DESALINATION & SUSTAINABILITY: RENEWABLE ENERGY DRIVEN DESALINATION AND BRINE MANAGEMENT

D.A. Xevgenos*, K. Moustakas, D. Malamis, M. Loizidou

Unit of Environmental Science and Technology (UEST), School of Chemical Engineering, National Technical University of Athens, Greece, Zographou Campus, 9, Heroon Polytechniou Str., 15773 Athens, Greece.

**Tel.: 0030 210 772 3108, Fax: 0030 210 772 3285, e-mail: xevgenos@central.ntua.gr*

Abstract

Water and energy are recognized as two of the most important issues of the international environmental and development agenda. These two critical resources substitute indispensable commodities not only for the welfare of the modern world (including industrial development, economic growth and social wellbeing) but also for the preservation of life. However they are currently both under significant pressure.

The current regime for balancing the fresh water supply with the demand is based on the availability of fresh water in the underground aquifers or other water resources, having a strong site-dependent character. Even though desalination has been proved to be a mature and well established procedure for fresh water production, it is not considered as a conventional water supply method in the portfolio of possible alternatives, as it is considered as an energy and capital intensive water production option. What is more there is an increasing concern over the environmental pressures on the marine environment due to the current practice of uncontrolled brine discharge into the sea and other surface or underground water bodies.

In this paper, these two obstacles for the wide deployment of desalination are discussed, namely energy considerations and brine management. With reference to the former, a review for renewable energy driven desalination systems is provided. After having outlined the main desalination techniques applied today, possible combinations with renewable systems are provided, while presenting certain case studies worldwide. With reference to the latter, the brine release from desalination plants is raising particular concerns. Desalination produces a lot of wastewater. For the case of Reverse Osmosis (which is the predominant desalination technique used today worldwide), for every liter of freshwater, two liters of brine are produced. This poses a significant management challenge. In order to address this challenge effectively, an innovative system for brine management has been developed in the framework of the SOL-BRINE project. This system is designed according to the Zero Liquid Discharge principle and apart from environmental protection can contribute significantly to resource efficiency also. It results to high water recovery (>90%) and to the production of dry salt saleable products. The prospect of this system is also discussed in this paper, providing therefore a holistic approach to the main challenges associated with desalination today.

1. Desalination Technologies

Desalination refers to any of several separation processes that remove excess salt and other minerals from water. Water is desalinated in order to convert salt water to fresh water so it is suitable for human consumption or irrigation. During the process, two discrete streams are produced, fresh water and saline solution (brine). Much attention has to be paid to the treatment and disposal of the brine waste stream generated during the operation. Suitable techniques for treating the brine produced are analyzed and presented in the report "Evaluation of existing methods on brine treatment and disposal practices" developed under the scope of the first action of SOL-BRINE project.

Saline water is classified as brackish water when the salt concentration, mostly sodium chloride, is between 1,000 ppm and 10,000 ppm, hard brackish water when salinity is between 10,000 ppm and 35,000, and seawater when the salinity exceeds 35,000 ppm [1].

Large-scale desalination typically uses extremely large amounts of energy as well as specialized, expensive infrastructure, making it very costly compared to the use of fresh water from rivers or groundwater. As a consequence, most of the modern interest in desalination is focused on developing cost-effective ways of providing fresh water for human use in regions where the availability of fresh water is, or is becoming, limited.

Desalination can be achieved by using a number of techniques. Industrial desalination technologies use either phase change or involve semi-permeable membranes to separate the solvent or some solutes [2]. Thus, desalination techniques may be classified into the following categories:

(i) phase-change or thermal processes;

(ii) membrane or single-phase processes; and

(iii) hybrid processes.

All processes require a chemical pre-treatment of raw seawater to avoid scaling, foaming, corrosion, biological growth, and fouling and also require a chemical post-treatment [2]. Following, a brief description of the aforementioned desalination technologies is given, along with operational and supplementary data.

It must be noted that this description is not meant to be all-inclusive, but rather to provide the whole picture of desalination approaches, focusing mainly on state-of-the art technologies that consist industrially mature practices.

