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An overview on desalination & sustainability: renewable energy-driven desalination and brine management

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ABSTRACT

Desalination is a water technology that is gaining increasing importance for addressing water needs, but it is costly and energy intensive and further strains the environment with brine disposal and greenhouse gas (GHG) emissions. In order to desalt seawater, either through membrane or thermal processes, a large amount of energy is required. Desalination has negative impacts in the form of depletion of fossil fuels and GHG emissions from the power production process to deliver this energy. What is more, the wastewater (brine) produced during the desalination process causes damages to the local sea environment where the brine is discharged. In order for desalination to be considered a sustainable water solution, both issues must be successfully resolved. This paper discusses the potential for coupling desalination with renewable energy (RES-D). Different renewable technologies can be combined with certain desalination techniques. The technical development stage of the RES-D combinations already applied is given. Currently applied management as well as an innovative alternative for brine management based on zero liquid discharge (ZLD) is also presented. This pilot system was developed in the framework of an European project with the acronym SOL-BRINE (LIFE09 ENV/GR/000299).

Keywords: Renewable energy; Solar energy; Wind energy; Ocean energy; Desalination; Brine treatment; Desalination; Zero liquid discharge (ZLD); SOL-BRINE

1. Introduction

Desalination technologies are used to produce drinking water from brackish water (salinity between 1,000 and 35,000 ppm) or/and seawater (salinity greater than 35,000 ppm). Industrial desalination technologies use either phase change or involve semi-permeable membranes to separate the solvent or some solutes [1]. Thus, desalination techniques may be classified into the following categories (see also Fig. 1):

(1) phase-change or thermal processes;
(2) membrane or single-phase processes; and
(3) hybrid processes.

As of June 2011, 15,988 desalination plants have been installed and operated in 150 countries

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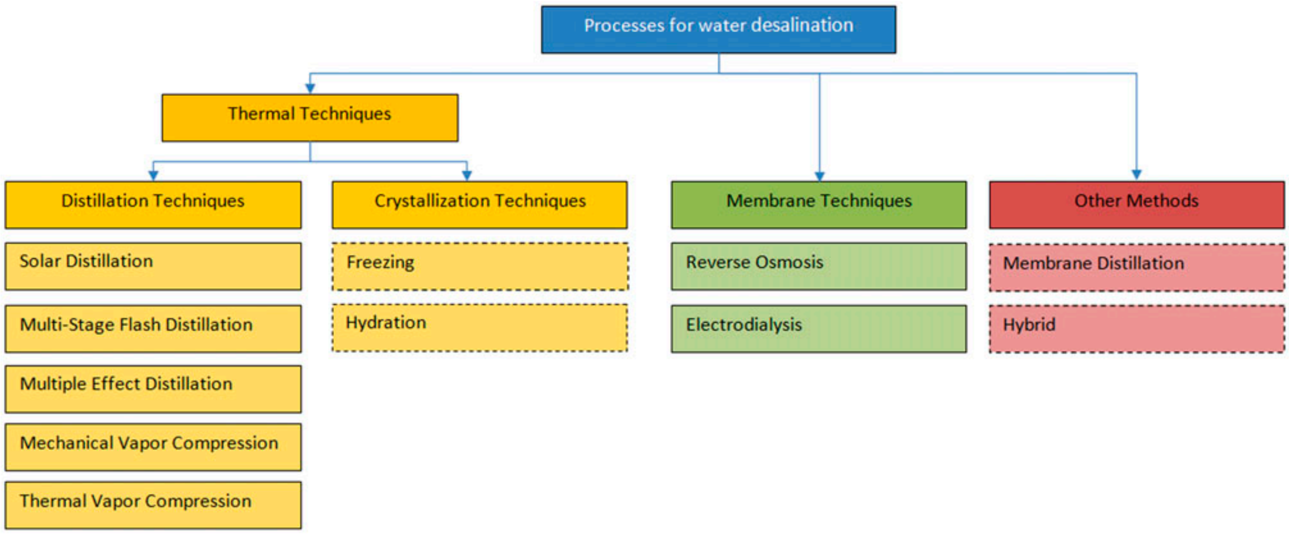


Fig. 1. Processes for water desalination. Adapted from [2].
Note: The dashed boxes indicate processes that are in the R&D stage.

