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Coupling a brackish water greenhouse desalination system with membrane distillation for Southern Algeria

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ABSTRACT

The aim of this study was to evaluate emerging desalination technologies that can be integrated with renewable energy systems. Emphasis was placed on membrane distillation and humidification–dehumidification greenhouse desalination. A case study was presented on the feasibility of coupling brackish water greenhouse desalination with membrane distillation for Southern Algeria. Finally, the environmental concerns, market potential, and regulatory factors of integrated systems are discussed.

Keywords: Integrated systems; Greenhouse desalination; Humidification–dehumidification; Membrane distillation; Market potential; Environmental concerns; Regulatory factors

1. Introduction

Water stress is a major challenge facing societies worldwide especially in arid regions [1]. The increase in population and consequent necessity for food production have expanded human water intake over the previous decades [1]. Escalating pressure for water in urban regions and worsening of water quality owing to flow of industrial wastes has also added to water stress. Man-made generated climate change is also related to variations in water availability and heightened risk of drought [2]. Rising changes in seasonal precipitation and evaporation will affect global water availability. These issues have caused rising strain on the world's water reserves, and thus impacts universal access to health and sanitation.

Renewable energy and desalination are technologies that can be blended in various ways to help alleviate the world's water stress problems [3,4]. Effective combined schemes rely on merging efforts of experts of two distinct disciplines – renewable energy and desalination [5]. The latter can be aided by energy produced on site from nearby accessible renewable energy supplies. This power can be manufactured in numerous forms: as heat, electricity, or mechanical energy. In theory, any renewable energy technology can be integrated with a water desalination plant, particularly in the framework of desalination approaches that employ electricity. There is a need to be able to better assess how to integrate different technologies to help resolve the global water stress problems considering economic and environmental sustainability [6].

The aim of this study was to evaluate emerging desalination technologies that can be integrated with renewable energy (RE) systems. Emphasis was placed on membrane distillation and humidification–dehumidification greenhouse desalination. A case study was presented on the feasibility of coupling brackish water greenhouse desalination with membrane distillation for Southern Algeria. Finally, the

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market potential, environmental concerns, and regulatory factors of integrated systems are discussed.

2. Challenges and applications of integrated systems

Existing renewable energy (RE) systems can be merged with desalination. However, technological, and economic limitations hamper large-scale applications [5,6]. A recent study has provided an overview of the standing of RE-driven desalination technologies, with an emphasis on integrated systems, and possible applications, as well as their economic and technological limits [5]. Bundschuh et al. [5] argued the need to optimize energy processes, particularly by generating more energy-efficient and economically valuable solutions, energy storage, the expansion of off-grid systems and energy recovery. Likewise, there is a requirement to make changes to conventional desalination practices to make them more appropriate for integrated approaches. There are groupings of desalination and RE technologies (Fig. 1), which are especially hopeful in regard of their economic and technological feasibility. Certain groupings are more appropriate for large-scale desalination plants, while others are more applicable for small-scale.

3. Emerging desalination technologies

Developments in promising desalination technologies were assessed by Ahmed et al. [7]. The authors focused on systems nearing commercialization such electrochemical processes, forward osmosis, and membrane distillation. It was argued that a membrane-based approach only will not reach commercialization. Usage of low-grade heat in membrane distillation, as well as hybrid systems powered by renewable energy are expected to accelerate growth. Ahmed et al. [7] determined that advances in desalination batteries to eliminate salt ions using high-capacity battery materials may lead to the resurgence of electrochemical practices for seawater desalination. Upcoming efforts should be geared towards economic assessment of upscaling and optimization of system design.

Fig. 2 shows an outline of the kinds of energy from several renewable energy sources. To date, the most popular blend is the integration of photovoltaics with reverse osmosis (PVRO). Shortened membrane life has been recognized as a technological challenge of incorporating RO with renewable energy systems, especially solar and wind energy [7,8]. Decreased membrane life can be due to intermittent operation. Ali et al. [8] pointed out that solar technologies that concentrate solar heat, such as concentrating solar power (CSP), are well fitted for forward osmosis (FO) and membrane distillation (MD).

