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Renewable energy-driven for sustainable off-grid desalination: A comprehensive review on technical highlights and process

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ABSTRACT

Despite the traditional desalination processes have achieved tremendous progress in terms of technology and cost, it is still limited by the high energy consumption and carbon emissions brought about by expensive fossil fuels. Finding alternative energy sources is essential to meet the growing demand for desalination. Over the past few decades, plenty of efforts have focused on driving the desalination process through renewable energy sources in order to achieve the goal of environmentally friendly off-grid desalination and zero liquid discharge. However, limited by technology and economic cost, the desalination processes driven by renewable energy are difficult to carry out large-scale application, and they are more used as an auxiliary unit of the traditional desalination processes. First of all, this article reviews the basic principles of solar interface evaporation technology, and further, summarizes the sustainable desalination technologies driven by solar and geothermal energy completely. In the end, the current global environment and energy troubles are discussed, and the necessity and significance of promoting renewable energy for desalination in the future are emphasized. This review will assist to promote attention to the development and utilization of renewable energy sources, with a focus on large-scale renewable-driven off-grid desalination projects in the future.

1. Introduction

Global environmental pollution is becoming serious by the day, seriously affecting the ecological surroundings, including water sources. This has led to a critical shortage of freshwater. An increasing number of areas are purifying seawater and salty groundwater to extract sufficient freshwater to meet daily needs [1,2]. However, the traditional desalination technique is energy intensive and usually consumes large amounts of fossil fuel, which in turn results in serious air pollution and accelerates global warming [3,4]. Especially in recent years, the COVID-19 epidemic, Russia-Ukraine war, and many such global problems have worsened problems such as energy shortage, freight costs, and inflation. This has affected traditional seawater desalination seriously.

In the previous decade, seawater desalination technology developed rapidly. Methods such as membrane distillation (MD), multi-stage flash (MSF), multiple-effect distillation (MED), and even forward osmosis (FO) are being gradually applied in the area of seawater desalination. Compared with the customary reverse osmosis (RO) desalination process, the new desalination process can increase freshwater production and decrease energy consumption significantly [5,6]. As an electricity-intensive process, RO consumes 3–7 $kW{\cdot}h/m^3$ of distilled water. For MSF, MED, and MD, the energy consumption is 2–5, 2–2.5, and 0.6–1.8 $kW{\cdot}h/m^3$ of distilled water, respectively [4,7–9]. Low electricity-consumption seawater desalination can be used to overcome water shortage and drought problems, suffice for daily domestic requirements, enhance industrial and agricultural development simultaneously, and can be used as the major source of drinking water in the Middle East and other coastal, barren, and arid areas [10]. However, at present, only RO is being used widely. According to the statistics, RO production accounts for about 64 % of the market share. Nevertheless, other processes are developing rapidly. For example, the greatest MSF, MED, and RO desalination projects in operation in the world today are

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Saudi Shoaibah iii (880,000 t/d), Saudi Al Jubail (800,000 t/d), and Israeli Sorek (620,000 t/d). The 900,000 t/d desalination plant in the UAE, launched in October 2019, is the biggest RO desalination project in the world. In March 2021, the UAE launched Mirfa ABU Dhabi's large-scale RO desalination project, with a production capacity of about 682,000 t/d. Along with the rapid development of seawater desalination technologies and the expansion of the application scale, the investment and operation costs also have diminished significantly. Forty years ago, the cost of water production was higher than 10 $/m^3, but now the desalination price has been reduced to 0.32 $/m^3.

At present, more than 160 countries and regions in the world are equipped with seawater desalination equipment. The global desalination ability has increased from 30 million m^3/d in 2000 to more than 100 million m^3/d in 2021. According to statistics, about 62 % of the global desalination production is used for municipal water supply, which has solved the water shortage problem for millions of people, while the rest is used for industrial and agricultural production, irrigation, tourism, and military. Saudi Arabia has the largest-scale desalination systems in the world, with 70 % of the country's drinking water coming from seawater desalination. Israel, close to the Mediterranean Sea, has also built several large desalination plants that can desalinate seawater to meet up to 30 % of the country's annual water consumption needs. The increasing numbers exhibit that the desalination market is growing fast.

One of the primary aims of seawater desalination is to overcome freshwater scarcity and sustainable water resource development. Seawater desalination plays a necessary role in alleviating freshwater scarcity in coastal areas. As it uses electricity for water production, seawater desalination is an energy-intensive industry. For instance, in an RO desalination system, it consumes fossil fuel, which not only incurs high costs but also contributes to greenhouse gas emissions. Huge energy consumption is a principal element in the excessive cost of seawater desalination, which influences the development of the seawater desalination industry on a large scale. However, in some faraway island areas, it is sometimes difficult to use traditional electric energy for seawater desalination because it is far away from the mainland and lacks a power grid. If alternative energy sources can be used to drive desalination, they can meet the water demand of island residents [11–13]. Especially at a time when fossil fuels are increasingly scarce, the continuous upgrading of renewable energy-driven desalination approaches also helps to develop sustainable desalination industries. In recent years, the combination of solar energy, wind energy, geothermal energy, nuclear energy, wave energy, and seawater desalination technology has emerged as a research hotspot. More importantly, renewable energy technology is reliable and environment-friendly, with a high degree of industrialization. The utilization of solar energy and other renewable energy for seawater desalination has called for research efforts from many countries in the world, and its development prospects are very broad. At present, more than 120 countries in the world have set up the "Carbon Neutral" time node; therefore, the development and utilization of renewable energy, even industrial waste heat, nuclear energy, and different new energy desalination technology, are of utmost importance [14–16].

This review article presents a comprehensive analysis of the current state and future prospects of renewable energy-driven off-grid desalination technology. Specifically, the article provides an overview of two widely adopted renewable energy sources - solar and geothermal energy - as drivers for off-grid desalination technologies. Moreover, the article emphasizes the essential role of solar-driven interface evaporation technology in achieving efficient and cost-effective off-grid desalination. The review also summarizes the critical requirements for developing and deploying renewable energy-based solutions to address global water scarcity and mitigate climate change. Ultimately, this article contributes to advancing the state of knowledge on renewable energy-driven off-grid desalination technology and its potential to tackle pressing environmental challenges. Fig. 1 illustrates the structure of the review article.

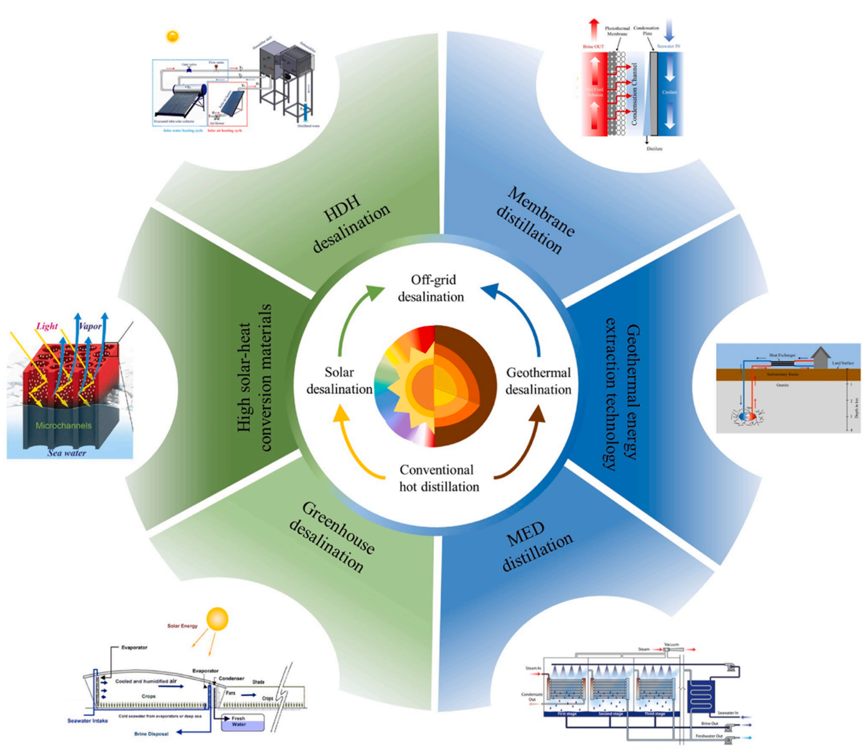

Fig. 1. Schematic view of the structure of this review article.

2. Off-grid desalination technology

2.1. Renewable energy

Off-grid desalination technologies driven by renewable energy sources are still in their early stages of development. Nevertheless, continuous development, upgrading, and improvement of renewable energy technology can significantly enhance the operating efficiency of desalination systems. Despite this, traditional RO technology still holds a dominant market share, particularly with the advancements of PV-RO technology. However, in coastal areas where there is a shortage of freshwater, such as islands and ships, utilizing renewable energy for seawater desalination has been shown to be the most effective solution since large-scale grid connection for power supply is not feasible. Off-grid desalination technologies driven by renewable energy sources can provide high-quality freshwater while offering numerous advantages, such as low capital cost, easy equipment maintenance, and a small carbon footprint, particularly in low-demand freshwater areas. Large-scale seawater desalination equipment required by traditional RO, MSF, and MED technologies are not appropriate for small and medium-scale applications in these specific areas. As a result, developing off-grid desalination technologies driven by renewable energy sources in these specific areas presents the best prospect for achieving sustainable and clean water supply.

