which enables a high evaporation rate and exhibited stability (b) [5]. **(c, d)** Janus absorbers for salt rejection [27]. Different hydrophilicity of multiple layers manipulated the salt repelling capability (c), where the evaporation rate would leave uncompromised with time accumulating (d). **(e, f)** Alternating layers of insulating polystyrene foam and white cellulose fabric [28], which allows for both water wicking and salt repelling (e). The evaporation rate of saline water is almost the same as that of freshwater (f).

In addition, Li *et al.* conducted a systematic investigation on the thermodynamic and kinetic properties of ISVG enabled solar sterilization, which clarified both response time and stability of steam generation based on a

recyclable steam sterilization system. The rapid response of the whole sterilization system enables the prompt establishment of multiple steam sterilization cycles. With enhanced stability, the system can be maintained in high

Figure 3



Solar sterilization by advanced solar vapor generation.

(a–c) Compact solar autoclaves by dispersing gold nanoparticles into bulk water [29], with configuration (a) and plots of temperature rise of the generated steam in open-loop and closed-loop systems (b). Temperature of the two different locations in autoclave (top and bottom) is also presented for comparison and the ambient temperature. The dashed line represents the required temperature for sterilization, and the red box represents the sterilization regime (115°C for 20 min or 132°C for 4.6 min). Sterilization effects were characterized via biological indicators, where the notable color change presented a successful elimination of bacteria (c). **(d–f)** Biochar-based solar absorbers for solar steam generation [30]. Configuration (d), as well as temperature oscillations for several cycles to demonstrate strong stability and fast responsivity (e). Pictures of samples before and after sterilization are also presented.

temperatures for a long period, which further ensures the performance of sterilization. Interfacial evaporators, by targeting at merely thin layers at the water-vapor interface, are more flexible in adjustment of temperatures, with characteristic heating period largely diminished compared to bulk evaporators [30]:

$$\frac{\tau_{\text{bulk},121^{\circ}\text{C}}}{\tau_{\text{interfacial},121^{\circ}\text{C}}} = 1 + 148 \frac{V_W}{V_S} \quad (3)$$

Note that Eq. (3) provides the quantitative figure of merit for the response time of an ideal interfacial solar sterilization system, in which all the potential heat dissipation channels are ignored. $\tau_{\text{bulk},121^{\circ}\text{C}}$ and $\tau_{\text{interfacial},121^{\circ}\text{C}}$ represent the characteristic heating time to a steam of 121°C, respectively, in bulk and interfacial evaporators. V_W and V_S refer to volumes of liquid water and steam, respectively, with a ratio typically close to unity. As can be apparently seen from the formula, interfacial systems are hundreds of times faster at establishing a dynamic equilibrium. Systems with larger volume ratio

can further accelerate the sterilization procedure. One should comprehensively consider the time cost and sterilization capability when large volume ratio is employed. In addition, to achieve comparable performance to the ideal case, at least four indispensable issues should be carefully considered: (1) Reduce the heat capacity of the container; (2) Reduce heat conduction to air and water bodies; (3) reduce heat convection to the external environment; (4) Increase the light absorption rate.