4. Membrane distillation

Current industrial reverse osmosis (RO) membranes cannot physically withstand the high pressures needed to

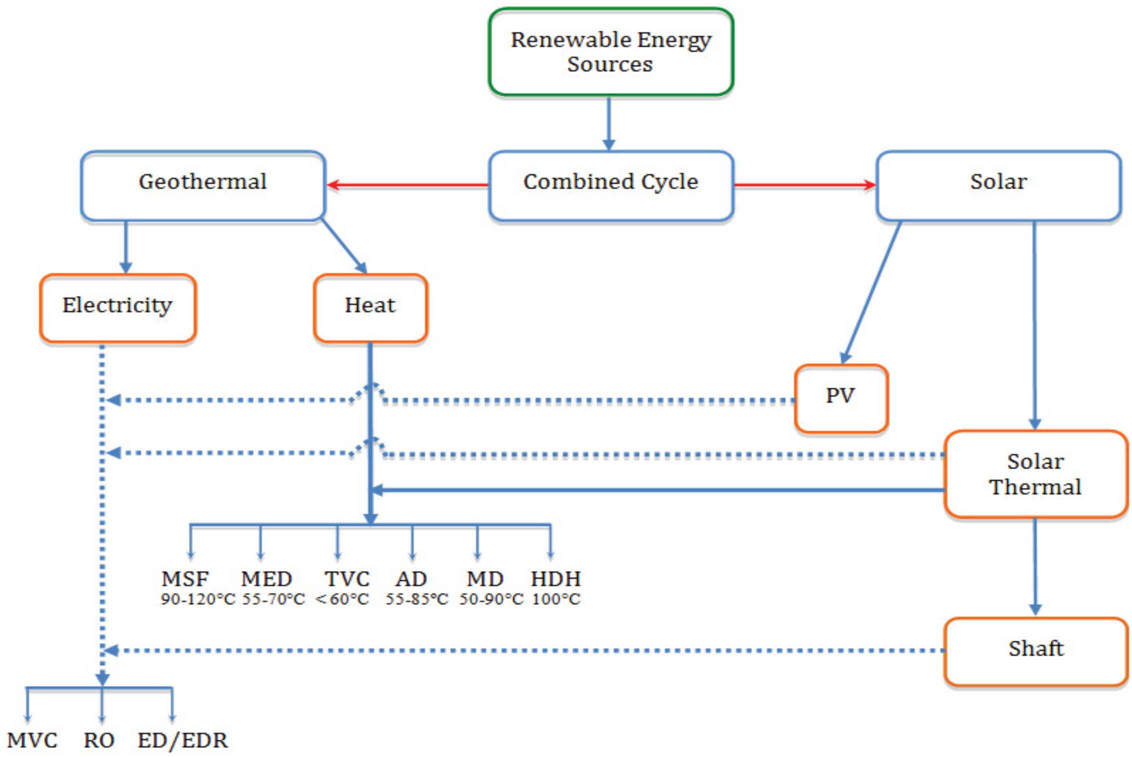

Fig. 1. Possible combinations of integrated systems: RES with conventional and innovative desalination processes AD: adsorption desalination; ED: electrodialysis; EDR: electrodialysis reversal; HDH: humidification–dehumidification; MD: membrane distillation; MED: multi-effect distillation; MSF: multi-stage flash; MVC: mechanical vapor compression; PV: photovoltaic; RO: reverse osmosis; TVC: thermal vapor compression [6].