producing a combined 66.5 million m^3 of fresh water per day [3]. The desalinated water is used for different applications: municipal use (63%), industries (25.8%), power stations (5.8%), irrigation (1.9%), tourism (1.9%) and others. The sources of the water treated are: seawater (60%), brackish water (21.5%), river water (8.3%), wastewater (5.7%), pure water (4.3%) and brine (0.2%) (see also Fig. 2). Among the different desalination technologies, reverse osmosis (RO) predominates with a total share of 53%, followed by multistage flash distillation (MSF), multiple effect distillation (MED) and electrodialysis (ED). This pattern changes drastically across regions, with countries around the Arabian Gulf using mostly thermal techniques (MSF and MED), while almost all plants in Europe and USA use RO (see also Figs. 3 and 4).

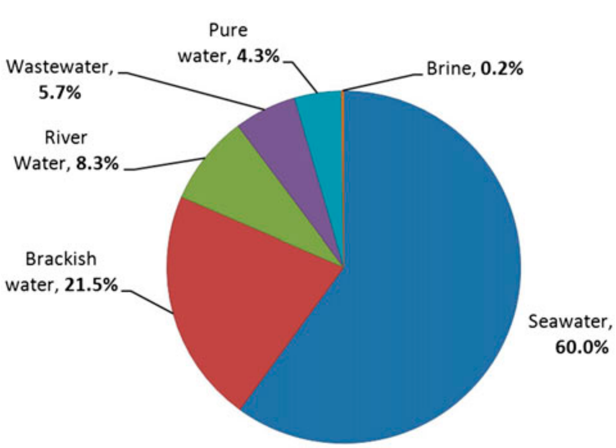


Fig. 2. Sources of water treated by desalination technologies (Worldwide) [3].

2. Desalination & energy considerations

Desalination uses a significant amount of energy. Energy usage affects the technology's carbon footprint and hampers its wider deployment. Currently, RO is the most efficient water treatment technology, with its consumption ranging between 2 and 5 kWh/m^3 (according to the type of treated water, i.e. brackish or seawater). No thermal energy is required for driving the RO process. In general, it can be said that thermal techniques require a greater amount of energy than membrane technologies. However, in order to compare the energy requirements of these techniques, it is necessary to reflect the primary energy consumption and not only the final energy consumption (see Fig. 5). For instance, RO uses electricity which is produced in most cases by fossil fuel-fired power stations.

3. Renewable desalination (RES-D): a win–win technological partnership

The main challenge of RES-D is how to make two different technologies work together. Even though, both components comprise mature technologies, their combination is currently at the R&D stage at the moment. This is why RES-D plants are limited both in

