Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.933621

53 (2015) 3151–3160
March

Taylor & Francis
Taylor & Francis Group

Sustainable management of brine effluent from desalination plants: the SOL-BRINE system

D. Xevgenos[a,*], A. Vidalis[b], K. Moustakas[a], D. Malamis[a], M. Loizidou[a]

[a]*Unit of Environmental Science and Technology (UEST), School of Chemical Engineering, National Technical University of Athens, Zographou Campus, 9, Heroon Polytechniou Str., Athens 15773, Greece, Tel. +30 210 772 3108; Fax: +30 210 772 3285; email: xevgenos@central.ntua.gr (D. Xevgenos)*
[b]*Programming and Development Office, Municipality of Tinos Island, 72 Evaggelistrias St., Tinos Island 84200, Greece*

Received 18 October 2013; Accepted 17 March 2014

ABSTRACT

Desalination comprises a non-conventional water resource practice that is currently gaining importance internationally for filling the gap in the water balance. Even though it is a well proven technique, it is associated with certain economic considerations (high energy consumption) and environmental concerns regarding brine management: around 2 L of wastewater are generated for every liter of freshwater produced. The high concentration of salts in this wastewater can create serious disposal problems. The SOL-BRINE project sought to eliminate water pollution and environmental damage associated with brine release, by introducing a new technique capable of achieving zero liquid discharge from desalination plants. The demonstration plant that is presented in this paper was installed at Agios Fokas area, Tinos Island in Greece in October 2012 and has been operated regularly since January 2013. The plant has the capacity to treat over 200 tons of brine per year.

Keywords: Brine treatment; Desalination; Zero liquid discharge (ZLD); Solar energy; Mediterranean Sea; Tinos Island

1. Introduction

Desalination comprises a non-conventional water resource practice that is currently gaining importance internationally for filling the gap in the water balance [1]. Its capacity has more than doubled between 2001 and 2011. As of June 2011, 15,988 desalination plants have been installed and operated in 150 countries producing a combined 66.5 million cubic meters of fresh water per day [2].

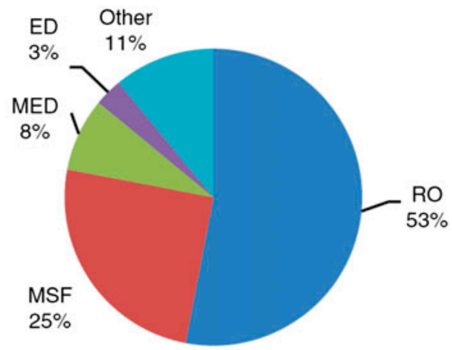
Saudi Arabia (10.6 million m^3/d), the United Arab Emirates (8.7 million m^3/d), the United States of America (8.3 million m^3/d), and Spain (5.4 million m^3/d) are the top desalination producers [3]. The desalination technologies that are being employed vary significantly in different regions across the globe. At a worldwide level, reverse osmosis (RO) is by far the predominant desalination technique used. However, this is not the case for Middle-East and particularly Saudi Arabia and the United Arab Emirates, which comprise today the two biggest desalination markets [3]. Thermal techniques, such as multi-stage flash distillation (MSF) and

*Corresponding author.

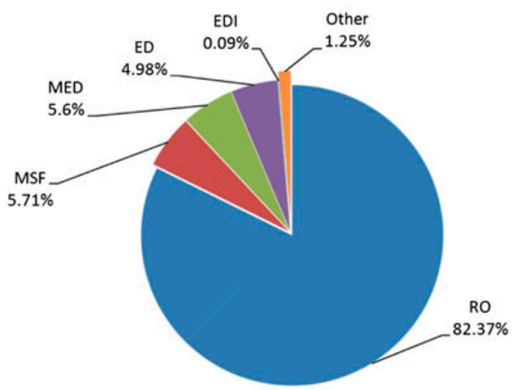
Presented at the International Conference WIN4Life 19–21 September 2013, Tinos Island, Greece

1944-3994/1944-3986

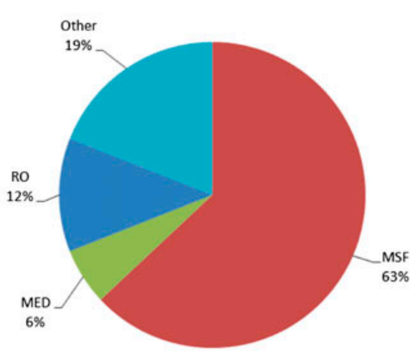
multiple effect distillation (MED), prevail there (see also Fig. 1), the main reason being the abundance of fossil fuels, the use of which is required for the operation of the thermal desalination plants.