2. Desalination powered by renewable energy

The installed capacity of desalinated water systems in year 2000 was about 22 million m^3/day, a figure expected to increase drastically in the upcoming decades. It has been estimated that the production of 22 million m^3/day requires about 203 million tons of oil per year (about 8.5 EJ/yr or $2.36 \cdot 10^{12}$ kWh/yr of fuel) [2]. Considering that the development of sustainable and energy efficient schemes has to been mainstreamed in all energy related sectors, the coupling of desalination with renewable energy sources constitutes an appealing and promising option. It must be noted that the share of the total worldwide renewable energy desalination installations amount to capacities of less than 1% of that of conventional fossil fuel powered desalination plants, mainly due to the high capital and maintenance costs required by renewable energy [3, 4].

Apart from sustainable development, RES-D (Renewable Sources-Desalination) applications are considered as the most attractive option for addressing and resolving the water scarcity problems in arid, remote areas characterized by lack of potable water or/and lack of an electricity grid. For these purposes, many RES-D plants have been developed up to the present, the majority of which are custom designed for specific locations and constitute experimental or demonstration scale plants.

However, one of the major constraints in RES-D applications to be addressed is the reliability of the system given the intermittence character of most renewable energy sources [5].

In the present study, only industrially-tested desalination technologies are included and they comprise: (i) the phase change processes, which include the multistage flash, multiple effect boiling and vapor compression and (ii) membrane processes, which include reverse osmosis and electrodialysis, coupled with the following renewable energy sources:

(a) Solar energy;

(b) Wind energy; and

(c) Geothermal energy

There are a number of ways that renewable energy can be harnessed for desalination. It can be used directly (such as the solar still) or indirectly by converting the incoming solar energy to the appropriate form of energy that suits the different desalination technologies, i.e (a) to mechanical energy to drive pumps wind powered RO plants, (b) to electrical energy via photovoltaics, wind turbines, solar ponds, water turbines, wave or tidal power, and the electrical energy used to drive pumps, as with reverse osmosis, or provide a field, as with electrodialysis [6].

However, there is no best RES-D combination, but on the contrary the selection of the appropriate RES desalination technology depends on a number of factors. These include, plant size, feed water salinity, remoteness, availability of grid electricity, technical infrastructure and the type and potential of the local renewable energy resource. Even though some RES-D couplings seem to be more promising in terms of economic and technological feasibility than others, it must be stressed that their applicability strongly depends on the local availability of renewable energy resources and the quality of water to be desalinated. In addition to that, some combinations are better suited for large size plants, whereas some others are better suited for small scale application.

The following sections present various RES-D approaches involving the above renewable sources. Only methods which are industrially mature are reviewed. There are, though other methods, as freezing and hydration which are not included as they are developed at a pilot, laboratory scale and have not been used on a large-scale for desalination [2]. Technical, operational and economical data are provided, as well as various case studies are examined. To this end, a horizontal approach on RES-D systems is developed, concluding in the thorough examination of desalination systems powered by solar energy.

3. Solar Desalination

Renewable energy source powered desalination (RES-D) systems has been the focal point of much research work worldwide. Different significant projects (such as AQUASOL, PRODES, ADIRA, AQUA-CSP, MEDESOL, MEDINA etc.) have been developed, examining and evaluating the barriers and challenges stemming from the coupling of these technologies (i.e renewable source collector and desalination technology) with the view to promoting RES-D techniques from research to commercial application development stage. As a consequence, many renewable energy powered desalination plants have been developed until now, most of which consist pilot plants for research activity. According to PRODES project developed under the FP7 funding tool, 131 representative plants have been installed between 1974 and 2009. The breakdown of the different combination of technologies is summarized in Table 1.

Table 1. Breakdown of renewable energy driven desalination applications

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**

It must be noted that the vast majority of the RES-D applications employ solar powered techniques, with the combination of photovoltaics with reverse osmosis (*PV-RO*) being the dominant coupling, amounting to a share of 31%. Solar energy techniques substitute 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: (a) direct and (b) indirect processes.