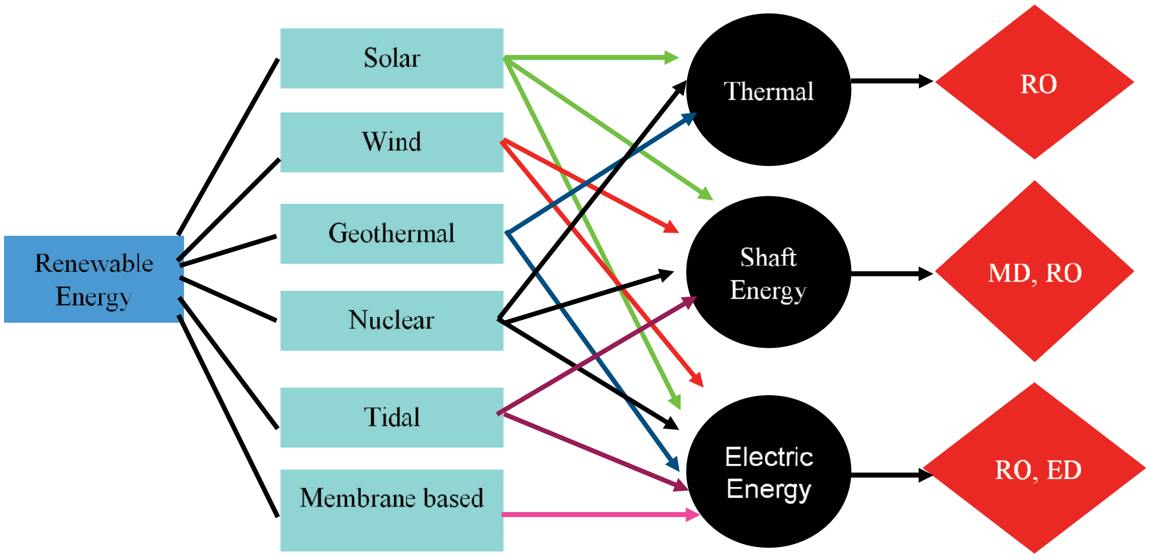

Fig. 2. Overview of renewable energy technologies with RO, FO, MD and ED [7,8].

desalinate hypersaline solutions with total dissolved salinity (TDS) > 50,000 ppm solutions (>80 bar). MD becomes an appealing option as energy consumed does not depend on feed salinity [7]. There has been a steady rise in research attention on MD, as is evidenced by an growing trend in quantity of publications (Fig. 3) on MD. One of the primary benefits of MD over conventional thermal processes such as multi-stage flash and multi-effect distillation include low heating requirements

Membrane distillation (MD) is a thermally driven process. It employs a hydrophobic, microporous membrane as a contactor to attain separation by liquid–vapor equilibrium. The driving power for the MD process is the partial vapor pressure variation maintained at the two sides of a hydrophobic microporous membrane (Fig. 4). After being heated, the feed solution is brought into contact with the membrane which allows only the vapor to go through the dry pores so that it condenses on the permeate side (coolant). A difference of 7°C–10°C between the water streams is theoretically adequate to produce freshwater [7]. This process works at relatively low temperatures (range of 50°C–90°C), which is very suitable for treating thermal brines which are already preheated. Separation occurs as pure water vapor with its greater volatility, contrasted with sodium chloride, goes through the membrane pores by a convective or diffusive process.

A thermal gradient is employed across a membrane in MD dividing the feed and the permeate. The heated feed