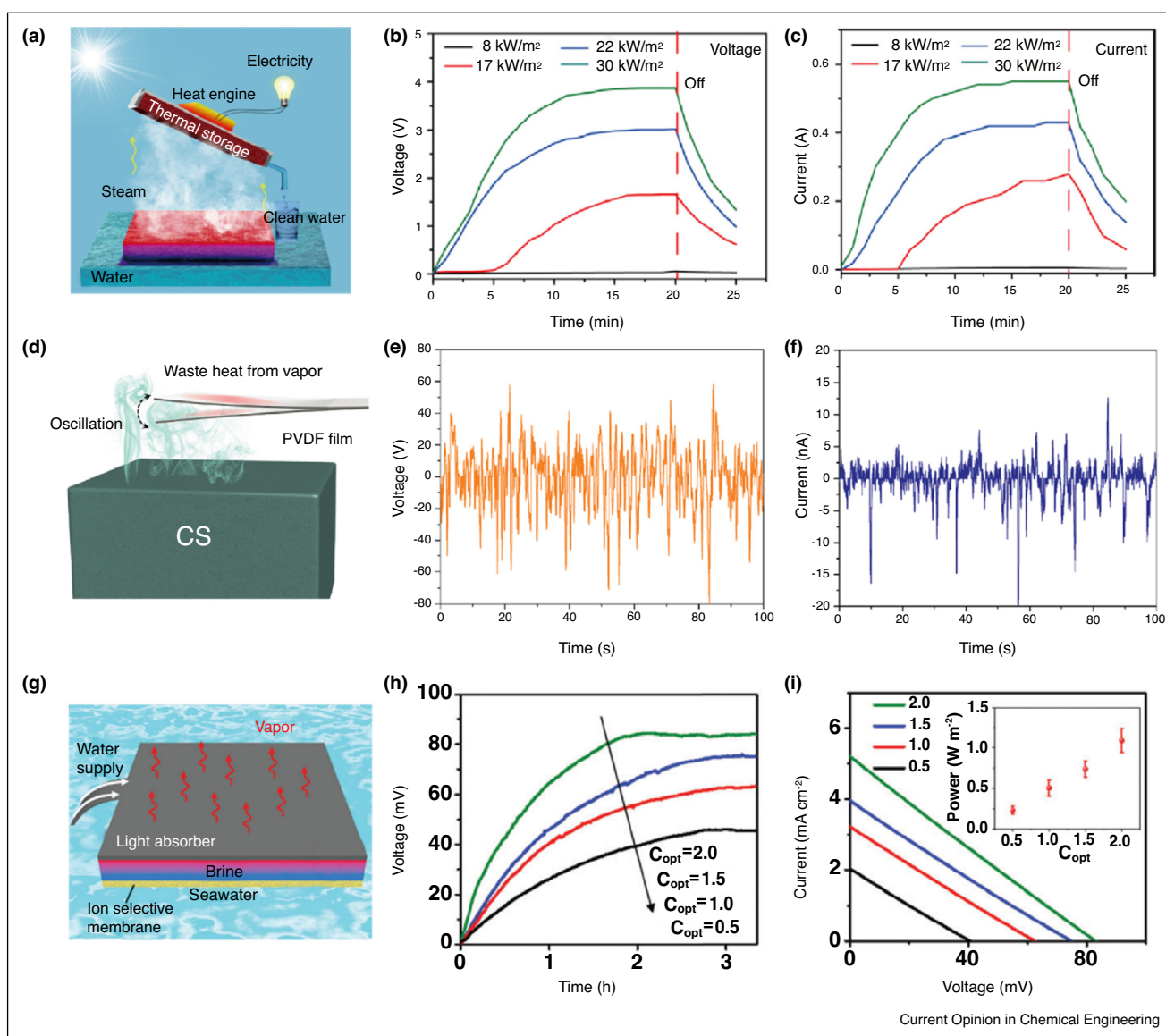
Traditional volumetric sterilization has long been suffering from complicated circulation due to long heating and cooling time period. Taking the representative commercial autoclave for example [31], it commonly takes > 15 min to heating up from 20°C to 121°C and ~ 50 min to cool down from 121°C to 100°C (the standard medical sterilization procedure), which can be distinctly shortened to ~122 s and 14.8 s respectively (Figure 3e). Such a fast-responsive performance can essentially promote the sterilization speed and capability. By employing solar interfacial sterilization system, one can finish a complete sterilization cycle within 17.3 min

(121°C) or 8.4 min (132°C) respectively, one order of magnitude shorter than that of a typical volumetric heating-based sterilization cycle. The advantage of interfacial steam generation system can be attributed to the low thermal mass of the water layer which leads to the dramatical temperature change. Moreover, the low thermal capacity of the outside steam container also reduces the heating and cooling time. This short sterilization cycle together with stable continuous sterilization performance makes this interfacial-heating-based system very high throughput, ideal for resource-stress areas.

Solar power generation

So far, most progresses on solar thermal utilizations are focusing on the direct energy transfer efficiency from the sun to the water, during which the steam enthalpy is totally wasted during condensation. A more efficient strategy for solar thermal utilization is to recycle the phase change enthalpy. Typically, high optical concentrations are required to generate much higher temperatures in order to fully realize the recycling of enthalpy, compared to applications such as solar desalination (<100°C) and sterilization (<200°C) [1*].

Figure 4



Phase-change enthalpy reusable solar power generation.

(a–c) Electricity generation by storing and recycling steam enthalpy [3]. System configuration (a), as well as time-dependent open-circuit voltage change (b) and short-circuit current change (c). (d–f) Ferroelectric fluoropolymer polyvinylidene fluoride (PVDF) to harvest thermomechanical responses [34]. Diagram (d), as well open-circuit voltage (e) and short-circuit current (f) characteristics. (g–i) Salinity gradient for building potential gradient and hence electricity generation [35]. Diagram (g), as well open-circuit voltage (h) and short-circuit current (i) characteristics for different optical concentrations (C_{opt}).