The first category involves the solar still technology while the second involves:

(a) Solar collectors;

(b) Solar ponds, and

(c) Photovoltaic units.

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

Table 2. Possible combinations of solar energy with desalination technologies [7]

Desalination Technique	Thermal Collectors	CSP		PV	Solar Pond
		Thermal	Electrical		
SD	✓				
MEH	✓	✓			
MD	✓	✓			
TVC		✓			
MSF		✓			✓
MED	✓	✓			
ED			✓	✓	
MVC			✓	✓	
RO			✓	✓	

4. The SOLBRINE concept

The overall scope was to develop an energy autonomous brine treatment system for the total elimination of the brine generated from Tinos seawater desalination plant, with market opportunities, adding one more valuable output to the entire system. In order to succeed in doing so, the steps included literature review, design of the prototype, construction, operation, optimization, overall evaluation (LCA and economic) and suggestions for the full scale application. contributing to high water recovery (>90%) and to the production of a dry salt product

The innovative features of the system include:

- **Total brine elimination.** The system has been designed in line with the Zero Liquid Discharge principle

- **Water Recovery** (>90%)
- **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.
- **Energy autonomous operation**. Solar thermal collectors are used for delivering hot water (10 KW_{th} at approximately 70°C) and a photovoltaic generator (10 kW_{el}) for electricity. All energy requirements are covered exclusively through the use of solar energy.
- **Use of state-of the art technology**: the evaporation of water is realized through custom designed vacuum evaporation technology (evaporator and crystallizer) and solar dryer.

The SOL-BRINE concept is summarized in Figure 1.