Renewable energy that can be applied to off-grid desalination technology includes solar energy, biomass energy, wind energy, small hydropower, ocean energy, geothermal energy, hydrogen energy, and other energy resources, except for conventional energy and large-scale hydropower. In recent years, renewable energy-applied technologies have observed rapid development across the globe. For instance, photovoltaic (PV) power, wind power, and tidal power have a series of market applications and have observed industrial growth rates of above 20 %. Renewable energy can help achieve the goal of energy diversification since in order to cope with climate change and achieve sustainable development, alternative energy sources are required [17–20]. Especially recently, with the rising international oil price and the global advocacy of energy conservation and emission reduction, the development of renewable energy technology has gained the attention of many countries and has emerged as a hotspot in the field of worldwide energy research [21–23].

2.2. Solar interfacial evaporation technique

Over the last few years, many researchers have developed efficient solar interfacial evaporation technologies to desalinize seawater in order to overcome freshwater scarcity in coastal areas [23–25]. To attain high efficiency of solar interfacial evaporation, the following conditions should be met: (1) convert solar energy into heat energy; (2) use the obtained heat energy for water heating and evaporation; (3) condense the vapor produced into water. To this end, it is important to identify materials with high photo-heat conversion efficiency, latent heat recovery, and salt resistance [18,26–28].

2.2.1. Mechanism of solar interfacial evaporation

Traditional use of a solar energy heating evaporation device, such as a solar distiller, usually in the distillation unit surface is to generate heat, and then through the heat transfer, indirectly heat water to certain temperatures to produce steam. In this type of device, the heating zone and water vapor area are separated. The heat loss in the process of transmission is inevitable, so the efficiency is relatively low, that is, only 30–45 % [29,30]. Challenges in heat preservation management are widespread, necessitating solutions like thermal insulation and the efficient capture of latent heat. An innovative approach to solar volumetric heating is the incorporation of nano-absorbent materials into water. The core objective of this method is to transfer the generated heat directly to the water, thereby maximizing its thermal efficiency. However, this approach is not without its unique challenges, prominently revolving around addressing thermal insulation concerns and optimizing the capture of latent heat [31–33]. Volumetric heating, while a well-established method, presents certain limitations when it comes to substantially enhancing evaporation efficiency. It often demands intense solar radiation to attain the desired high evaporation temperatures, which can be challenging to achieve consistently. Recognizing these challenges, researchers have turned their attention to an innovative alternative: solar-driven air-water interfacial evaporation. This approach introduces a significant acceleration in the process of interfacial heating and surface thermalization. By doing so, it effectively reduces heat transfer losses, making it a promising avenue for improving overall evaporation performance. Moreover, this approach allows for selective heating and evaporation of the water's surface, a departure from the conventional practice of heating the entire volume. This selectivity can be achieved through simplified water insulation techniques and the utilization of photothermal materials, demonstrating the potential for a more efficient and sustainable evaporation process. Types of water evaporation driven by solar energy are shown in Fig. 2(a). By optimizing and fine-tuning photothermal materials, an optimal steam flow rate can be achieved, facilitating the attainment of the desired evaporation temperature, even under conditions of relatively low solar energy radiation [34,35]. Solar-driven air-water interfacial evaporation technology holds significant potential for addressing seawater desalination and freshwater generation challenges in remote areas, owing to its numerous advantages. This innovative approach harnesses solar energy to facilitate efficient evaporation at the air-water interface, offering a sustainable and cost-effective solution. By utilizing this technology, remote regions can access a reliable source of fresh water while mitigating the environmental impact associated with traditional desalination methods.

Energy can be generated through typical solar-driven evaporation at the air-water interface, as illustrated in Fig. 2(b). The incident solar radiation, the sole energy input, interacts with thermal materials at the air-water interface, undergoing energy conversion through the following processes: (1) thermal radiation heat loss; (2) heat convection at the air-water interface; (3) reflective optical loss; (4) heat conduction within the water; (5) heat consumption during water evaporation.The incident solar energy radiation is mainly used for water evaporation. Therefore, minimizing the loss of remaining heat is key to enhancing the efficiency of solar steam evaporation effectively.

The solar energy radiation spectrum reaching the Earth's surface spans from 300 to 2500 nm [36], as shown in Fig. 2(c). In recent years, the focus on enhancing solar energy absorption through photothermal materials has prompted substantial research and innovation. This quest has led to the emergence of nano-materials as frontrunners in this endeavor, primarily due to their impressive broad-spectrum absorption capabilities and high photothermal conversion efficiency. These nanomaterials have found practical applications in areas such as solar interfacial evaporation.Efficiency in photothermal conversion relies heavily on materials that minimize light reflectance, ensuring maximal solar energy capture. To facilitate continuous water evaporation, a crucial aspect of various applications, photothermal materials have been designed with a porous and loose structure [37]. This unique design not only allows for the replenishment of evaporated water through capillary action but also capitalizes on high porosity to enable multiple internal reflections, thereby enhancing solar energy absorption.In scenarios where interfacial evaporation systems employ planar structures for evaporating materials, the incident angle of the light source becomes a significant consideration. Remarkably, nano-materials with high porosity mitigate material surface reflectivity owing to their rougher surface characteristics. Consequently, they contribute to the more efficient utilization of solar energy, making them invaluable assets in the realm of photothermal energy absorption [38]. When sunlight interacts with the surface of photothermal materials, it induces an electric field within these materials. The solar energy absorbed by the charge carriers

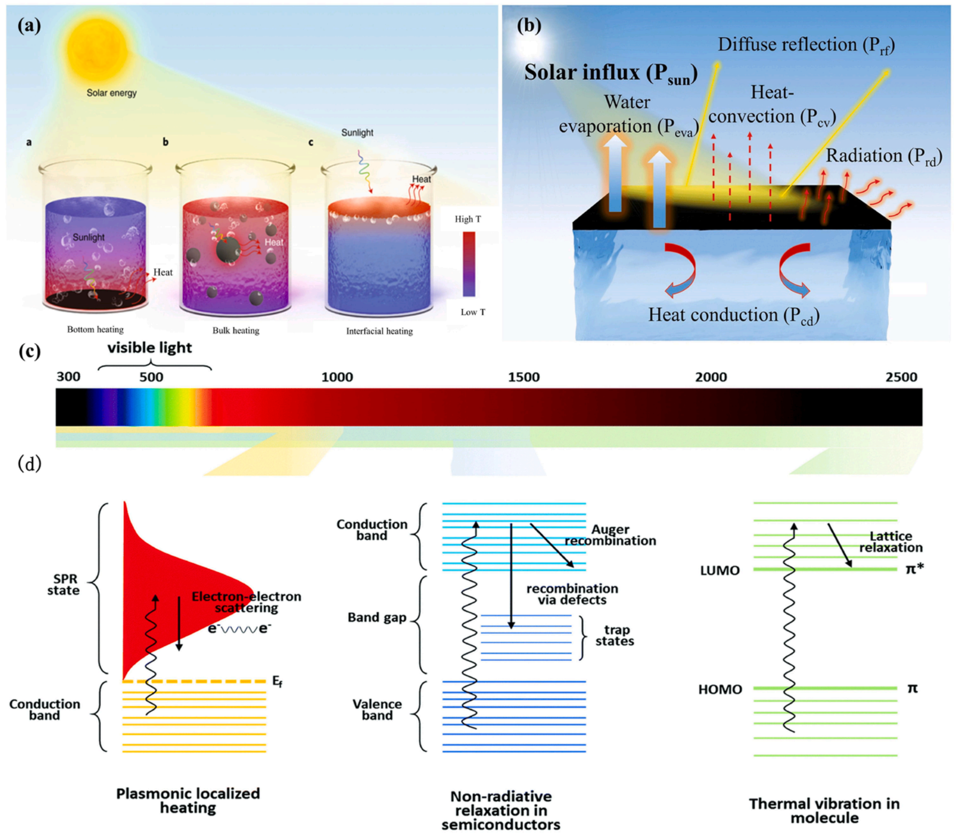

Fig. 2. (a) Solar energy-driven water evaporation types. (b) Energy balance of solar interfacial heating system. (c) Absorption range of earth spectrum [44]; (d) Photothermal effect mechanisms in diverse materials.
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is subsequently transformed into heat energy through processes such as plasmonic localized heating, non-radiative relaxation in semiconductors, and molecular-level thermal vibrations [39], as shown in Fig. 2(d). Photothermal effects are common in materials science and photonics, involving the conversion of absorbed light energy into localized heat. They occur in a wide range of materials, including plasmonic metals, semiconductors, carbon-based materials, polymers, and composites. These effects are fundamental and play a crucial role in various applications such as photothermal therapy, sensing, energy harvesting, and optoelectronic devices. A deeper understanding of the underlying principles and mechanisms across diverse materials holds great promise for advancing science and technology in multiple fields [40–42]. Photothermal materials convert solar energy into heat energy and often utilize multiple photothermal mechanisms when composed of multiple components [43].