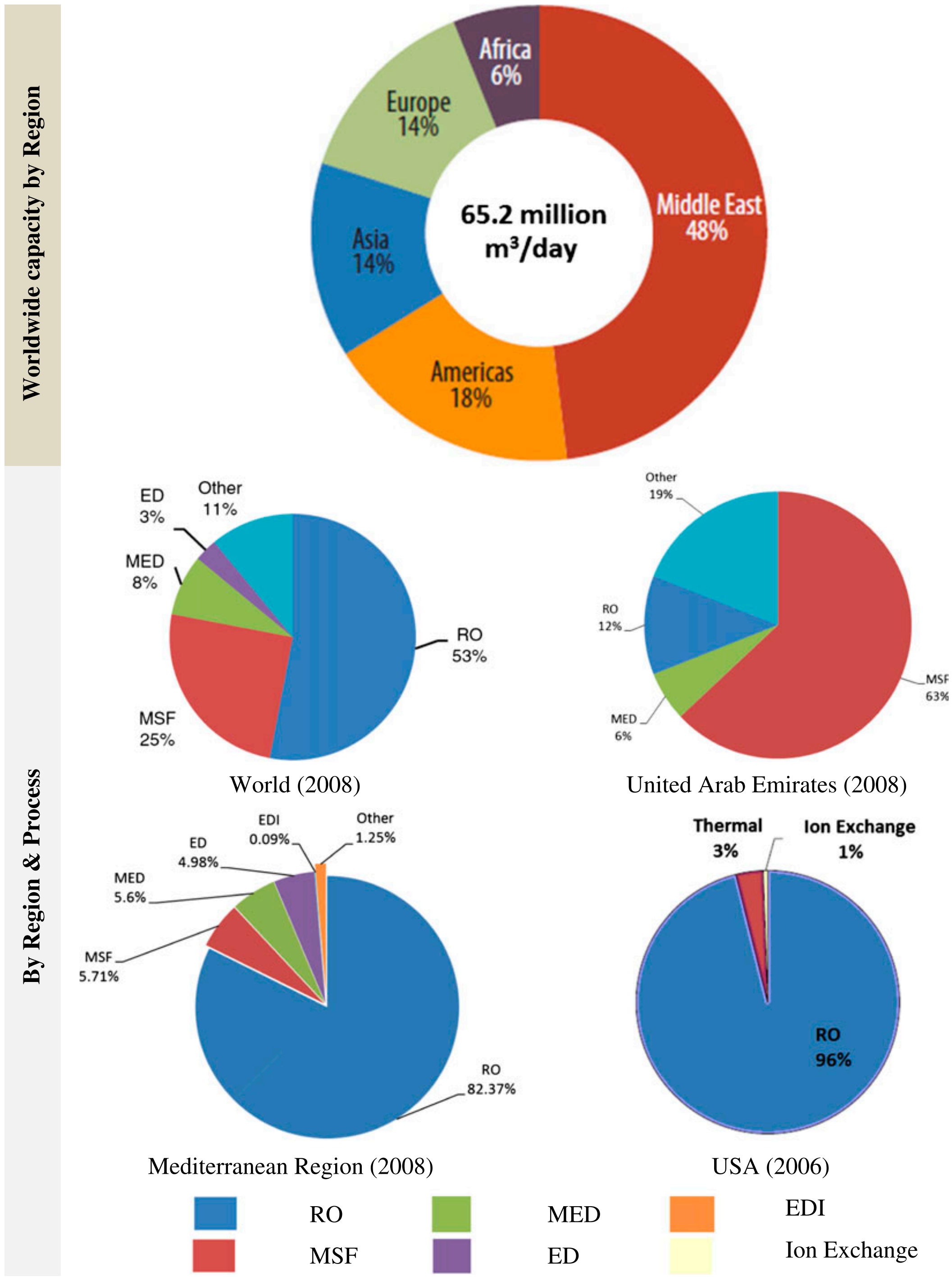


Fig. 3. Desalination capacity. Adapted from [4,5].

number and water production capacity. Kalogirou [1] reports that RES-D plants make up less than 1% of the total installed desalination capacity worldwide. Most of these plants are installed in arid areas e.g. the Middle East and North African region (MENA), with capacities between a few m^3 up to 100 m^3.

RES-D systems have been the focal point of much research work worldwide. Many projects (such as