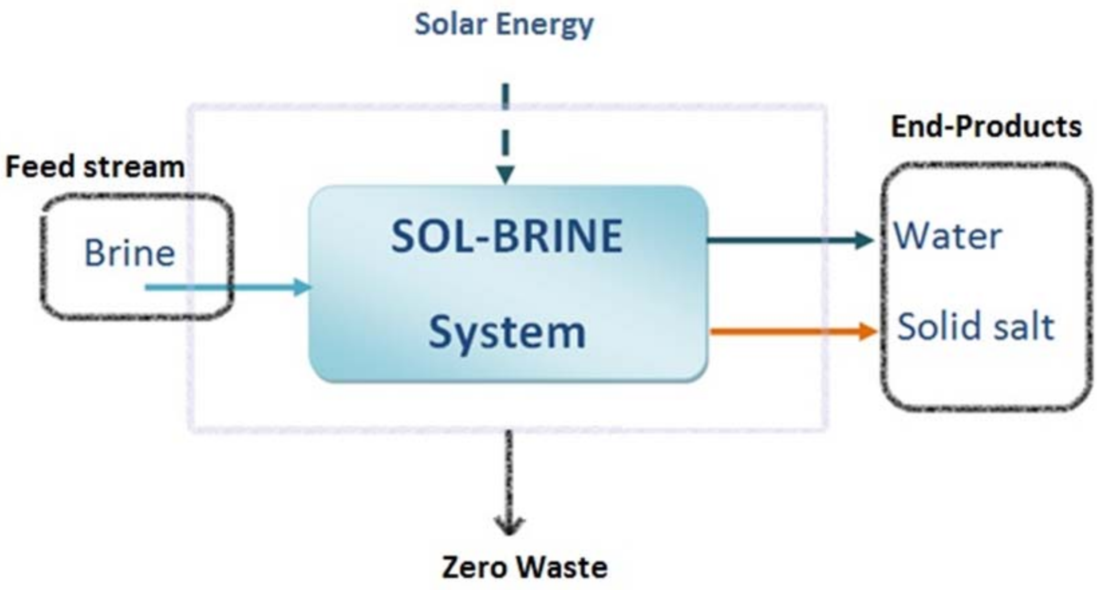

Figure 1. The SOL-BRINE concept

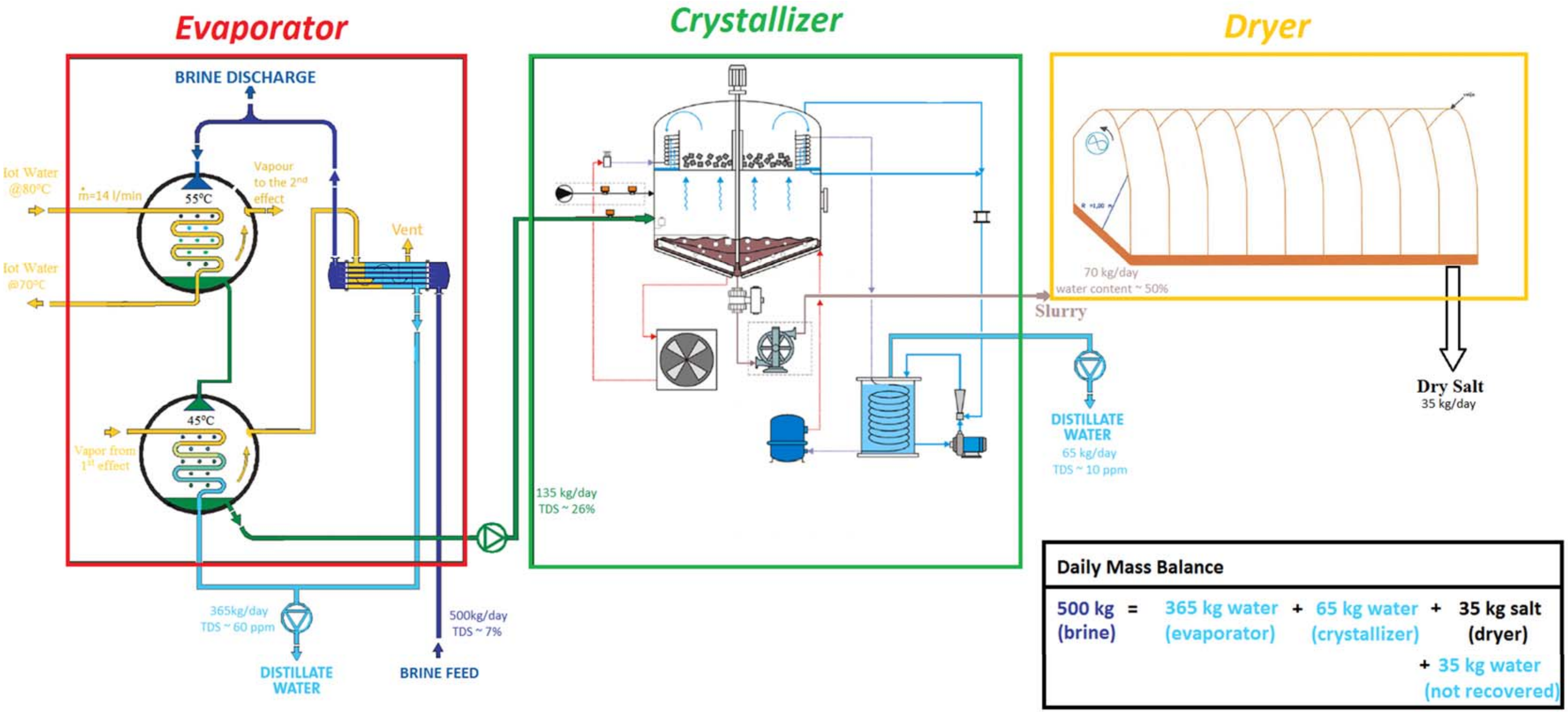

Figure 2. Process flow diagram of the SOL-BRINE system (The figure represents the daily mass balance of the system)

5. Process description

In order to achieve Zero Liquid Discharge, all the amount of water must be gradually removed from the brine effluent until solid salt crystals are obtained. In order for this to be achieved, the following units are employed:

- Evaporator unit;
- Crystallizer unit; and
- Dryer.

Following, a brief description of the process involved within each of these units is discussed.

Intake: A small portion of the brine rejected from Tinos seawater desalination plant (~500 kg/day) is driven to the prototype system. The brine treatment system is fed with brine at 7% (measured at normal operating conditions) from the existing desalination plant situated in Agios Fokas. This means that some 35kg of salt are produced by the pilot unit per day of operation. The daily mass balance is given in Figure .