World



Mediterranean Region:
16% share of total installed capacity



United Arab Emirates:
13% share of total installed capacity

Fig. 1. Installed capacity by process, on a worldwide basis (top figure), the Mediterranean Sea (middle figure), and the United Arab Emirates (bottom figure).
Notes: The data used for the graphics were taken from [2,4]. ED stands for Electrodialysis, EDI stands for Electrodialysi Inversal.

In contrast, within the Mediterranean region RO comprises approximately the 'sole desalination practice that is being currently applied with a share of more than 82% of the total installed capacity [4].

Mediterranean countries and more importantly the Southern and Eastern Mediterranean Countries are emerging into a dynamic desalination market [5]. Should all Mediterranean countries be seen as a whole, the total desalination capacity installed is estimated over 11.6 million m^3/d (see also Table 1).

1.1. *Water availability and role of desalination within the Mediterranean region*

The climate conditions and the water stress in the Mediterranean Sea (see also Fig. 2) have led to the use of alternative water resources, such as water reclamation and desalination, so as to ensure a water-secure policy [6]. The availability of conventional water resources (fresh surface water and groundwater resources) in the Mediterranean is currently under significant pressure mainly due to the following reasons: (1) declining precipitation levels; (2) reduction in river run-off: 20% change between 1960 and 2000 [7]; (3) groundwater overexploitation, and (4) increasing water demand from different water users especially tourism. With reference to the latter, the Mediterranean region, if considered as a single area, is by far the world's top tourism destination, attracting almost

Table 1
Water desalting production capacity in selected Mediterranean countries (2011 data)

No.	Country	Production (m^3/d)
1	Spain	4,769,582
2	Algeria	1,700,046
3	Israel	1,169,474
4	Libya	809,875
5	Italy	698,891
6	Egypt	683,277
7	Turkey	468,749
8	Malta	251,151
9	Jordan	248,855
10	France	233,104
11	Cyprus	228,853
12	Greece	149,250
13	Tunisia	93,276
14	Morocco	85,471
15	Lebanon	29,125
16	Portugal	17,087
17	Syria	13,981
Total		11,650,047

Note: The data used were obtained from [4].

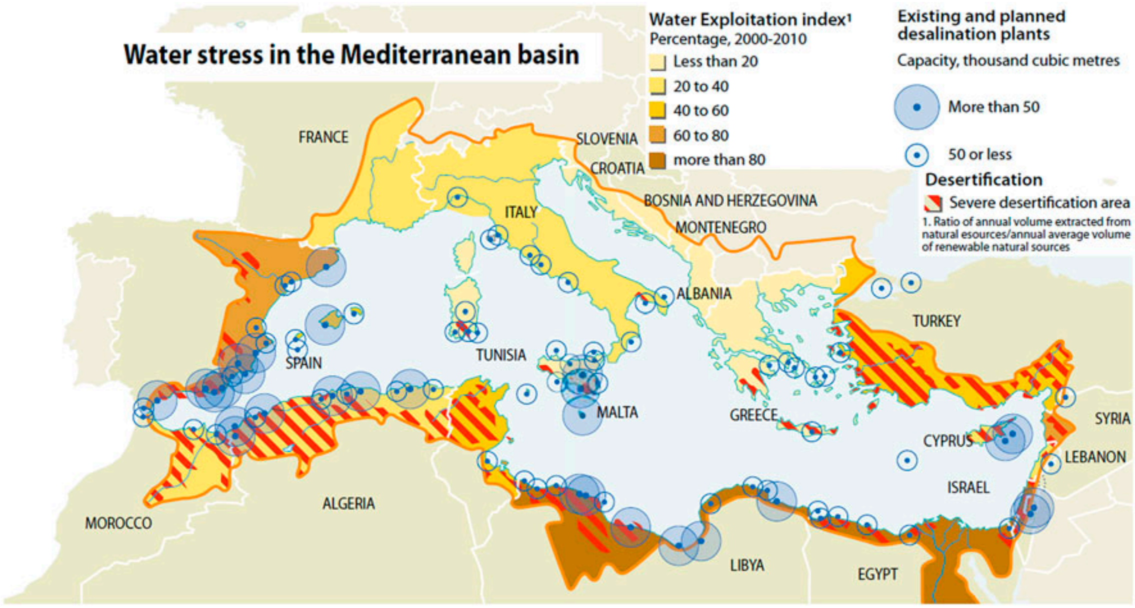


Fig. 2. Water stress in the Mediterranean basin.
Source: [7].