2.2.2. *High solar-heat conversion materials*

Carbon-based nano-materials demonstrate exceptional photothermal conversion efficiency, featuring a wide absorption spectrum across the solar spectrum, thanks to their loose π-electron levels, enabling efficient heat dissipation as excited electrons readily return to their ground states [45]. Carbon-based nano-materials mainly include carbon black bodies, carbon nanotubes, graphene, graphene oxide, reduced graphene oxide, etc [46–48]. Carbon-based nanomaterials have found extensive applications in the research and development of light-absorbing materials due to their exceptional attributes, including low quality, consistent performance, excellent solar absorption, adaptability, as well as their non-toxic and environmentally safe nature. In the realm of emerging photothermal materials for solar interfacial evaporation applications, carbon nanotubes and graphene have garnered significant attention for their impressive water evaporation efficiency. However, one critical drawback to these materials is their exorbitant cost, rendering them unsuitable for deployment in remote or economically disadvantaged regions. Fortunately, there exists a promising alternative in the form of carbon black and porous carbonized plant materials. These materials not only offer affordability but also possess the invaluable attribute of renewability, making them an environmentally friendly choice. Through specific treatments, carbonized mushrooms, carbonized wood, and sunflower, among others, have exhibited remarkable water evaporation efficiency, representing a compelling avenue for further research and application in the field of solar-driven water steam evaporation. These readily available and sustainable materials hold the potential to address the pressing need for accessible and cost-effective water desalination and purification technologies, particularly in resource-constrained regions [1,49,50],as shown in Fig. 3(a). Chen et al. [1] present a significant breakthrough in the development of a sustainable Janus wood evaporator with unique asymmetric surface properties. The innovation lies in the dual functionality of this evaporator, where the top surface serves as a hydrophobic solar energy absorber while demonstrating exceptional water and salt resistance. On the other hand, the bottom surface exhibits rapid hydration capabilities and excellent insulation properties. The research achieved an impressive 82.0 % evaporation efficiency when using a 20 % NaCl aqueous solution under sunlight, and the evaporator exhibited long-lasting salt resistance in extended tests, outperforming other reported Janus evaporators in terms of both efficiency and sustainability. This Janus wood evaporator offers several advantages, including simplicity in production, compatibility with various wood materials, cost-effectiveness, stable performance, and

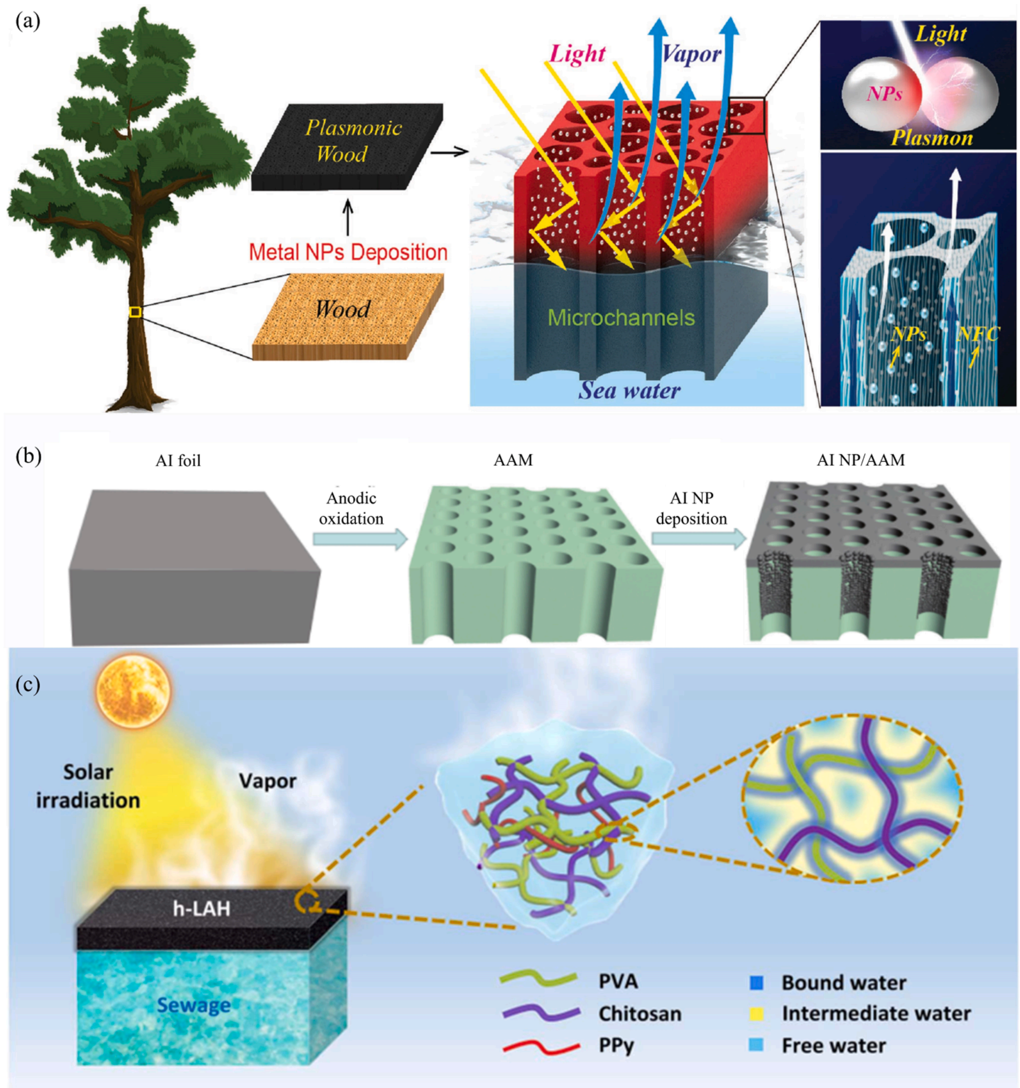

Fig. 3. (a) Plasmonic wood for a high-efficiency solar steam generation. (b) 3D self-assembly of aluminium nanoparticles for plasmon-enhanced solar desalination. (c) Schematic illustration of SVG based on the h-LAH.
(a) Reproduced with permission. [51] Copyright 2018, Wiley; (b) Reproduced with permission. [28] Copyright 2016, Springer Nature; (c) Reproduced with permission. [60] Copyright 2019, AAAS Publishing.

more. Moreover, it is ideally suited for sustainable desalination and zero liquid discharge applications. The use of carbon materials on the surface provides additional benefits such as enhanced light absorption, pore size control, and improved thermal properties. Combining the advantages of wood, such as its broad distribution, biodegradability, thermal insulation, and efficient water transport, with the use of economical and readily available functional carbon materials, underscores the significant research value of this innovation in solar interfacial evaporation applications.

In the context of materials and their interaction with light, it is crucial to highlight several key points. Firstly, certain materials, such as metal oxides, have the remarkable capability to manifest a robust plasma resonance effect when exposed to light. Secondly, the introduction of nano-particles onto these materials, either through doping or coating, holds immense significance. This introduction serves as a crucial step as it paves the way for intriguing phenomena to occur. Thirdly, when the frequency of incident light aligns with the oscillation frequency of these nano-particles, a fascinating outcome emerges: the excitation of hot electrons. Finally, this harmonious matching of frequencies between incident light and nano-particle oscillations instigates a resonance effect within the incident field itself, ultimately leading to the generation of heat. These interconnected phenomena underscore the profound intricacies of the interaction between materials, nano-particles, and light, providing valuable insights for various scientific and technological applications, as shown in Fig. 3(b). Zhu et al. [51] innovatively engineered plasma materials through the uniform incorporation of finely dispersed metal nano-particles of Pb, Au, and Ag into a three-dimensional mesoporous framework derived from natural wood. Their custom-designed evaporation device showcases remarkable solar absorption capabilities, achieving an impressive efficiency of approximately 99 % across a broad wavelength spectrum spanning from 200 to 2500 nm. Simultaneously, it effectively facilitates the upward movement of water from its source, with the added benefit of maintaining a stable rate of steam generation when exposed to sunlight.In 2014, Wang et al. [52] discovered a photothermal membrane capable of autonomously floating at the interface between water and air. This membrane material was enriched with Au nano-particles, a key enhancement enabling the efficient harnessing of both energy and materials during the process of evaporation. In their groundbreaking research,Zhou et al. [27] developed a remarkable plasma absorber through a streamlined one-step deposition process, involving the assembly of Au metal nanoparticles onto a nanoporous template. This innovative plasma absorber achieved an extraordinary average absorbance of 99 % within the expansive wavelength range spanning from 400 nm to 10 mm, establishing itself as the most efficient broadband plasma absorber documented to date. Notably, owing to its exceptional light absorption capacity and the unique porous structure, this plasma absorber exhibited a staggering water evaporation efficiency surpassing 90 % even under the demanding conditions of 4 solar intensity radiation. Furthermore, the study also delves into the exploration of alternative metal plasma materials, such as Ge, Al and In, for potential applications in nano-photothermal materials, expanding the horizons of this burgeoning field. For example, Sun et al. [53] researched metallic ncGe nanocrystal particles and demonstrated their application in the field of desalination. Bae et al. [54] developed an innovative adiabatic nano-focusing structure featuring surface-loaded plasma. This achievement was made possible through a meticulous process involving pore reaming on an alumina template and subsequent gold plating. The outcome was a remarkable black gold membrane exhibiting broadband absorption akin to ridge or valley structures, boasting an impressive average absorption rate of 91 % within the 400–2500 nm wavelength spectrum. This remarkable phenomenon is attributed to the photothermal mechanism in metal oxide semiconductor materials, where incident light exceeding the band gap energy triggers the generation of electron-hole pairs, leading to the conversion of excess energy into heat. This process is further accentuated by the recombination of electron-hole pairs within the semiconductor, generating additional heat. In 2016, Ye et al. [55] involved the utilization of synthetic black TiO_x nanoparticles to create a superhydrophobic surface on stainless steel mesh, enabling efficient solar water evaporation. Shi et al. [56] explored the potential of dragon fruit's multi-seed structure and successfully developed a $CuCr_2O_4$-SiO_2 composite membrane with impressive solar-driven evaporation capabilities. This composite membrane, incorporating stable $CuCr_2O_4$ particles on a quartz glass fiber support matrix, achieved an impressive steam generation rate of 1.32 kg/(m^2 h). Notably, metals and metal oxides have demonstrated exceptional photothermal conversion efficiency, durability, and stability, making them promising materials for solar applications. However, their high cost and light reflection properties necessitate careful consideration. To advance these technologies, enhancing their solar energy absorption efficiency is crucial, opening up possibilities for large-scale implementations in photothermal seawater desalination.