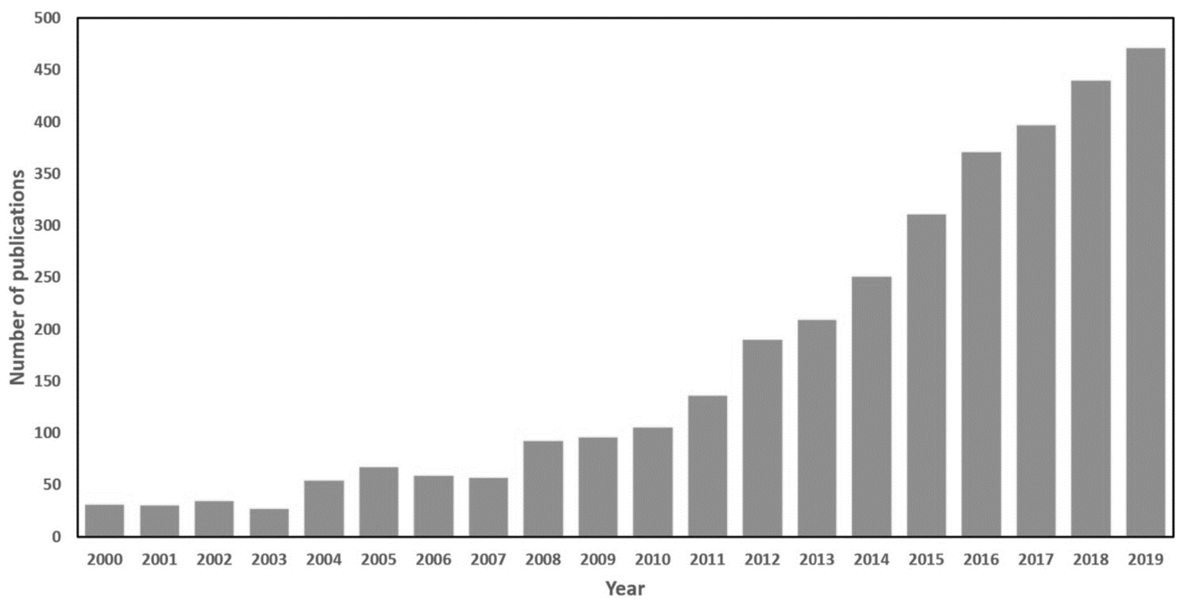

Fig. 3. Number of publications on membrane distillation from 2000 to 2020 (Scopus) [7].

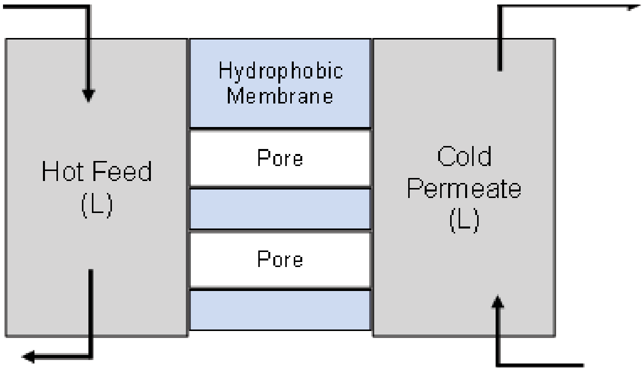

Fig. 4. Mechanism for desalination by direct contact membrane distillation (DCMD) (adapted from Chamani et al. [9]).

causes a temperature gradient across the membrane resulting in a vapor pressure difference. This forces water on the feed side to vaporize and go through the membrane pores and condense on the colder permeate side [6]. Large-scale commercialization of MD has been hindered by low water flux and high energy consumption. Four modes for MD operation currently exist depending on heat transfer on the permeate side. These are vacuum membrane distillation (VMD), air-gap membrane distillation (AGMD) direct contact membrane distillation (DCMD) and sweeping gas membrane distillation (SGMD). Even though DCMD has the least energy efficiency, it is most employed in the lab because of its straightforward layout.

5. Humidification–dehumidification greenhouse desalination

The greenhouse is a flexible structure that can be modified for water desalination by recreating a natural hydrological cycle within a controlled environment. A seawater greenhouse uses sunlight, sea/brackish water, and the atmosphere to produce freshwater and cool air, generating more better environments for crop cultivation (Fig. 5). The two humidifiers consist of cardboard honeycomb lattices producing humidified air. This helps to keep the greenhouse cool while allowing the crops to grow in high light conditions. Saturated air coming out of the evaporator passes over the condenser.