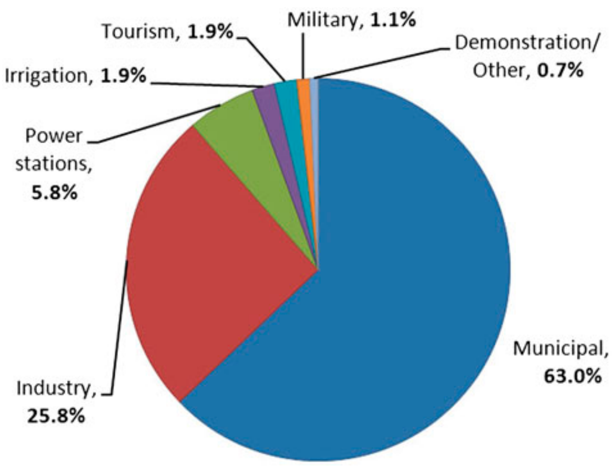


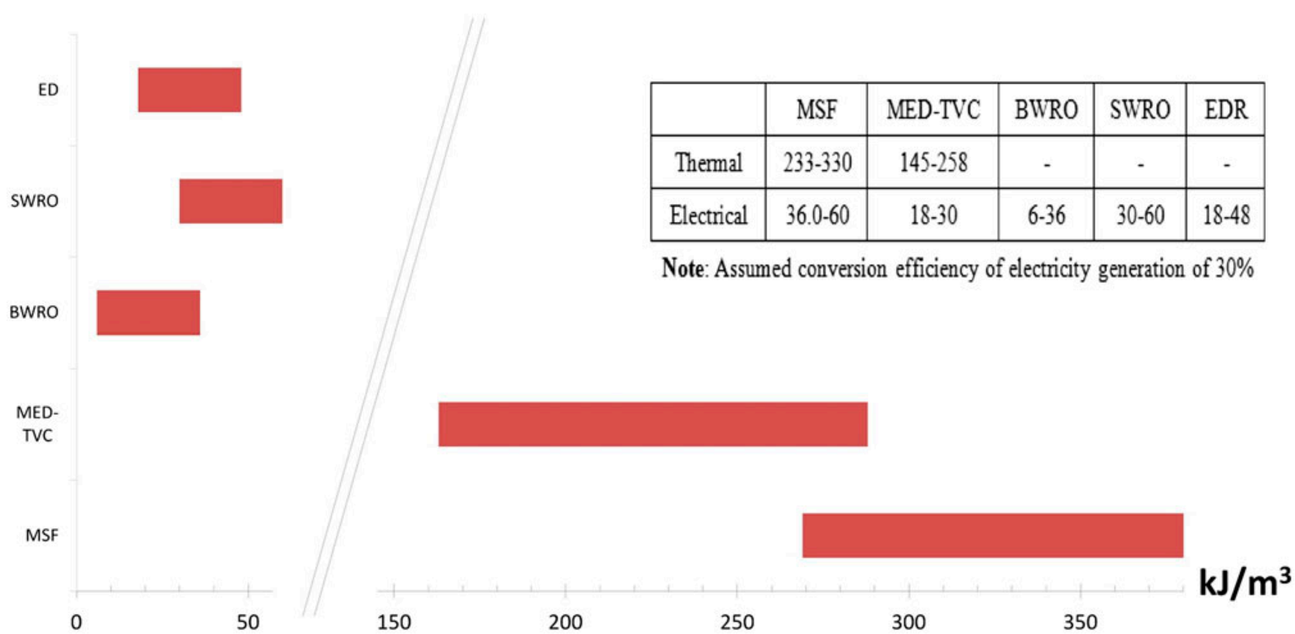
Fig. 4. End users of desalination plants (Worldwide) [3].

AQUASOL, PRODES, ADIRA, AQUA-CSP, MEDESOL and MEDINA.) have examined and evaluated the barriers and challenges stemming from the coupling of these technologies (i.e. renewable source collector and desalination technology) with the aim to carry forward the RES-D techniques from the research to the commercial application development stage (see also Fig. 6). One of the most often cited works on RES-D is the report titled "*Roadmap for the development of desalination powered by renewable energy*" which was developed in the framework of the European project PRODES [9]. The project PRODES has made significant contribution in collecting and reporting the available data for RES-D plants worldwide. Papapetrou [9] reports that until 2009, 131 renewable powered desalination systems have been recorded across the globe. The RES-D combinations recorded are presented in Table 1 [Figs. 7 and 8], while data for selected RES-D small applications are provided in Table 3.

It must be noted that the vast majority of the RES-D applications employ solar powered techniques with PV-RO being the dominant combination, amounting to a share of 31%. Solar energy techniques comprise proven, well-tested technologies, offering the potential of a reliable energy source for desalination practices. Solar powered desalination technologies can be divided into two broad categories: direct and indirect processes. The first category involves the solar still technology, while the second involves:

(1) solar collectors;
(2) solar ponds, and
(3) photovoltaic units.

Solar energy collector devices can either drive both thermal desalination and membrane desalination systems. A list of the possible combinations, according to the type of the solar device, is presented in Table 2.



	MSF	MED-TVC	BWRO	SWRO	EDR
Thermal	233-330	145-258	-	-	-
Electrical	36.0-60	18-30	6-36	30-60	18-48

Note: Assumed conversion efficiency of electricity generation of 30%

Fig. 5. Energy consumption of desalination systems and overall primary energy requirements. Compiled based on data collected from [2,6–8].