High flexibility allows a material to be molded into various shapes, as shown in Fig. 3(c). Photothermal polymer materials have emerged as a promising avenue for solar-driven water desalination and evaporation, offering unique advantages in terms of their spectral absorption properties and stability compared to other materials. Kashyap et al. [57] demonstrated the potential of PEDOT-PSS hydrogel applied to a graphite blanket surface, resulting in the creation of a flexible solar desalting device capable of efficiently and stably processing high-saline water. Meanwhile, Zhao et al. [26] innovatively designed a nanostructured gel incorporating polyvinyl alcohol and polypyrrole, serving as a solar steam generator with a remarkable water evaporation rate of 3.2 kg/(m^2 h) under a single solar irradiation. Jiang et al. [58] introduced a double-layer evaporator employing bacterial nanocellulose and polydopamine particles, optimizing solar absorption, photothermal conversion, heat localization, and water transport efficiency. Furthermore, Wu et al. [59] achieved impressive results by creating a wood-polydopamine composite for solar interfacial evaporation, achieving an outstanding water vapor production efficiency of up to 87 %. Notably, the versatility of polymer materials extends to their adaptability for shaping into floating bodies, enhancing their applicability in water purification devices. However, it's essential to consider the limitations of polymer nanomaterials, as they may degrade, become damaged, or age when exposed to intense light, thereby limiting their environmental tolerance and application scope in certain conditions.

3. Innovative desalination techniques driven by solar energy

3.1. Solar thermal desalination process

In recent years, significant advancements have been made in the field of solar evaporation processes, with a focus on enhancing their efficiency and applicability [61]. One key development involves the integration of nano-photothermal materials and interfacial heating design into traditional methods. This innovative approach has led to the reduction in the size of evaporation devices, thereby expanding their suitability for clean water production in environments characterized by limited freshwater resources, such as ships navigating vast oceans and arid desert regions [18]. In the newly designed evaporation device, nano-photothermal materials, known for their exceptional conversion efficiency, are strategically suspended directly on the water's surface. This configuration harnesses solar energy effectively, and transparent materials like glass facilitate light transmission and water vapor condensation. Consequently, these simplified solar evaporation devices have proven highly effective in various applications, including seawater desalination, the treatment of polluted natural water bodies, the management of oily brine, and sewage treatment. Nonetheless, it is important to acknowledge the persisting challenges related to aspects like water vapor interface condensation, heat transfer, and device preservation, which currently limit their scalability and widespread implementation. Addressing these challenges will be pivotal in realizing the full potential of this promising technology.

For large-scale solar evaporation systems, MSF or MED systems are commonly coupled with solar photovoltaic power generation systems to obtain electricity and connected to solar heaters [62–65], as shown in Fig. 4(a) and (b). MSF and MED are mature seawater desalination technologies intended to facilitate the recovery of condensation latent heat [2]. Using these techniques, relatively low temperatures can be maintained and rapid water evaporation can be achieved by decreasing the vapor pressure in the upper space, so the energy consumption required for evaporation can be decreased by removing water vapor from the device during operation [66], and the efficiency of seawater desalination is further improved by multistage evaporation process.

3.2. Membrane distillation seawater desalination technique

Membrane distillation (MD) represents a groundbreaking approach to water separation. In this process, raw water is subjected to heating, causing water vapor molecules to permeate through hydrophobic membrane materials situated on one side. Subsequently, on the opposite side of the membrane, the vapor undergoes a phase transition, transforming back into liquid water due to the introduction of cold flow [4, 67,68]. Based on the key points provided, a concise sentence for an English paper could be: "Membrane distillation relies on temperature differences to induce vapor pressure disparities on the membrane surface, facilitating the transport of water vapor; various forms of membrane distillation, such as direct contact membrane distillation (DCMD), air-gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD), and vacuum membrane distillation (VMD), are employed in this process [69–71]. Each process has its own characteristics, but AGMD has unique advantages in the field of solar interfacial evaporation [72–74], as shown in Fig. 4(c). In the context of solar-driven air-gap membrane distillation (AGMD), a remarkable and sustainable water purification method is employed. This innovative process harnesses the power of direct solar energy to recycle both incoming and outgoing water in a highly efficient countercurrent mode. At its core, AGMD operates by allowing high-temperature water vapor to permeate through a specialized membrane into a distillation chamber. As the vapor encounters the colder flowing water within this chamber, it undergoes condensation, transforming into a liquid state. This phase transition is accompanied by the release of heat energy, which remarkably contributes to the continued warming of the material in the

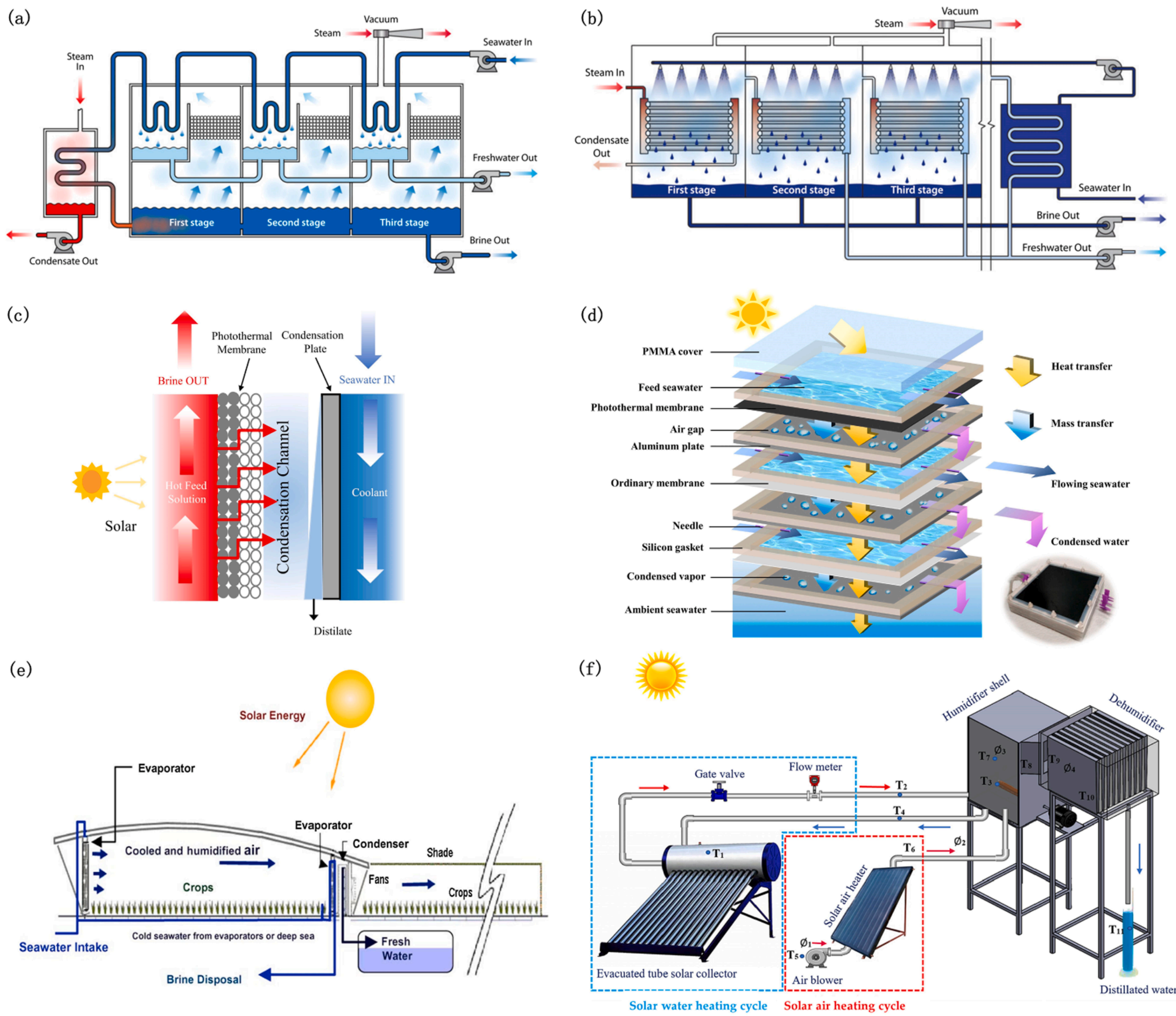

Fig. 4. (a) MSF distillation driven by solar-thermal energy [2];(b) MED distillation driven by solar-thermal energy. (c) Schematic diagram of AGMD; (d) Schematic diagram of MS-PMD. (e) Schematic diagram of Greenhouse desalination. (f) Schematic diagram of solar HDH desalination system.
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system, primarily driven by the latent heat of water. Moreover, AGMD incorporates cutting-edge solar-thermal materials, which further elevate the water's temperature and, critically, enhance the overall utilization of heat energy through latent heat recovery. This integration of advanced materials and heat recovery mechanisms not only bolsters the efficiency of the process but also significantly reduces energy consumption, marking a significant step towards sustainable and eco-friendly water purification solutions [75–77].