The freshwater condensing from the humid air is piped to the storage tank for irrigation. The first pilot plant was constructed and tested by Paton and Davies in the Canary Island of Tenerife in 1992 [12].

6. Coupling brackish water humidification–dehumidification greenhouse desalination with membrane distillation for Southern Algeria: a case study

The main aim of this case study was the proposition of a brackish water greenhouse desalination unit coupled with membrane distillation battery designed for the southern part of Algeria (Fig. 6). The brackish water with low salinity and high temperature is pumped from an aquifer and fed to the membrane distillation battery. The fresh water produced is stored in a big tank to be used in the irrigation

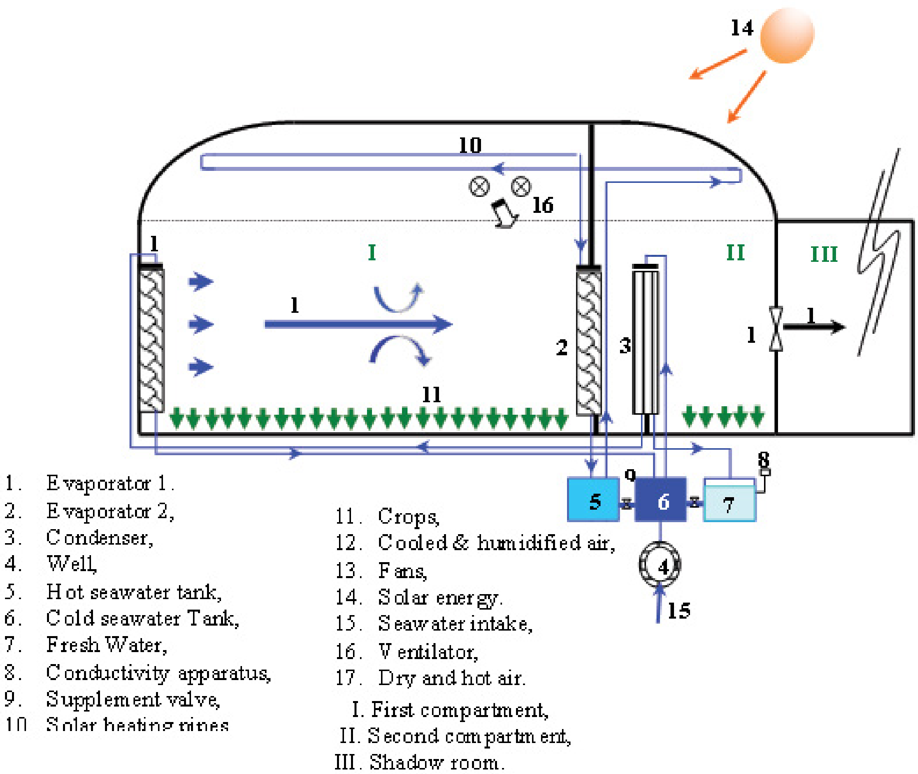

Fig. 5. Process schematic for seawater greenhouse [10,11].

of crops inside the greenhouse. The brine produced which is the bottle neck for all the desalination processes, feed the greenhouse in aim to produce fresh water using humidification dehumidification process. The brine produced by the greenhouse is mixed with brackish water which feeds the distillation membrane battery.

Algeria is a country in the Maghreb Region of North Africa. It is the largest country in Africa and covers an area of 2,381,741 square kilometers, with a population of 44 million [13]. The country is divided into four main physical regions, which extend from east to west across the country in parallel zones. The southern part is 80% of the land (1,905,932 km^2) and is uninhabitable because of the Sahara Desert. It is characterized by a chronic lack of potable water forcing people to migrate to the northern part. This arid region, surprisingly, has an enormous geothermal reservoir called the Albian Aquifer which is one of the largest groundwater systems in the world. It is a low salinity gigantic geothermal reservoir (temperatures of water ranging from 35°C to 70°C), that extends to more than one million km^2 [14]. The southern part is also known with its important non-conventional energy resources potential, highly favorable for photovoltaic and thermal solar applications [13].