306 million out of 980 million tourists worldwide [7]. Around the Mediterranean Sea seasonal water demands from the tourism industry increase the annual water demand by 5–20% according to estimations, while the number of tourists is expected to reach 500 million tourists by 2030 from 306 million in 2008 [7].

The International Panel on Climate Change observes that many arid and semi-arid areas, such as the Mediterranean Sea, are particularly exposed to the impacts of climate change and are projected to suffer a decrease of water resources, meaning that global climate change may exacerbate the problem of local water availability in the Mediterranean. This implies that a potential future water availability challenge is ahead. In recognition of this fact, more and more Mediterranean countries are turning to desalination for safe water supply.

The total installed desalination capacity in the Mediterranean is 11,650,047 m^3/d, which represents around 16% of the world total installed capacity. Countries, such as Spain, Algeria, Israel, and Libya, comprise top desalination producers in the region, while countries, such as Malta and Cyprus, have traditionally relied on the desalination practice for meeting their water needs. In terms of capacity, RO is the predominant desalination technology in the Mediterranean Region, with a share of 82.37%, followed by MSF methods (5.71%), MED (5.60%) and electrodialysis (4.98%) [4].

1.2. Greece and Aegean Islands

Greece has today a total installed desalination capacity of 149,250 m^3/d, being produced by 192 desalination plants. RO is the predominant method with a total share of 74.41%, followed by ED (10.20%), MED (8.47%), and MSF (6.75%) [4].

The water shortage problem is very acute in Aegean islands, and as islands comprise isolated areas, there are few options available for water management [7]. These typically include: (1) water conservation; (2) further development of water resources (dam construction, wells, etc.); (3) water importation from the mainland; (4) water desalination; and (e) water reclamation and reuse [8,9].

The only islands that are water sufficient within the Cyclades complex are perhaps only the largest ones, namely Naxos and Andros. Tinos and the majority of the rest Cyclades islands are water deficient and there have been times in the past, when water transportation from the mainland was necessary in order to satisfy the freshwater demand.

2. The case of Tinos Island

Cyclades is a complex of 19 islands in the South Aegean Sea in Greece. Tinos is a small island with an area of 195 km^2 (see also Fig. 3) in the middle of the complex and one of the most popular tourist destinations in Greece. According to the last census (2011),

Fig. 3. Tinos Island, Cyclades complex, Greece.

the population of Tinos Island is 8,636, while tourists' arrivals during the summer months can increase the population as much as four times.

According to the Greek Secretariat General for the Aegean and Island Policy, certain islands from the Cyclades and Dodecanese complexes in the Aegean Archipelago (see also Fig. 4) are water deficient and cannot provide for all their water needs, especially in summer time. For this reason, water supply in islands of the Cyclades complex is performed through ship transportation from the Attica Region (port of Lavrion), while in islands of the Dodecanese complex water is supplied from the neighboring island of Rhodes [8,9,11].

2.1. Water demand

The total potable water demand for the year of 2012 is estimated at 1,749,000 m^3, while the water used for agricultural purposes is estimated to be almost threefold greater. There is very little industrial activity in Tinos and is limited mainly to small industrial units for local products and handicrafts manufacturing. The daily water requirements in Tinos Island amount to 6,000 and 4,200 m^3 in summer and winter period, respectively. More than half of this volume is consumed in the capital of Tinos Island (Chora).

2.2. Water availability

Water management relies on the following water sources: (1) groundwater abstraction (boreholes); (2) surface waters (few rivers), and (3) desalination plants. Tinos Island has limited water resources and there have been times that water demand surpassed water availability. In 2001 and 2007 there was a need for imported water. The latter implies the transportation of water from surrounding islands with all economic (water cost: ~€12/m^3), environmental (GHG emissions from ship transportation), and other impacts associated (low water quality).