Scholars have explored MD with photothermal conversion materials on the membrane surface, directly heating it with solar energy [78]. In this passage, scholars have undertaken a pioneering research effort aimed at harnessing the power of solar energy for water purification. Their approach involved the amalgamation of carbon black and PVA, which were skillfully applied to the surface of a PVDF membrane through the electrospinning method. This innovative combination served as a foundation for the development of a photonic nano-solar membrane distillation system. What sets this system apart is its direct utilization of solar energy, with sunlight playing a pivotal role in heating the water surrounding the membrane. As a result of this solar-induced heat, vapor pressure is established, facilitating the condensation process on the opposite side of the membrane. The practical implications of their work are evident in the outdoor pilot-scale system, which consistently yields an impressive average of 0.5 kg/(m^2 h) of pure water within a 1 m^2 illuminated area. This breakthrough not only highlights the potential for sustainable water production but also underscores the significance of harnessing renewable energy sources in addressing critical global challenges. Wu et al. [79] improved membrane distillation performance by introducing either carbon black nanoparticles or SiO_2/Au onto the membrane surface, resulting in a 33 % increase in flux when exposed to simulated solar irradiation. In 2018, Eliodoro et al. [80] have introduced an innovative passive multi-gradient solar distillation system that promises to revolutionize water production in remote and underserved regions. At the heart of their design lies the ingenious concept of multi-level latent heat recovery and multi-level water evaporation. This unique approach harnesses the power of photoconversion materials to evaporate seawater efficiently, while the return water undergoes multiple cycles to effectively separate salt. This dual process not only enhances water evaporation efficiency but also optimizes energy utilization by utilizing the latent heat from water vapor condensation to directly heat the water. In real-world testing with seawater, the device demonstrated an impressive capability, producing 1.77 kg of water per kilowatt in outdoor conditions, thereby fulfilling the daily drinking water requirements of remote and impoverished areas. The invention holds great promise for addressing the pressing water scarcity issues faced by marginalized communities worldwide. Dong et al. [81] developed a multi-stage photothermal film distillation (MS-PMD) device with a free-flowing evaporation channel. As shown in Fig. 4(d), solar radiation penetrates the top polymethyl methacrylate (PMMA) cover and thin water layer, directly heating the seawater on the surface of the photothermal film, and the water vapor condenses through the membrane hole in the aluminum plate, and is used to heat the next stage feed water to achieve effective recovery of latent heat. The solar energy absorption, steam transmission and energy transfer of the device are all in the evaporation channel, which stabilizes the temperature of the evaporation surface, greatly reduces the temperature polarization, and significantly improves the water production and salt resistance, and can operate stably for 8 h without salt deposition.

An essential advantage of multistage integrated MD systems is that the top layer is heated by solar energy, which eliminates a portion of the water delivery and pressurization equipment because the device can absorb water spontaneously and continuously by filling the porous, hydrophilic, and core-absorbing materials [82–84]. This advantage is extremely important for miniaturization, that is, low-cost solar interfacial evaporation systems allow pump-free circulation, no longer require additional PV panels for heating, and reduce the risk of subsequent equipment maintenance failure.

3.3. Greenhouse desalination technique

Especially the arid and semi-arid areas of the earth are short of water. Hence, seawater desalination can be used for agricultural production [85]. Greenhouse desalination is the desalination of seawater/brackish water using renewable energy, which can provide clean water resources for agriculture in water-scarce areas, reduce CO_2 emissions, enhance crop yield further, and improve the economy in arid areas [86–89], as shown in Fig. 4(e). Traditional greenhouse desalination technology uses a greenhouse roof, seawater/brackish water to the upper roof, solar energy radiation, and evaporation; the water vapor condenses into liquid droplets indoors and is transported by gravity to the crop in the soil. This decreases the power consumed by traditional sprinkler irrigation and drip irrigation systems, and excess water can be stored in a tank for further irrigation. The water vapor absorbs heat and keeps the room cool, making it easier for crops to grow under strong light conditions [89–91]. The equipment required for greenhouse desalination is easy to handle, flexible, highly maneuverable, and has low installation and operation costs. The technique can utilize solar energy and geothermal energy directly to produce fresh water for irrigating crops [91,92]. In 2004, Chaibi et al.[84] evaluated greenhouse roofs in Tunis and studied the impact of roof light transmittance on water evaporation from solar distillers and crop yields. Jenny et al. [93] proposed a condensation irrigation process for both desalination and irrigation. By using a solar heat source to heat seawater for evaporation, the generated water vapor was cooled in the horizontal pipeline on the ground and allowed to permeate into the soil so as to achieve the purpose of irrigation; the study simulated a 50-m-long pipeline whose daily average water yield was 1.8 kg/m, which can meet the basic irrigation requirements.

3.4. Solar energy humidification-dehumidification seawater desalination technique

Solar humidification-dehumidification (HDH) seawater desalination obtains fresh water by humidifying and dehumidifying the air using solar energy as a heat source. A typical solar HDH system includes four main processes: solar heat collection, seawater heating, freshwater precipitation, and air circulation [94–97]. The solar HDH seawater desalination systems are illustrated in Fig. 4(f). First, the seawater is fed into a solar energy collection system and then heated and evaporated using solar energy. After that, vaporized seawater is sent to the humidifier to spray the humidified air, and the concentrated salt water is discharged from the back end. In the process of HDH, the air is circulated within the closed chamber. In the condenser, the air is condensed and dehumidified to produce fresh water, then collected into the water tank. Subsequently, air enters the humidifier to get humidified and heated, and after pressurization, it enters a new cycle [98–100].

Compared with the traditional seawater desalination methods, solar HDH technology has the advantages of less investment and normal pressure. The operating temperature is about 70–90℃. Further, solar heat acquisition is easy. It needs mild vaporization and small-scale equipment to produce high water quality. Hence, it can be operated in hot and humid climates economically and efficiently [101,102]. A. Fouda et al.[96] carried out theoretical research on the performance of solar HDH desalination. Through researching the air temperature, air humidity, and solar collector area, the review discussed the freshwater production rate, cooling capacity, power consumption, and water recovery capacity of the system. Al-Hallaj et al. [103] constructed a small-scale closed air circulation HDH process for solar desalination in Basra, southern Iraq, with a production capacity of 12 kg/(m^2 d). Soufari, S. M. et al. [104] built a solar HDH test device in Iran with a production capacity of 10 kg/h. The device mainly included a flat panel solar collector, humidifier, and dehumidifier. These experiments demonstrated that the HDH desalination system has broad development prospects.

3.5. Multi-energy-coupled desalination technique

Although solar energy is widely used in seawater desalination, it has some shortcomings, such as the instability of solar energy, especially in a rainy climate or at night, when its efficiency gets reduced or suspended, unfortunately, which impedes solar thermal desalination. In order to make up for such defects, by means of coupling and integrating solar energy with other varieties of renewable energy, complementary advantages can help to solve the disadvantages of solar instability [105–108]. As we all know, wind energy is a dynamic renewable energy with various advantages, for instance, pollution-free, inexpensive, abundant, and widely available. Solar-wind energy-coupled desalination can also solve the problem of the unavailability of solar energy at night [109,110]. Currently, there are mainly two methods for solar-wind energy-coupled seawater desalination technique. One is complementary power generation of wind and solar energy for heating desalination. This method can make full use of the power generation advantages of wind and solar energy and carry out RO desalination using electric energy. Another way is to use solar energy to heat seawater directly and wind power to drive RO, which is much more energy-efficient. Koroneos et al. [111] researched desalination using an integrated model of wind and solar energy, by combining the two technologies and found that it decreased the cost of desalination and enabled power storage effectively. Dimitrios [112] carried out scenic desalination on islands in the Aegean Sea, and the price of clean water produced is much lower than the market price. In 2017, the solar-wind complementary seawater desalination equipment was installed on Zhaoshu Island, Sansha City, which solved the problem of lack of drinking water in Laihai Island effectively. Solar-wind complementary technology can improve the optimal allocation of resources comprehensively and ensure the steady and safe operation of the system. Therefore, multi-energy-coupled seawater desalination technology has broad development and application potential for optimal utilization of natural resources, heat transfer enhancement, energy recovery, and comprehensive efficiency improvement.