The greenhouse humidification dehumidification desalination unit, uses sunlight, saline water, and the atmosphere to recreate a natural water cycle in a controlled environment and producing fresh water and cool air, creating ideal temperature conditions for the cultivation of crops. Hot groundwater after being pumped from the Albion aquifer, passes through conventional sand filtration unit which allows the elimination of solid particles and other impurities. Filtered water is send to a large hot water tank, where it is fed in a cascade to a battery of membrane distillation modules. The produced permeate is send to the freshwater tank to be used for the irrigation. The concentrate (Brine) fed to the first evaporator then to the second evaporator (Fig. 6). The brine water from the second evaporator returns to the hot water tank where it is mixed with the hot and filtered groundwater.

The two evaporators have the dimension of the greenhouse structure front wall. They are constructed from cardboard honeycomb lattices. The greenhouse should be oriented towards the prevailing wind direction. The concentrate brine from the membrane distillation modules trickles down over the evaporators lattice. The air passing through into the planting area is cooled and humidified due to the direct contact between water droplets and the dry air in the first evaporator. Fans are used to recirculate the air inside the greenhouse and to draw it through the shade room. The second evaporator humidifies the air to its saturation point. The saturated air passes over the condenser, where it is condensed. The resulting fresh water is piped to a storage for irrigation. The condenser is the bottle neck of the greenhouse desalination by humidification and dehumidification (SWGH).

For an effective commercialize prototype, the condenser must be efficient, uncomplicated, inexpensive, and low in maintenance. Mahmoudi et al. [15] proposed two new designs for the greenhouse condenser: a passive cooling system with a condenser (IC) immersed in a water basin, and an external passive condenser (EPC) connected to a basin of water placed on top of the condenser.

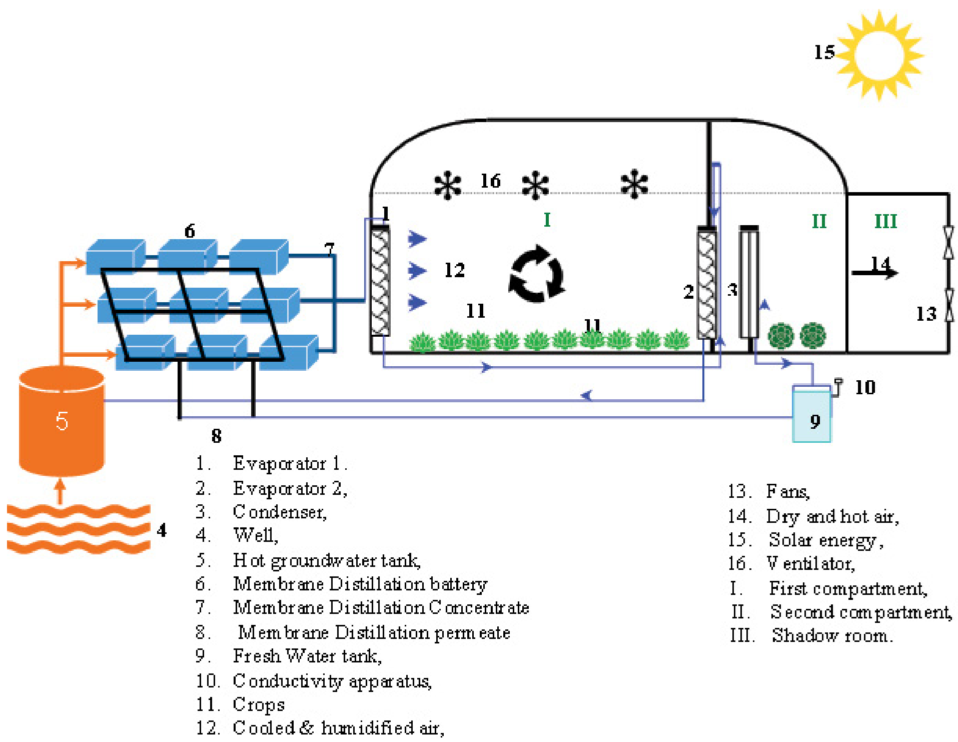

Fig. 6. Process schematic for membrane distillation battery coupled with humidification–dehumidification brackish water greenhouse.