However, in 2002 a compact-type desalination unit was installed and started operation, covering most of the needs of the island since then.

The water supply mix is significantly diversified across the Island, with the capital of Tinos Island being very dependent on desalinated water, while the water supply from the surrounding villages being obtained solely from groundwater and surface resources.

The main sources of water that balance the freshwater requirements of Chora are as follows:

- Four groundwater boreholes with a total capacity of 900 m^3/d;
- Three surface water sources from the Tsaknia mountain: 360 m^3/d;
- Two desalination units with a total capacity of 1,500 m^3/d; and
- Vaketta dam: 700 m^3/d.

The main sources that balance the freshwater requirements of the surrounding 48 settlements are underground (40 boreholes) and surface waters.

3. The SOL-BRINE system

3.1. Literature review

Until today, there is no commercially available technology that has been developed and tested to achieve zero liquid discharge (ZLD) in the desalination sector. The cost is the most significant prohibitive factor. However, the growing development of the desalination sector, both in terms of capacity and importance for safe water supply, as well as the increasing awareness of the environmental pressures on the marine environment, has brought the issue back to focus. Some attempts have been made, but these include mostly pilot applications. These include indicatively the following:

- *AQUASOL*: A pilot system was developed in the context of the EU project AQUA-SOL (2002–2006): "Enhanced Zero Discharge Seawater Desalination using Hybrid Solar Technology", based on the multi-effect distillation (MED) process. The MED plant was connected to a 500 m^2 stationary CPC (compound parabolic concentrator) solar collector field which supplied heat at medium temperature (60–90˚C) and a prototype of double-effect absorption heat pump was developed. The brine produced was further treated with the use of a specially designed solar dryer.