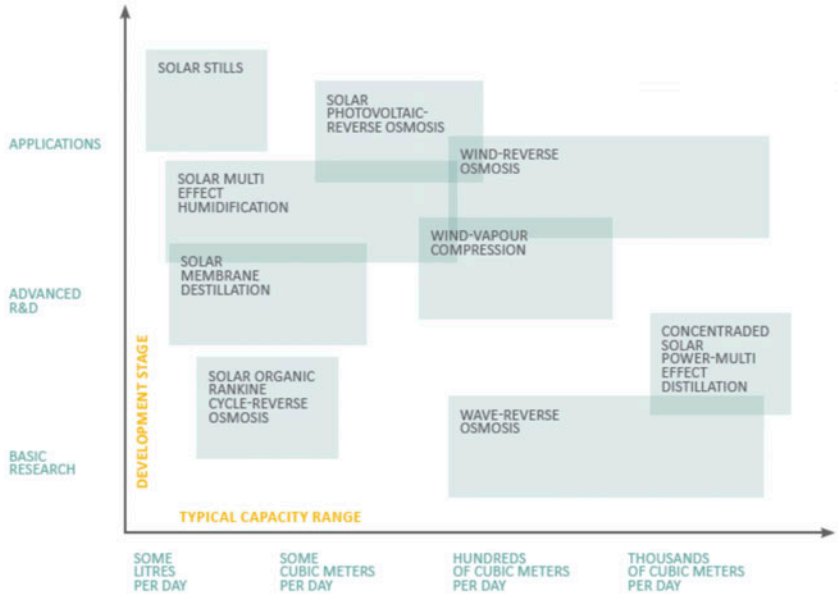


Fig. 6. Development stage and capacity of the main renewable powered desalination plants [9].

Table 1
Breakdown of renewable energy-driven desalination applications[1]

RES-D technology combination	Share (%)
PV–RO	31
Wind–RO	12
Solar–MD	11
Solar–MED	9
Solar–MSF	7
PV–ED/EDR	3
Hybrid	3
Others	15

[1]PV: photovoltaics, RO: reverse osmosis, MD: membrane distillation, MED: multiple effect distillation, MSF: multi-stage flash distillation, ED: electrodialysis, EDR: electrodialysis reversal.
Source: Papapetrou et al. [9]

The technical and economical potential of renewable energy (RE) resources vary significantly by country and region, across the globe. For instance, the MENA region has very abundant solar potential, with large area availability, meaning that the MENA region has a comparative advantage for solar applications and especially concentrated solar power (CSP) [6,10]. In contrast, North European countries such as Denmark have a very good renewable potential for wind applications. The water production cost varies significantly according to the type of RES-D and the water type treated, as illustrated in Fig. 8. Even though costs are prohibitive at the moment, cost reduction is anticipated due to technology improvements, learning effects and scaling-up. Trieb and Müller-Steinhagen [11] reports that RES-D cost is expected to fall to 0.9$/m^3$ by 2050.

4. Brine management

4.1. Concentrate management options

The desalination process produces a significant amount of wastewater: 2 L of brine for every litre of freshwater produced. The generated wastewater has to be managed properly, while the concentrate management options depend heavily on site characteristics and the wastewater volume. These options typically include the following:

(1) deep well injection;
(2) evaporation pond;
(3) spray irrigation;
(4) sewer;
(5) surface water, and
(6) brine concentrator/zero liquid discharge (ZLD).

Every concentrate management method has different costs, benefits, environmental impacts and limitations. The costs are highly dependent on the concentrate volume (see also Fig. 9).

The main characteristics of the above-mentioned brine treatment and discharge methods are provided in Table 4.