Evaporator unit

The evaporator unit is consisted of two (*2*) consecutive effects operated at decreasing levels of pressure:

- 1st effect pressure: 0.30 atm(a);
- 2nd effect pressure: 0.10 atm(a).

In each of the evaporator effects, the brine is evaporated and two subsequent streams are produced: (a) a water vapor stream, which is subsequently condensed and recovered as fresh water, and (b) a more concentrated brine stream, which is driven to the subsequent treatment stage. The vapor stream of the first effect is used for heating the concentrated brine produced which is sprayed on the top of the bundle and runs down from tube to tube by gravity. This way, the required latent heat for the vaporization of the brine in the second effect is provided by internal heat gain (heating steam from the first effect) and, thus, energy recovery is achieved.

The vapor stream produced by the second effect is used for pre-heating purposes. More pertinently, the vapor is passed through and condensed in a plate heat exchanger, transferring its thermal energy to the inlet feed brine stream. Thus, thermal energy and fresh water is recovered to the best possible extent.

The concentrated stream produced by the second effect is then passed to the crystallizer unit where it is further concentrated. The concentration of the evaporator exit stream is designed to be near saturation point (~26%).

Crystallizer

Both the crystallizer and the evaporator unit are based on the physical process of vacuum evaporation. The crystallizer is consisted of a single vessel maintained at lower levels of pressure (normal operating conditions: 5kPa ≅ 0.05 atm(a)). The crystallizer unit is equipped with scraping blades inside the boiling vessel for allowing high evaporation rates through cleaning of the heat transfer surfaces from the formed salt crystals and good agitation. The vacuum is maintained through the combined use of a pump and an ejector. Its purpose is to crystallize the brine effluent, producing slurry (magma) with humidity levels of approximately 50%. The whole process is characterized by energy efficiency through the combined use of vacuum technology and heat pump. The crystallizer unit was manufactured by Veolia Water Solutions & Technologies according to the specific characteristics and needs of the brine treatment process involved.

Solar Dryer

The magma resulting from the crystallizer acquires excess moisture content that it is effectively removed by employing a solar dryer system and producing dry salt.

Solar Energy System

The energy requirements of the pilot brine treatment system are covered through the use of solar energy. The thermal requirements are supplied by concentrating vacuated tube collectors through hot water at 80^{o}C, while the electrical requirements through the use of an autonomous photovoltaic generator (equipped with batteries for one day autonomy).

Acknowledgments

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References

[1] R. A. Khaydarov and R. R. Khaydarov, Solar powered direct osmosis desalination, Desalination, 217 (1-3) (2007) 225-232.
[2] S. A. Kalogirou, Seawater desalination using renewable energy sources, Progress in Energy and Combustion Science, 31 (3) (2005) 242-281.
[3] L. Garcia-Rodriguez, Seawater desalination driven by renewable energies: a review, Desalination, 143 (2) (2002) 103-113.
[4] E. Delyannis, Historic background of desalination and renewable energies, Solar Energy, 75 (5) (2003) Solar Desalination 357-366.
[5] I. Houcine, F. Benjemaa, M. Chahbani and M. Maalej, Renewable energy sources for water desalting in Tunisia, Desalination, 125 (1-3) (1999) European Conference on Desalination and the Environment, 123-132.
[6] D. G. Harrison, G. E. Ho and K. Mathew, Desalination using renewable energy in Australia, Renewable Energy, 8 (1-4) (1996) Special Issue World Renewable Energy Congress Renewable Energy, Energy Efficiency and the Environment, 509-513.

[7] M. Papapetrou, M. Wieghaus and C. Biercamp, Roadmap for the development of desalination powered by renewable sources, PRODES project co-financed by the Intelligent Energy European funding tool for Europe programme (contract number IEE /07/781/SI 2.499059) (2010) 1-79, Available at: http://www.prodes-project.org/fileadmin/Files/ProDes_Road_map_on_line_version.pdf