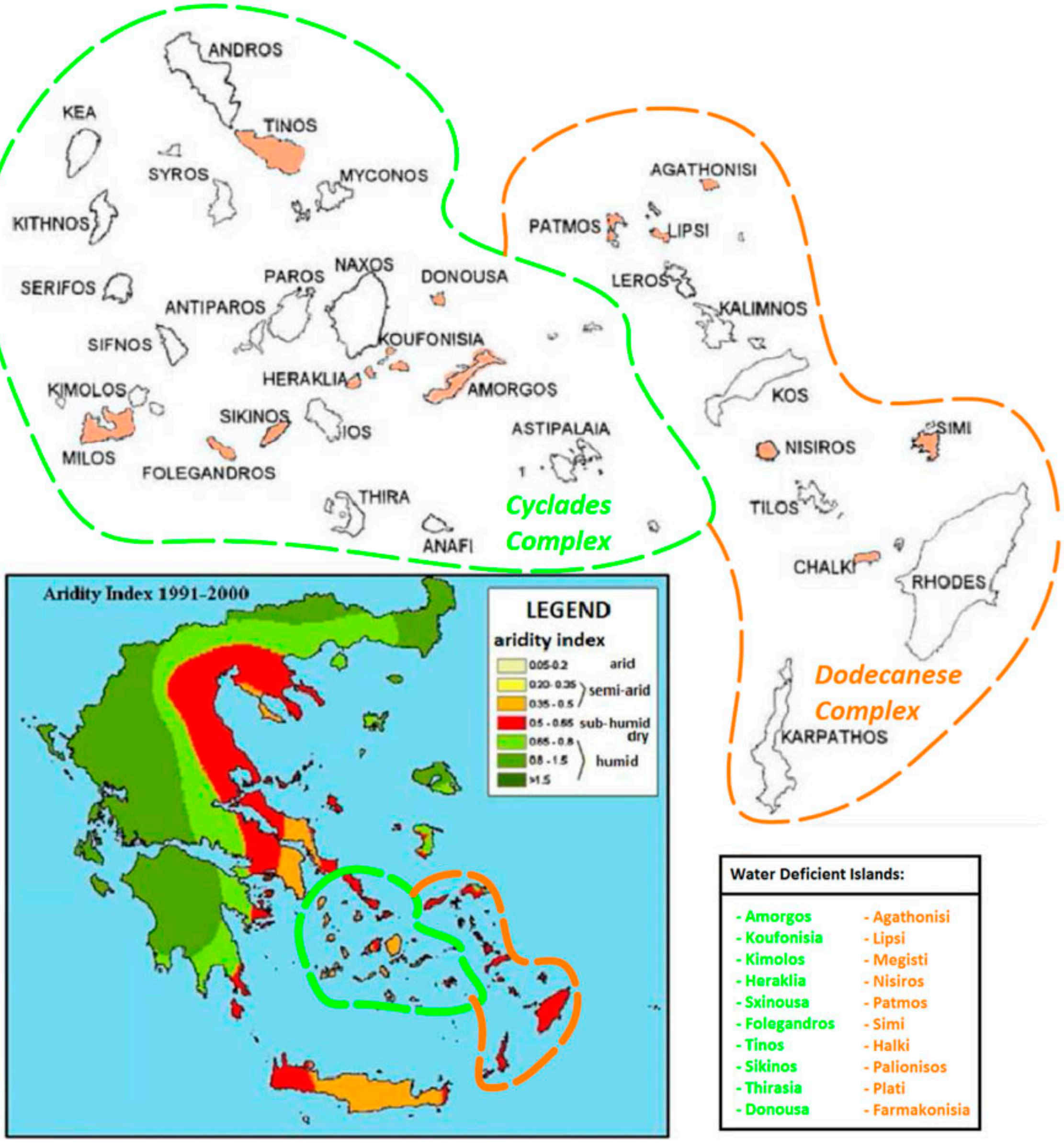


Fig. 4. Aridity Index and water deficient islands in the Aegean Archipelago, Greece.
Source: Adapted from [10,11].

More information are provided at the project website: http://www.psa.es/webeng/aquasol/

- *SAL-PROC™*: A proprietary ZLD process developed by geo-processors that allows the recovery of dissolved salts as commercial byproducts. The technology has been applied mostly in pilot scale for the treatment of other types of wastewater (power plant and mine industry).
- High efficiency reverse osmosis: It has been applied in six industrial applications (power stations and mining industries) by the US supplier Aqua Tech, but not to the desalination industry. It comprises three treatment steps: (1) hardness and suspended solids removal, (2) CO_2 removal, and (3) RO pretreatment at high pH values. High recoveries have been achieved—up to 95%—but still some quantity must be disposed to landfills.
- *ZELDA*: This is an ongoing LIFE+ project which aims to develop a system for ZLD from desalination plants. The process involves electrodialysis for brine concentration and metathesis for resource recovery.

Following the SOL-BRINE project the developed pilot system is described.

3.2. The SOL-BRINE 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, contributing to high water recovery (>90%) and to the production of a dry salt product 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 (life cycle assessment and economic evaluation), and suggestions for the full scale application.

The innovative features of the system include:

- *Total brine elimination*. The system has been designed in line with the ZLD 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.

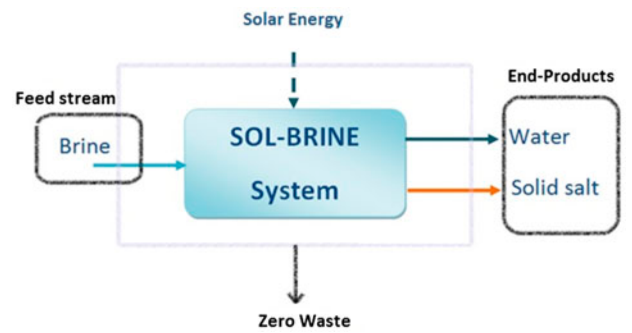


Fig. 5. The SOL-BRINE concept.

The SOL-BRINE concept is summarized in Fig. 5.

3.3. Process description

In order to achieve ZLD, all the amount of water must be gradually removed from the brine effluent