4. Innovative desalination techniques driven by geothermal energy

4.1. Background of geothermal desalination technology

The utilization of geothermal energy boasts a rich history, spanning over 25 countries and dating back thousands of years, as evidenced by its extensive use in China for over two millennia (Dickson, et al., 2003). Over time, global installed capacity for direct geothermal utilization has seen a remarkable increase, reaching 107,727 megawatts by the end of 2019. This marks a substantial growth of 52.0 % compared to WGC2015, with a compound annual growth rate of 8.7 %. Correspondingly, total annual energy usage has surged to 1020,887 TJ (283,580 GW/h), representing a notable 72.3 % increase compared to WGC2015, with a compound annual growth rate of 11.5 %.

Despite these advancements, the global capacity coefficient, indicating the ratio of actual output to the maximum possible output, has experienced a decline from its peak of 0.40 in 2000 to 0.300 in 2019. Nevertheless, this figure remains higher than the 0.265 recorded in 2015 and the 0.28 in 2010. The recent surge in capacity factor and annual energy use primarily stems from the widespread adoption of geothermal heat pumps, although their global capacity factor stands at 0.245. The growth of global geothermal energy installed capacity (MWt) and annual energy use (TJ/yr) from 1995 to 2020 is depicted in Fig. 5. Particularly noteworthy is the expansion in the number of countries with an installed capacity exceeding 100 megawatts, rising from 11 in 1985 to 38 in 2020.

The five countries leading in annual energy use (TJ/year) of geothermal energy are China, Türkiye, Japan, Iceland, and New Zealand, collectively accounting for 76.5 % of the world's energy consumption [116].

Seawater desalination technology utilizes thermal and electrical energy for processes such as evaporation, hydraulic flow, and water transportation in thermal desalination. In contrast, membrane desalination relies on electrical energy to facilitate membrane separation. Geothermal seawater desalination offers a promising avenue to lessen reliance on conventional energy sources, resulting in lower energy expenses and reduced greenhouse gas emissions. This, in turn, can play a crucial role in mitigating climate change. Additionally, the adoption of geothermal seawater desalination technology holds the potential to spur local economic progress, generate employment opportunities, and drive technological innovation and industrial expansion.

Geothermal seawater desalination technology presents numerous advantages, including the harnessing of geothermal energy, high efficiency, environmental friendliness, geographical versatility, comprehensive utilization, and commitment to sustainable development. These features position it as a potent tool in tackling the pressing issues of freshwater scarcity, energy sustainability, and climate change. By tapping into the earth's internal geothermal energy reservoirs alongside seawater desalination processes, this technology offers a pathway to achieving sustainable freshwater supplies, thereby driving positive outcomes for social and economic development as well as environmental conservation. Looking ahead, the widespread adoption of geothermal seawater desalination technology is anticipated on a global scale, offering pivotal solutions to the challenges of water resource management and energy sustainability.

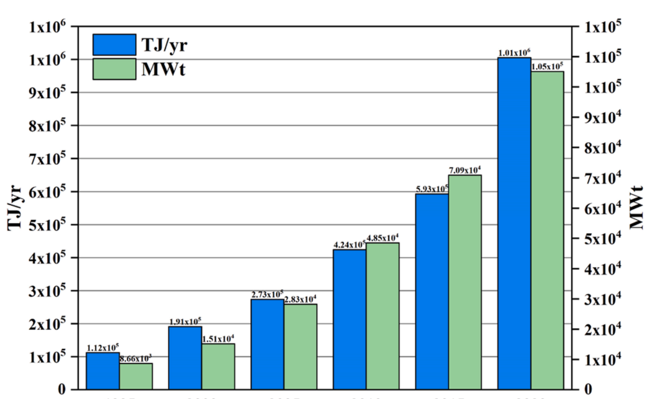

Fig. 5. The installed direct-use geothermal capacity and annual utilization from 1995–2020.

4.2. Geothermal seawater desalination technology

Geothermal energy, a variant of thermal energy, resides within the Earth's crust and originates from the decomposition of lava and radioactive substances. Stored in the form of geothermal fluids such as hot water, steam, and magma, this energy source can be captured by tapping into underground reservoirs of hot water or steam, subsequently converting it into either electricity or thermal energy. Geothermal energy exhibits a widespread distribution across the globe, notably concentrated in regions characterized by geological activity such as volcanic zones, hot spots, and tectonic fault lines [117]. The enthalpy of a geothermal source is subject to variation, influenced by factors such as the depth of the well and the composition as well as the structure of the underlying rock layers. Geothermal energy can be classified into two main categories: high enthalpy and low enthalpy, primarily determined by temperature thresholds. High enthalpy energy typically features temperatures surpassing 150 °C, while low enthalpy energy registers temperatures below this threshold [118]. As a renewable energy source, geothermal energy is not limited by climatic conditions or seasonal changes, making it a stable and reliable source of heat for seawater desalination.

The maturity of geothermal production technology, which revolves around extracting geothermal water from underground aquifers, has led to comparatively low costs for converting geothermal energy and implementing energy storage devices. Consequently, the supply cost of geothermal energy typically falls below that of other renewable energy sources like solar, wind, and tidal energy. This advantage stems from the well-established nature of the technology, enabling cost-effective production and efficient energy storage solutions. As a result, geothermal energy emerges as a promising avenue for fulfilling energy needs sustainably and economically.

Seawater desalination involves the removal of salt and other impurities from seawater to produce fresh water suitable for human consumption. As global water resources face growing scarcity, seawater desalination technology has emerged as a crucial solution to mitigate water shortages across multiple sectors, including drinking water supply, agricultural irrigation, and industrial water usage. Common methods employed in seawater desalination include distillation, reverse osmosis, electrodialysis, and evaporation, all of which have found widespread application in arid and coastal regions.

Geothermal seawater desalination technology represents an innovative fusion of geothermal energy and seawater desalination processes. This method harnesses geothermal energy as the primary power source for driving the desalination of seawater. Leveraging geothermal energy offers a stable and uninterrupted energy supply, thereby reducing dependence on conventional energy sources and curbing greenhouse gas emissions. The potential applications of this technology are extensive, particularly in regions endowed with abundant geothermal resources but limited freshwater reserves, such as Iceland, New Zealand, the Philippines, and other nations. Geothermal fluids can be extracted through geothermal-driven production wells, as depicted in Fig. 6(a) and (b) [9,119].

4.3. Classification and process of geothermal seawater desalination technology

Geothermal energy plays two key roles in seawater desalination:

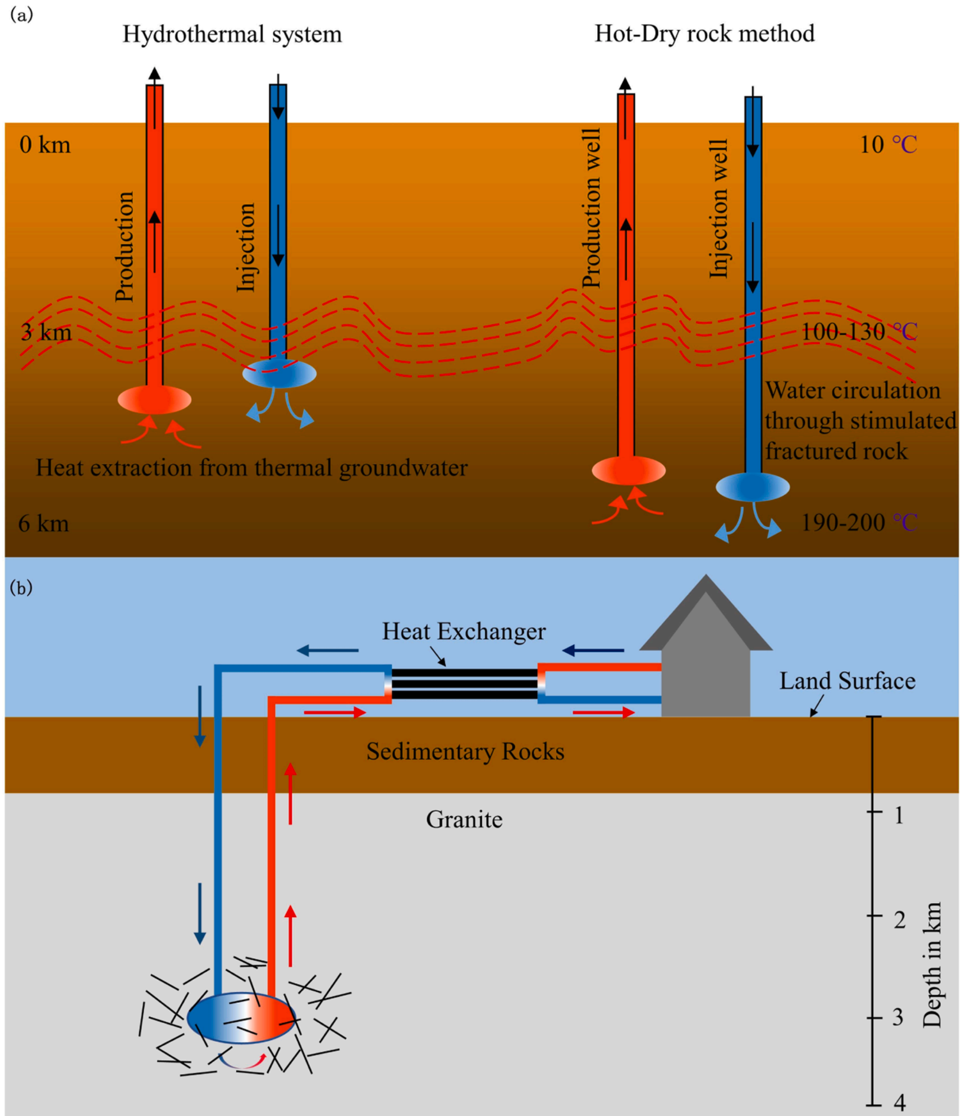

Fig. 6. (a) Geothermal energy extraction process. (b) Extracting geothermal energy source to power thermally driven desalination processes. (a) Reproduced with permission. [9] Copyright 2015, Elsevier; (b) Reproduced with permission. [119] Copyright 2010, Elsevier.