Basically, the performance of electricity generation is calibrated via the following equation, where P_I and P_{solar} refer to electric and solar power, respectively:

$$\eta = P_I/P_{solar} \quad (4)$$

The inchoate attempts at solar steam-based electricity generation were focusing exclusively on the output power; high-temperature steam, although produced simultaneously, was not intended for practical use. Chen *et al.* in 2015, for example, made a first attempt by proposing an evaporation-driven engine that can perform tasks such as locomotion and electricity generation [32]. Later, Xue *et al.* discovered an open-circuit voltage as large as 1 V between electrodes of carbon nanotube films, whilst evaporating highly deionized water with the same carbon sheet [33]. The application of the density functional theory suggested that the generated stable current 0.7 e in the graphene layer output is attributable to a charge redistribution of approximately, induced by the massive C–O–C group underneath.

However, for practical applications, the results in experiments are far from satisfactory. For one thing, a complicated predisposal process for normal liquids, especially seawater, is required to avoid the negative effect induced by salinity. The overall performance of the system is also far below the industrial requirements. Because of both high consumption and great complexity of the processes, hopes of synchronically performing desalination and outputting electricity were considered highly unattainable.

Recently, researchers are exploring electricity generation utilizing the latent heat of vapor, a more feasible approach regarding evaporation of saline waters, both the instant change of temperature and mechanical structure can be served as power resources. In 2018, Li *et al.* fabricated a graphene-oxide coated non-woven fabric, which can enable the generation of electricity besides traditional desalination, by storing and recycling steam enthalpy (Figure 4a). The generated high-temperature steam was directly guided into a chamber for thermal-electric energy conversion, and under 30 suns, the open-circuit voltage and short-circuit current were observed to be 4.15 V and 0.61 A (Figure 4b and c), while the maximum efficiency reaches 1.23% [3]. Zhu *et al.* used a ferroelectric fluoropolymer polyvinylidene fluoride (PVDF) to harvest thermomechanical responses (Figure 4d), and obtained an 80 nA short-circuit current and 20 V open-circuit voltage (Figure 4e and f) apart from a carbon-sponge enabled solar-vaporization [34].

Instead of directly recycling of latent heat, multiple effects may be brought along with the continuous generation of steam and is likely to be used for secondary utilization, such as the variation of salinity concentration. In 2017, Yang *et al.* proposed an innovative way of extracting electricity from

the saline waters (Figure 4g). The rapid evaporation of water at the interface resulted in considerable concentration difference of salt, and with the assistance of ion-selective membranes such as Nafion, a voltage difference was readily established. Under 2 suns, a saturated voltage of 84 mV and a short-circuit current of 5.2 mA cm⁻² were obtained, leading to an overall efficiency of ~0.6% (Figure 4h and i) [35].

The enthalpy recyclable multifunctional devices provide a promising proof of concept applications for energy-water nexus as can effectively increase the output efficiency over 1%, which means an output power of higher than 10 W/m², without negatively suppressing the water production rate. A portable solar electricity generator with common sizes (solar absorption area of more than 50 cm²) can possibly provide sufficient energy to motivate some of the household appliance such as electric fan and lighting device, as well as a clean water output that can meet the requirement of daily drinking water for more than five people. Despite the efficiency remains dissatisfactory with industrial standards, but in order to depend on the considerable potential in this field, further researches will have to be carried out to combine several of the electric-generation approaches mentioned above, so as to achieve a higher electricity yield.

Summary and outlook

In this review, we briefly introduced the basic concepts of solar-driven evaporation, and demonstrated its unique photothermal properties and recent progresses in solar thermal utilizations, including solar desalination, solar sterilization and solar power generation. Aiming at point-of-use solar evaporation enabled solar thermal applications, we figured out a couple of crucial components or issues for each application, such as salt resistance, tunable steam temperature, waste-heat recycling, which both indicate the unique advantages and point out the new develop orientation for solar thermal utilization. However, it is worth noting that, most of the above solar thermal applications are still on the road toward commercialized technologies, during which the low thermal stability, structural complexity, and insufficient scalability are calling for further investigations. The ISVG system when combined with systematic optimizations on scalability, long-term stability, as well as high energy transfer efficiency, would shed lights on one of the most promising solutions for the next generation of water-energy nexus.

Conflict of interest statement

Nothing declared.

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