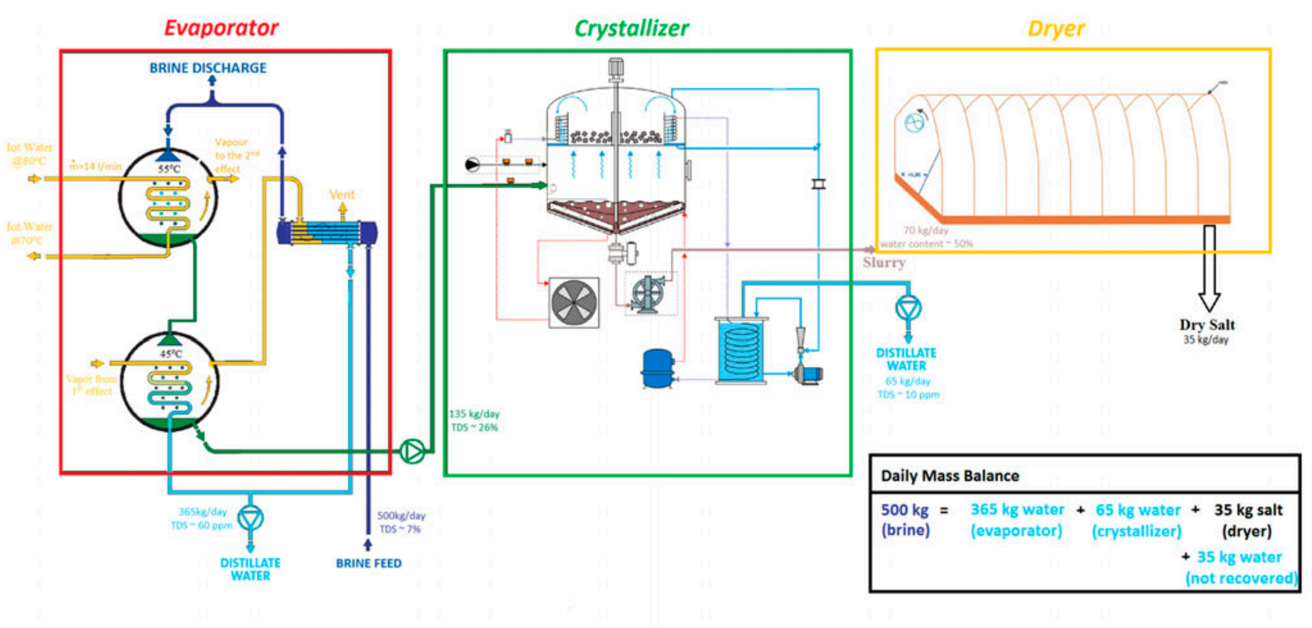


Fig. 6. Process flow diagram of the SOL-BRINE system.
Note: The figures represent the daily mass balance of the system.

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.

3.3.1. Intake

A small portion of the brine rejected from Tinos seawater desalination plant (~500 kg/d) 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 35 kg of salt are produced by the pilot unit per day of operation. The daily mass balance is given in Fig. 6.

3.3.2. Evaporator unit

The evaporator unit is consisted of two consecutive effects operated at decreasing levels of pressure:

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

In each of the evaporator effects, the brine is evaporated and two subsequent streams are produced: (1) a water vapor stream, which is subsequently condensed and recovered as fresh water, and (2) 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.

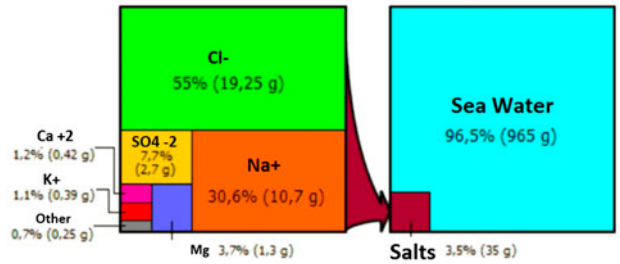


Fig. 7. Typical chemical composition of seawater.
Note: Numbers in brackets represent the mass of each constituent for 1 kg of seawater.

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%).

Fig. 8. Photo from the installed SOL-BRINE system: evaporator, crystallizer, and photovoltaic generator units.
Note: The photo was taken during the second site visit to the SOL-BRINE system.

3.3.3. 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: $5\,\text{kPa} \cong 0.05\,\text{atm(a)}$). 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 and Technologies according to the

Fig. 9. Photos from the installed SOL-BRINE system.

specific characteristics and needs of the brine treatment process involved.

3.3.4. 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.

3.3.5. 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 evacuated tube collectors through hot water at 80˚C. No auxiliary heaters are used.

The electrical requirements (~3 kW) are supplied through the use of an autonomous photovoltaic generator (equipped with batteries for one day autonomy). The main electric load of the system is the heat pump of the crystallizer unit (single phase load, ~2.3 kW).