Firstly, it involves utilizing low enthalpy geothermal energy to directly heat Multi-Effect Distillation, Mechanical Vapor Compression, and other heat-driven desalination devices. Secondly, it entails harnessing high enthalpy geothermal energy to generate electricity, which in turn powers Reverse Osmosis (RO) and other electrically driven desalination devices. The choice between these methods hinges on the enthalpy level of geothermal fluids.

4.3.1. Geothermal energy membrane distillation technology

Membrane distillation technology operates at normal pressure and requires low operating temperatures, making it well-suited for utilization with low enthalpy geothermal energy sources (typically less than 363 K). These sources utilize medium and low-grade heat to fulfill energy requirements effectively. Geothermal energy is transferred to the heat energy of water, creating a temperature difference between the hot feed side of the hydrophobic membrane and the osmotic pressure difference, which forms the vapor partial pressure difference. This vapor pressure difference serves as the driving force for completing the desalination process. In geothermal energy-driven membrane distillation technology, geothermally heated water serves as the feed water for the membrane distillation process.Zhu et al. [120] investigated the factors influencing brackish water desalination through a hollow fiber Direct Contact Membrane Distillation (DCMD) system utilizing geothermal hot springs. The experimental setup is depicted in Fig. 7(a), comprising a feed circuit, a permeation circuit, and a membrane component.Both the feed and permeate flow through the membrane simultaneously in this system. Temperature control is achieved using constant temperature water baths A and B. Initially, the brackish water is preheated, and the rotor flow meter is adjusted accordingly. Subsequently, a magnetic circulation pump is employed to transport the feed to the inlet of the hollow fiber membrane module. As the vapor pressure difference increases, the liquid phase on the hot feed side transitions into steam, which then permeates through the fiber pores to reach the permeate side. After condensation, the steam is collected in constant temperature water bath B and cooled by a chiller.

4.3.2. Geothermal energy reverse osmosis technology

Reverse osmosis (RO) technology stands out as a highly efficient desalination process that relies on creating a pressure difference across a semi-permeable membrane. Unlike methods involving phase change, RO is straightforward to operate. However, its notable drawback lies in its high power consumption, posing a significant challenge to its

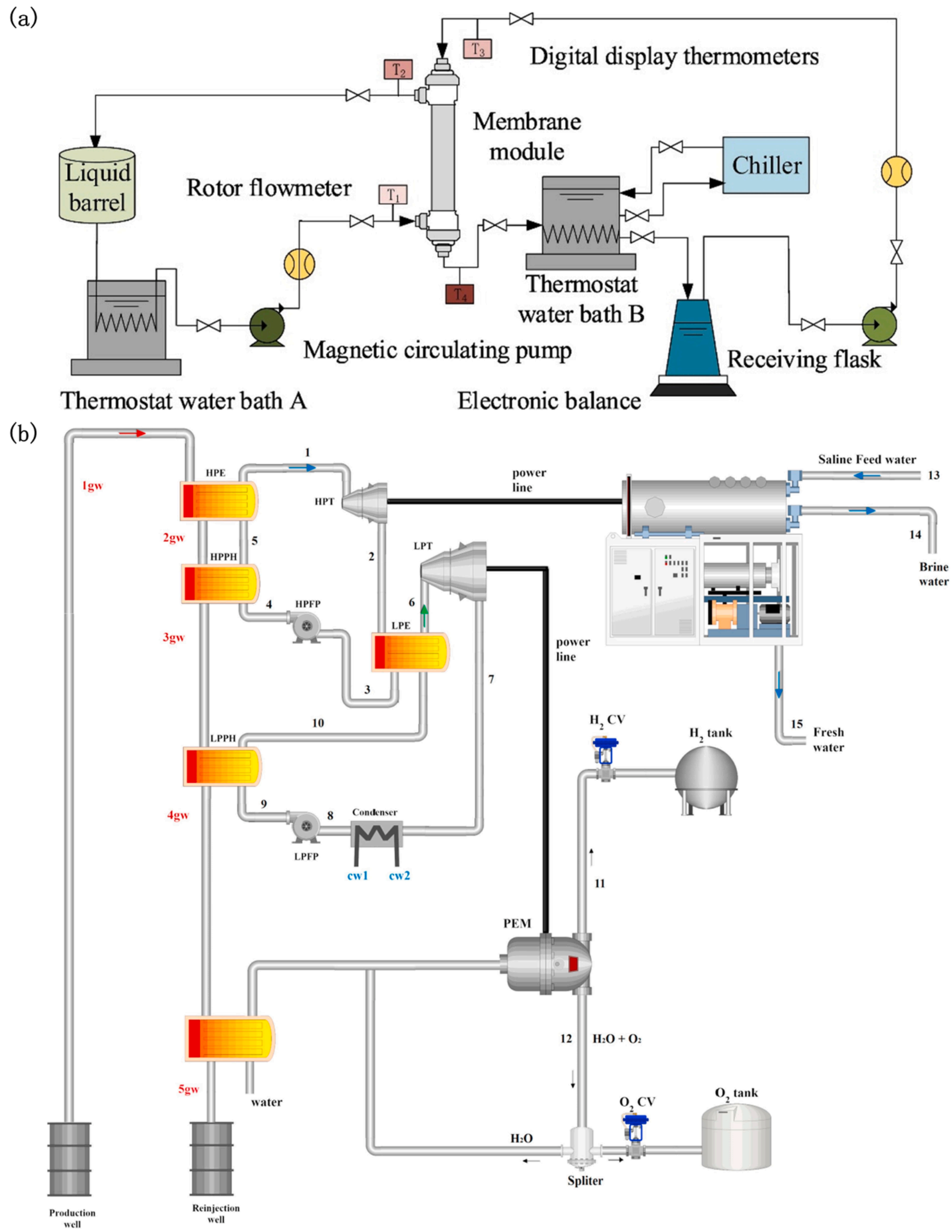

Fig. 7. (a) Schematic representation of the experimental setup. (b) Schematic diagram of the proposed cogeneration system.
(a) Reproduced with permission. [120] Copyright 2021, Elsevier; (b) Reproduced with permission. [121] Copyright 2018, Elsevier.

widespread adoption. Fortunately, by integrating a geothermal energy power generation system, these limitations can be substantially mitigated, offering a promising avenue for enhancing the feasibility and sustainability of RO desalination technology. Kianfard et al. [121] devised and evaluated the operational performance of a geothermal energy-integrated cogeneration system, comprising a dual-fluid Organic Rankine Cycle (ORC), Proton Exchange Membrane (PEM) electrolyzer, and reverse osmosis seawater desalination device, as depicted in Fig. 7 (b). The dual-fluid ORC encompasses a high-pressure circuit and a low-pressure circuit, with waste heat from the former being harnessed by the latter. Geothermal water facilitates the evaporation of the organic working fluid in the high-pressure circuit, driving the high-pressure turbine to generate electricity. Simultaneously, the high-pressure pump pressurizes seawater for delivery to the RO membrane, facilitating desalination and fresh water production. The organic working fluid is introduced into the low-pressure evaporator (LPE) and discharged post-saturation, while the vapor in the LPE propels the low-pressure turbine (LPT), subsequently condensing and entering the low-pressure pump (LPP). Geothermal energy is utilized to preheat the working fluid in both the high and low-pressure circuits. A cost analysis of the system revealed a production cost of 32.73 cents per cubic meter of water.

4.4. Application examples and optimization innovation of geothermal seawater desalination technology

Geothermal energy emerges as an appealing renewable energy option for seawater desalination, given its modest operating temperature demands and the accessibility of medium to low-grade heat sources. In Tunisia, five principal geothermal regions boast temperatures spanning from 294 to 340 K. Nonetheless, Tunisian geothermal water tends to exhibit high levels of hardness, necessitating substantial energy inputs for cooling tower and membrane distillation treatments. To tackle this challenge, Bouguecha et al. [122] introduced a geothermal energy desalination solution that integrates a fluidized bed crystallizer and air gap membrane distillation, aimed at bolstering Tunisia's freshwater resources. The fluidized bed crystallizer plays a pivotal role in mitigating hardness in crucial components while minimizing temperature losses. Meanwhile, according to the US Geological Survey (USGS), 13 states across the United States harbor low-temperature geothermal energy reservoirs. Collaborative research by the National Renewable Energy Laboratory and the Colorado School of Mines has explored the application of these resources in seawater desalination. Given that low-temperature geothermal energy is unsuitable for conventional power generation, the study advocates for the adoption of direct heating thermal desalination technologies such as MD. Their findings indicate that integrating geothermal energy and MD can slash the cost of water production to less than $1.5116 per cubic meter [123].