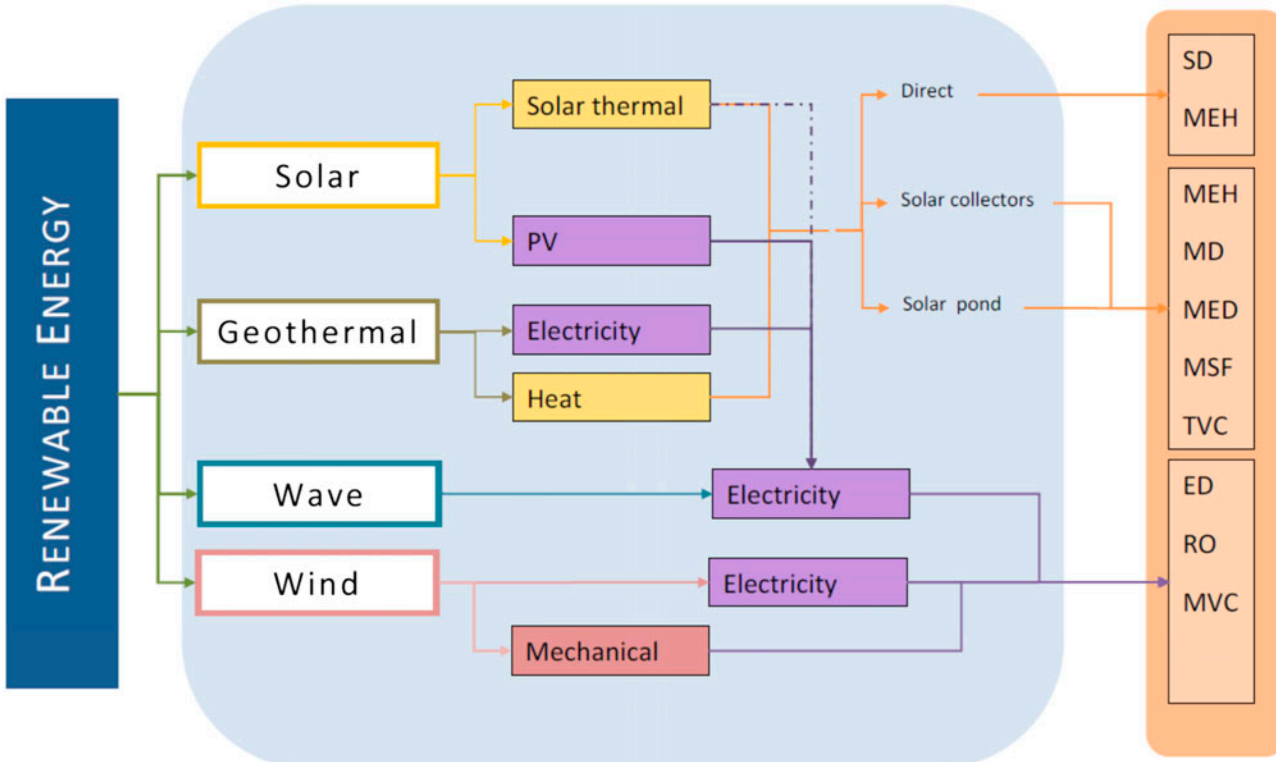


Fig. 7. Possible combinations of desalination processes with renewable processes. Adapted from [2].

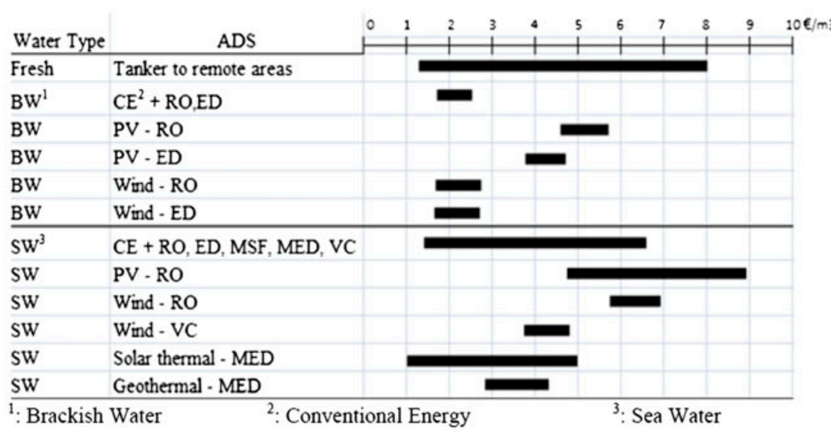


Fig. 8. Range of cost for various RES-D technologies [12].

4.2. The SOL-BRINE system

ZLD desalination can provide a sustainable source of potable water. Desalination is an energy-intensive process which produces a significant amount of wastewater: around 2 L of wastewater are generated for every litre of freshwater produced. This volume of wastewater poses a significant management problem, and critical problems to the discharge environments: the sea (for seashore desalination plants) and underground aquifers (for inland desalination plants). The United Nations Environment Programme (UNEP-MAP) has recognized the

Table 2
Combinations between solar technologies and desalination

		CSP			
Desalination technique	Thermal collectors	Thermal	Electrical	PV	Solar pond
SD	✓				
MEH	✓	✓			
MD	✓	✓			
TVC		✓			
MSF		✓			✓
MED	✓	✓			
ED			✓	✓	
MVC			✓	✓	
RO			✓	✓	