4. Results and discussion

The demonstration plant at Agios Fokas area has been operating regularly since January 2013. The plant has the capacity to treat 200 tons of brine per year. The results showed that useful end-products can be generated from the evaporation of brine release from the desalination plant.

4.1. End-products

The brine effluent carries approximately the same mass quantity of dissolved salts, as the seawater feed to the desalination unit. A typical chemical composition of the seawater is given in Fig. 7.

The SOL-BRINE system receives around 500 L of brine effluent per day. This effluent carries the following salts (in a dissolved form): $CaSO_4$, $CaCO_3$, NaCl, $MgSO_4$ etc. When the brine effluent is treated through evaporation, these salts begin to crystallize, each at different concentration ratio, according to its solubility characteristics. As a result, the aforementioned salts are recovered through the innovative SOL-BRINE process (Figs. 8 and 9).

4.2. Economic data

The cost for the pilot system has been estimated at €100,000. This figure can change drastically at full-scale development due to economies of scale.

The commercial value of each of the recovered salts varies, according to local market needs and qualities. In general, it can be said that most of these products comprise saleable products and can contribute significantly to capital recovery of the SOL-BRINE system or even offset completely the treatment cost.

5. Conclusions

Recovery of salt, through ZLD desalination, is increasingly seen as the most environmentally friendly option to handle brine.

It has been demonstrated that the SOL-BRINE system can achieve high quality freshwater (TDS < 100 ppm) with a water recovery of more than 90% and saleable dry salts. The achievement of ZLD, though this novel technology, has made a concept of a closed loop water treatment, since disposal is eliminated.

The system is now optimized for achieving better product quality and energy performance.

Acknowledgment

This work has been carried out within the European project SOL-BRINE (LIFE09 ENV/GR/000299). Financial support by the European Commission under the European financial instrument for the environment, LIFE+ is gratefully acknowledged.

References

[1] P. Campling, L. Nocker, W. Schiettecatte, A.I. Iacovides, T. Dworak, E. Kampa, M. Álvarez Arenas, C. Cuevas Pozo, O. Mat, V. Mattheiß, F. Kervarec, Assessment of Alternative Water Supply Options, 2008. Available from: http://ec.europa.eu/environment/water/quantity/pdf/Summary%20Report_extended%20version.pdf (accessed 21 September 2013).

[2] K.S. Tree, Water Industry Report Desalination, February 2013. Available from: http://www.sdwtc.org/Resources/WEMI/Segment%20Report/130226.Desalination.pdf (accessed 8 October 2013).

[3] T. Mezher, H. Fath, Z. Abbas, A. Khaled, Techno-economic assessment and environmental impacts of desalination technologies, Desalination 266(1–3) (2011) 263–273.

[4] J. Canovas Cuenca, Report on Water Desalination Status in the Mediterranean Countries, September 2012. Available from: http://www.imida.es/docs/publicaciones/06_REPORT_ON_WATER%20DESALINATION.pdf (accessed 10 September 2013).

[5] H. Boyé, Water, Energy, Desalination & Climate Change in the Mediterranean, August 2008. Available from: http://planbleu.org/sites/default/files/publications/regional_study_desalination_en.pdf (accessed 21 September 2013).

[6] E. Tzen, M. Papapetrou, Promotion of renewable energy sources for water production through desalination, Desalin. Water Treat. 39 (2012) 302–307.
[7] United Nations Environment Programme/Mediterranean Action Plan (UNEP/MAP), State of the Mediterranean Marine and Coastal Environment, 2012. Available from: 195.97.36.231/publications/SoMMCER_ENG.pdf (accessed 9 September 2013).
[8] P. Gikas, G. Tchobanoglous, Sustainable use of water in the Aegean Islands, J. Environ. Manage. 90 (2009) 2601–2611.
[9] J.K. Kaldellis, E.M. Kondili, The water shortage problem in the Aegean archipelago islands: Cost-effective desalination prospects, Desalination 216 (2007) 123–138.
[10] P.T. Nastos, N. Politi, J. Kapsomenakis, Spatial and temporal variability of the Aridity Index in Greece, Atmos. Res. 119 (2013) 140–152.
[11] P. Gikas, A.N. Angelakis, Water resources management in Crete and in the Aegean Islands, with emphasis on the utilization of non-conventional water sources, Desalination 248 (2009) 1049–1064.