Geothermal energy has the potential to be a valuable resource for seawater desalination. However, further improvements in the process, system, and devices are still necessary to fully harness its potential. Goren et al. [124] conducted a study on a hybrid RO/MDC system utilizing geothermal energy to treat waste geothermal brine in Anatolia. The experiment yielded a COD removal rate of 91.7 % and a boron removal rate of 66.3 %, rendering the effluent suitable for irrigating high-tolerance crops like rice and oats. Hai et al. [125] introduced a multi-generation system that integrated the branch GAX cycle with other subsystems supported by RO devices and SFC. This innovative setup aimed for dual-objective optimization through MATLAB software, targeting CO emission rate and freshwater production efficiency. The experiment revealed that as generator temperature increased, the CO emission rate decreased, accompanied by decreases in net power, cooling load, and water production rate. These findings suggest that raising the generator temperature ultimately improves the long-term sustainable output performance of the system.In addition, Sarbatly et al. [126] conducted an economic analysis of geothermal energy vacuum membrane distillation desalination technology. They conducted experiments utilizing geothermal water from Ranau, Sabah, Malaysia, as the hot feed, employing both laboratory-made polyvinylidene fluoride (PVDF) membranes and commercial PVDF membranes. The results demonstrated that the effluent total dissolved solids (TDS) remained below 500 ppm, meeting drinking water standards. Moreover, the study revealed that geothermal energy could potentially save approximately 95 % (87–89 kW/(h kg)) of membrane distillation energy consumption. Additionally, a VMD seawater desalination plant operating at 20, 000 m^3/d in collaboration with GE could save about 59 % of water production costs ($0.72/$m^3$). Despite these promising findings, the application of geothermal energy in seawater desalination technology is still in its early stages, and further research is warranted to enhance the technology further.

4.5. *Challenges and solutions for geothermal seawater desalination technology*

Indeed, geothermal seawater desalination presents an innovative approach to augmenting freshwater resources, offering promising prospects. However, its progress is hindered by notable challenges spanning technology, economy, and environmental considerations.

(1) The utilization of geothermal energy entails extracting heat from deep wells situated beneath the Earth's surface. This process engenders a high-temperature and high-pressure milieu, posing numerous challenges to the development of effective equipment and materials, as well as the design and operation of systems. The exacting conditions of elevated temperature and pressure demand equipment endowed with exceptional levels of tolerance and performance. Hence, the meticulous selection of suitable equipment and materials stands as a critical determinant of the success of geothermal energy utilization.
(2) The economic feasibility and substantial energy consumption associated with geothermal seawater desalination technology are pivotal factors influencing its development. This process commonly requires significant energy inputs for both geothermal energy extraction and seawater desalination. Energy-intensive processes such as geothermal energy production, fluid treatment, upgrading, and the evaporation and condensation stages of desalination all contribute to overall energy consumption. Consequently, there exists a critical imperative to improve technical energy efficiency and undertake thorough economic assessments to ascertain the viability of geothermal seawater desalination technology.
(3) The adoption of geothermal seawater desalination technology generally entails considerable initial investment outlays. This stems from the costs associated with geothermal energy development, geothermal fluid upgrading and treatment, as well as the acquisition of requisite equipment and infrastructure for the desalination process. These financial demands represent a substantial barrier to the widespread adoption and dissemination of geothermal seawater desalination technology. Consequently, it becomes imperative to explore avenues for mitigating the costs associated with this technology and improving its affordability.
(4) The environmental ramifications of geothermal energy development and utilization hold paramount importance. The handling and disposal of geothermal fluids can exert a notable influence on groundwater and surface water resources, potentially impacting the underground geothermal environment as well. Consequently, rigorous environmental assessment and monitoring protocols are indispensable throughout the implementation of geothermal seawater desalination technology. These measures are imperative to effectively control and manage the environmental impact, thus averting any enduring adverse consequences.

In addition to the challenges mentioned earlier, the extraction of geothermal energy is further constrained by its geographical distribution. Given that not all regions boast abundant geothermal resources, the deployment of geothermal seawater desalination technology is feasible only in areas endowed with substantial geothermal reserves.

Despite these constraints, geothermal seawater desalination technology represents a promising solution for sustainable freshwater resource development. With ongoing advancements in technology, sustainable energy development practices, policy backing, and market promotion, geothermal seawater desalination technology is positioned to realize substantial and comprehensive breakthroughs across economic, environmental, and social spheres. Consequently, it stands poised to emerge as a potent tool in tackling challenges such as water resource scarcity and pollution.

5. Importance of developing sustainable clean energy-based seawater desalination technique

The desalination technique by renewable energy is still in its initial stages of development. Various high-efficiency photothermal materials, water evaporation structures and high temperature and high pressure resistant materials are emerging, which can increase the utilization efficiency of solar energy and geothermal energy and freshwater productivity. The traditional RO still occupies the majority of the market share, especially as the increasingly advanced PV-RO technology continues to update. However, in remote and underdeveloped regions where water requirement is low and land resources are not a key factor, as well as in locations where clean water is scarce and seawater is abundant, such as on islands and ships, renewable energy-driven off-grid desalination technology could prove to be most efficient. In these areas, where the demand for fresh water is low, solar steam evaporation technology can provide benefits such as high water yield, low funding cost, convenient equipment maintenance, and a small carbon footprint.

And in areas with abundant geothermal energy resources,geothermal seawater desalination technology can reduce dependence on traditional energy sources, leading to reduced energy costs and decreased greenhouse gas emission. Considering these factors, large-scale desalination equipment required for traditional RO, MSF, and MED cannot compete with simple solar steam evaporation techniques and geothermal seawater desalination technology. Therefore, the development of renewable-driven off-grid desalination technology in these specific regions offers the best prospects for achieving a sustainable clean water supply.

Desalination is an energy-intensive industry. Especially in current years, making use of renewable energy for desalination has grown to be important, driven by many factors such as the worsening of global warming and the increasing demand for drinking water. In numerous countries, desalinated seawater and saline groundwater are the main supply of domestic water. Since the industrial revolution, the rapid development of science and technology has led to high-speed economic growth and an improvement in living standards; however, these still largely rely on the consumption of fossil fuel, which has led to growing greenhouse gas emissions, increase in global temperatures, and extreme weather weathers, among other global problems [127]. At the same time, in the present variable and complex global environment, the dependency on fossil fuel has become unreliable since the supply is not stable and fuel prices continue to rise. In such a situation, achieving carbon neutrality requires renewable energy exploitation and utilization [128]. As shown in Fig. 8, the realization of efficient off-grid desalination is the latest embodiment in the context of the new generation of water-energy nexus. Renewable energy-driven off-grid desalination has several uses. (1) Energy supply: in remote or underdeveloped areas, the cost of long-distance traditional energy supply is extremely high, so solar energy and geothermal energy can be used as the energy source to maintain local life and development. (2) Geographical selection: remote, economically underdeveloped areas, islands or ships, areas with geothermal energy resources and areas with a high cost of freshwater resources development or less demand for water resources. (3) Maintenance and operation: the daily maintenance and operation of solar steam evaporation technology and geothermal desalination technology are simpler and more convenient than the traditional energy system. (4) Economic cost: in remote areas or inland cities, water transport costs are high and cause water pollution; the use of solar steam evaporation and geothermal energy can reduce pollution.

In conclusion, off-grid desalination technology powered by solar and geothermal energy offers a substantial reduction in dependence on fossil fuels. Compared to conventional desalination methods, which incur high costs for grid expansion and transportation, desalination utilizing renewable energy sources proves more cost-effective and directly mitigates environmental pollution.

6. Conclusion

Renewable energy-driven off-grid desalination technology has proven itself as a reliable method for small to medium-scale freshwater production, particularly in serving remote areas. However, to optimize system efficiency, significant opportunities exist for enhancing thermal energy utilization and technological advancements. Furthermore, concerted efforts are needed to reduce production and operational costs while refining operational techniques. Notably, ongoing innovation and the development of technologies such as MD tailored for renewable energy utilization will open up new avenues for off-grid desalination in the market. Such innovative research holds considerable reference value for future advancements in renewable energy utilization and the realization of off-grid desalination.

Fig. 8. Off-grid desalination in the context of new water-energy nexus.

CRediT authorship contribution statement

X. T. Yang: Manuscript framework design, data collection, writing-review & editing. **J. Zhou; P. X. Guo; X. J. Yao; L. Ma; H. Jiao; B. b. Tian:** Drawing the original images. **B. Xu; X. Y. Zhang*:** Conceptualization, Resources.

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.

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Declaration of Competing Interest

The authors declare no competing financial interest.

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