7. Environmental concerns, market potential, and regulatory factors

Goosen et al. [16] argued that the effective use of renewable expertise requires an awareness of sustainable growth. The authors noted that there is a need to find a balance between social, economic, and environmental issues. These objectives, however, are not always compatible, and compromises are necessary. Grubert et al. [17] reported that the association between these areas is a complex process. For example, what comes first, environmental protection and human health or economic growth? Goosen et al. [16] determined that one way to help achieve a sense of stability is to teach people including decision makers, students, and industrial personnel, as this represents the main tool available for catalyzing social changes.

To promote commercialization, various kinds of governmental policy instruments such as tax breaks and low interest loans, can be successful for renewable energy development [16]. Though, broad-based programs, such as tradable energy certificates, are more likely to result in innovation on technologies that are close to competitive with fossil fuels. Worrisome observation is that renewable energy (RE) sources have consistently accounted for only 13% of the total energy use over the past 40 y [17]. Based on selected criteria Geographic Information System (GIS)-multi-criteria decision analysis (MCDA) has been applied to desalination site selection to aid policy makers by providing a customizable tool for identifying favorable locations for desalination facilities. This work demonstrated how an integrated GIS- MCDA framework can enable decision-makers to simultaneously include environmental, economic, and other societally specified criteria when, for example, producing a decision concerning the best place for a desalination plant.

Frondel and Schubert [18] and Frondel et al. [19] reported on reducing vehicle cold start emissions through carbon pricing by using evidence from Germany. Similarly, government sponsorship of renewable energy (RE) projects in Germany is frequently cited as a standard to be copied, being based on environmental laws that go back more than 20 years. Frondel et al. [20] argued that the government's support structures had essentially failed because of enormous expenses that showed little long-term potential for stimulating the economy, protecting the environment, or improving energy security. The authors described that it is most likely that whatever jobs were created by RE promotion would disappear as soon as government assistance was terminated.

He et al. [3] calculated global urban water shortage in 2016 and 2050 under four socioeconomic and climate change situations and studied possible resolutions. They showed the global urban residents confronting water paucity is expected to increase from 933 million in 2016 to 1.7–2.4 billion people in 2050, with India projected to be most harshly impacted. He et al. (2021) [3] articulated that most water-scarce cities can mitigate or alleviate water scarcity by infrastructure investment. However, they noted substantial likely environmental trade-offs linked with large-scale water scarcity solutions.

Finally, Matar et al. [4] reported on applying integrated management systems (IMS) in desalination plants in war zones. They showed that there are encouraging impacts of employing the IMS on the running of desalination plants in terms of the managerial, technical, financial, environmental, and socio-economic attributes. They concluded that the top priority and best appropriate approach is the creation of a collaboration with UN institutions to gain global protection and expedite the access of any required materials.

8. Concluding remarks

This study has shown that emerging desalination technologies can be integrated with renewable energy systems such as having a membrane distillation set up coupled with a humidification–dehumidification greenhouse desalination unit. A case study indicated that it may be feasible to combine a brackish water greenhouse desalination with membrane distillation for Southern Algeria by taking advantage of a very large underground brackish water aquifer. In closing, a holistic approach must be taken when considering the scale up of hybrid systems. In particular, environmental concerns, market potential, and regulatory factors of integrated systems must all form part of the decision making process.

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