Source: Papapetrou et al. [9]

Table 3
Selected plants for small RES-D applications

Reference plants	Capacity	Site	Desalination system	Renewable technology	Water cost	Reference
Keio University Plant	100 kg/d	Yokohama, Japan	MED	Static Solar Collectors	–	[13]
Ebara plant	205 kg/d	Gaza, Palestine	MED	Static Collectors & PVs	–	[14]
Geroskipou Plant	~3 m^3/d	Paphos, Cyprus	MEH	Static Collectors	18 €/m^3	[15]
PSA plant	72 m^3/d	Almeria, Spain	MED	CPC	–	[16]
Jeddah plant	5 m^3/d	Saudi Arabia	MEH	Static Collectors	~ 6 €/m^3	[17]
Gran Canaria plant	480 l/d	Gran Canaria	MD	Static Collectors	–	[18]
Morocco plants	12–24 m^3/d	Morocco	RO	PV	3.99–7.01 €/m^3	[18]
Ydriada plant	80 m^3/d	Greece	RO	Wind Turbine	–	[18]
Kimolos Plant	200 m^3/d	Kimolos Island, Greece	MED	Geothermal		[19]
Oyster Plant	–	Scotland	RO	Wave energy	–	[9]

Note: An in-depth analysis of these plants was carried out in the report titled "Report on the evaluation of desalination systems driven by renewable energy sources: focus on solar energy systems used in different desalination applications" which was produced in the framework of the SOL-BRINE project (available at: http://uest.ntua.gr/solbrine/uploads/files/Deliverable1.2.pdf).

problem of brine disposal as one of the major threats to the Mediterranean Sea.[2] More specifically, one of the most significant seagrasses of the Mediterranean Sea (Posidonia Oceanica), which is protected under the Barcelona Convention, has been identified to be highly vulnerable to salinity changes and as a result to brine exposure [20–22].

The SOL-BRINE project sought to eliminate water pollution and environmental damage associated with brine release, by introducing a new technique capable of achieving ZLD from desalination plants. The demonstration plant that is presented in this paper was installed in Tinos Island in Greece and is in operation since January 2013. The plant has the capacity to treat over 200 tonnes of brine per year and can lead to high

[2]*"One of the two major, urgent threats to the Mediterranean Sea environment is the pollution caused by the increased number of desalination plants and the releases and the effects of brine to the Mediterranean Sea"*: part of the speech of the director, Ms Maria Luisa Silva Mejias to the launching conference of the project "Governance & Financing for the Mediterranean Water Sector" held in Barcelona on 28–29 May, 2013. See also: http://ufmsecretariat.org/mediterranean-water-governance/.

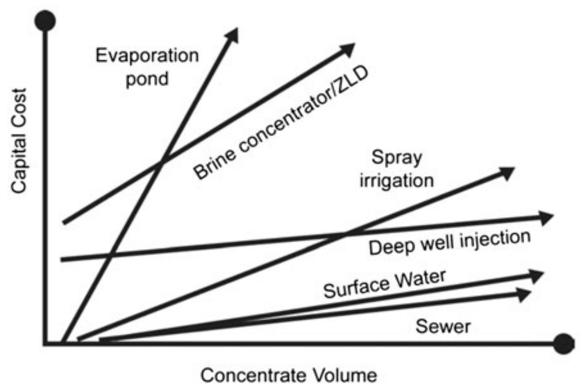


Fig. 9. Capital cost of different discharge methods versus concentrate volume [6].

recovery of resources, both water (recovery > 90%) and dry salt (full recovery).

4.3. The SOL-BRINE concept

The overall scope was to develop an energy autonomous brine treatment system for the total elimination of the brine, so as to address effectively the complex issue of sustainable water management and desalination. The innovative features of the system include [5]:

(1) Total brine elimination: the system has been designed in line with the ZLD principle;
(2) Water recovery (>90%);
(3) Production of useful end products: through the operation of the prototype system, the following two products are produced: (a) distilled water of high quality and (b) dry salt. Both products have increased market potential;
(4) Energy autonomous operation: solar thermal collectors are used for delivering hot water (delivered at 80°C approximately) and a photovoltaic generator for electricity. All energy requirements are covered exclusively through the use of solar energy;
(5) Use of state-of the art technology: the evaporation of water is realized through a custom designed vacuum evaporation technology (evaporator and crystallizer) and solar dryer.

The SOL-BRINE concept is summarized in the following Fig. 10.

4.4. The SOL-BRINE system

In the course of the project, an innovative and energy-autonomous (through solar energy) pilot system was developed for the treatment of brine from an existing desalination plant. The system was installed in Tinos Island with a capacity of 2 m^3/d (feed volume rate of brine effluent). It is able to treat a small portion (<1%) of the total quantity of brine effluent produced from the desalination plant. The system comprises three treatment stages: (a) an evaporator unit, (b) a crystallizer unit and (c) a dryer unit.

The prototype system has been tested thoroughly and the technology has been demonstrated at pilot scale. The system results are very promising and can be further exploited with its market uptake. The results of the project are available via the project website (http://uest.ntua.gr/solbrine).

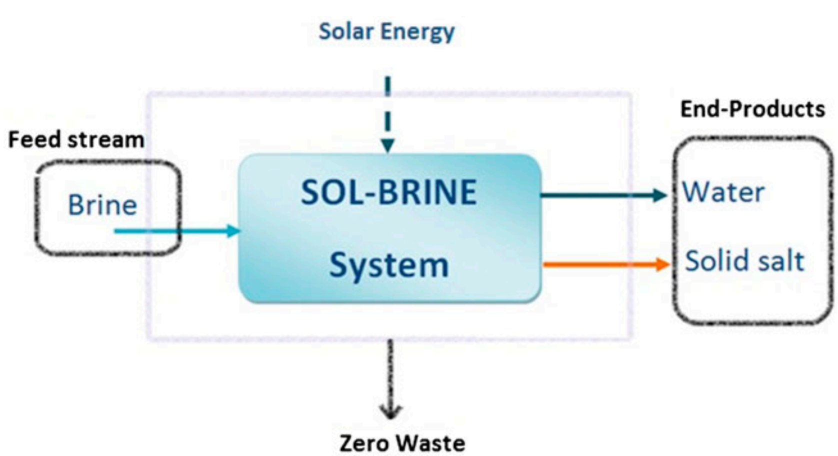


Fig. 10. The SOL-BRINE concept [5].

Table 4
Main characteristics of brine treatment and discharge methods [23,24]

Method	Costs	Land requirements	Benefits	Constraints
Surface discharge	Low capital and O&M cost (Often Least Expensive option)	Small	Can accommodate large volumes	Thermal pollution, reduction of dissolved oxygen in receiving waters, eutrophication, toxicity, pH increase and damage of biota Often requires a discharge permit
Sewer disposal	Cost-effective, if existing sewage and treatment plants nearby	Small	Uses existing infrastructure Lowers the BOD of the resulting effluent	Must meet sewer quality standards Can hamper the use of the treated sewage for irrigation Overload existing capacity of the sewage plant
Deep well injection	Cost efficient for larger volumes' High capital costs	Land required for injection wellfield	No marine impact expected	Risk of groundwater pollution No beneficial use of brine
Evaporation ponds	High cost	Large	Possible commercial salt exploitation Low technological and managing efforts	Only suitable in dry climates Storage and distribution system needed Risk of soil and groundwater pollution
Land application	Low economy of scale	Large	Can be used to irrigate salt-tolerant species No marine impact expected	Suitable for smaller discharge flows Can increase the salinity of groundwater and underlying soil
ZLD	Expensive	Large	Can commercially exploit concentrate No marine impact expected	Energy-intensive process

5. Conclusions

With no doubt, desalination will play a major role for the supply of potable water in the future, even in areas which now enjoy good water availability. It is now time to address the limitations of desalination which hamper its wider deployment, namely energy and brine considerations. This paper discusses solutions for both problems, suggesting the introduction of renewables for addressing the energy needs of desalination and the exploitation of research and innovation results for effective brine management. ZLD has very little application in the desalination sector worldwide and these are limited to evaporation ponds, where large land availability and suitable climate conditions (dry climate and sufficient insolation) are necessary. These limitations are both well addressed by the innovative SOL-BRINE system presented in this work. Such systems can eliminate negative environmental impacts, while contributing significantly to the offset of the treatment cost through high recovery of useful end products.

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