Desalination 336 (2014) 32–49

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Comparative study of brine management technologies for desalination plants

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HIGHLIGHTS

- Brine management systems for desalination plants
- Technologies for reducing the volume of the generated brines
- Technologies for salts recovery form brines
- Brine conditioning for other processes

ARTICLE INFO

Article history:
Received 11 October 2013
Received in revised form 30 December 2013
Accepted 31 December 2013
Available online xxxx

Keywords:
Seawater desalination
Reverse osmosis
Brine treatment
Water recovery
Salt recovery

ABSTRACT

In recent years, reverse osmosis (RO) has grown as an alternative to traditional potable water sources. A major disadvantage of the RO process is the huge amount of brine and its negative impact as a result of its high salinity. This brine is usually discharged to inland water bodies or to the sea and constitutes a threat to ecosystems and species, such as *Posidonia oceanica* in the Mediterranean Sea; thus, further research is needed for introducing environmentally friendly and economically viable management options for RO brines.

This paper gives an overview of recent research as well as different technologies available at several scales to overcome the environmental problems and evaluate profitability related to discharge of RO concentrates. The treatment options have been classified into four different groups according to their final purpose: 1) technologies for reducing and eliminating brine disposal, 2) technologies for commercial salt recovery, 3) brine adaptation for industrial uses and 4) metal recovery. Solar evaporation, two-stage reverse osmosis, electrodialysis, integrated processes and brine adaptation for the chlor-alkali industry are some of the topics that this paper deals with. In the conclusion section, all of the technologies are compared emphasizing all their advantages and drawbacks, feasibility and development stage in order to provide a decision tool to select the best technology for each situation.

1. Introduction

Potable water production has become a worldwide concern; for many communities, projected population growth and associated demand exceed conventional available water resources. Over 1 billion people have no access to clean drinking water and approximately 2.3 billion people (41% of the world population) live in regions with water shortages [1]. The shortage of water supplies for drinking and irrigation purposes is already a very serious problem for the North African countries, the Middle East and several countries in Southeast Asia and Latin America. If nothing is done, acute water shortages will also occur in many countries of the European Union and the northern Mediterranean by 2020, such as Greece, Italy (southern regions and islands), Portugal (Alentejo and Algarve regions and islands such as Porto Santo, Corvo, etc.) and Spain (southern and eastern regions). For the entire Mediterranean region, conservative estimates indicate a water shortage of about 10 million m^3/day by the year 2020 [2].

Desalination has become an important source of drinking water production, with thermal desalination processes developing over the past 60 years and membrane processes developing over the past 40 years [3]. Today, reverse osmosis (RO) is the leading technology for new desalination installations, with a 44% share in world desalting production capacity and an 80% share in the over 15,000 desalination plants installed worldwide [3]. The Middle East has forged ahead as the leader in large-scale seawater desalination. With only 2.9% of the world's population, it holds approximately 50% of the world's production capacity. In 2005, Israel opened the world's largest seawater RO desalination plant, with a production capacity of 330,000 m^3/day, or 100 million m^3/year [4]. The use of

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http://dx.doi.org/10.1016/j.desal.2013.12.038

membrane desalination has increased as materials have improved and costs have been reduced [3]. But the main reason why RO desalination has succeeded is because it requires less energy than thermal desalination [1]. Furthermore, improvements in membranes and energy recovery have significantly lowered the cost of RO desalination.

As a result of increased interest in RO desalination, the concern about potential environmental problems has grown. RO desalination plants extract large volumes of water and discharge a dense brine concentrate back into the environment [5]. It is widely suggested that desalination plant brines have a strong potential to detrimentally impact both physicochemical and ecological attributes of receiving environments [6]. There has been worry in Mediterranean countries about *Posidonia oceanica* for the last few years. *P. oceanica* is the most abundant sea grass species in the Mediterranean, where it covers about 40,000 km^2 of the sea floor [7] and forms large meadows from the surface to 40 m depths. In addition, it is considered a very important ecosystem and is recognized by the European Habitats Directive [8] as a habitat of priority interest. Nevertheless, meadows of *P. oceanica* have undergone regression in several coastal areas [9] and under field conditions, *P. oceanica* is very sensitive to brine discharges from desalination plants [10]. Many solutions have been developed to protect this plant, mainly based on diluting brine before disposal.

Brine disposal costs are high today, between 5 and 33% of total desalination cost [11], complicating implementation. This cost depends on the quality of the concentrate, treatment level before disposal, disposal method and the volume or quantity of concentrate [12]. Disposal costs for inland desalination plants are even higher than those for plants discharging brine into the sea [12]. Some of the options for brine disposal from inland desalination plants are deep well injection, evaporation ponds, discharge into surface water bodies, disposal to municipal sewers, concentration into solid salts and irrigation of plants tolerant to high salinity [12,13].

Due to the environmental problems that brine disposal can cause and high disposal cost, many technologies have been developed for recovery. Examples are renewable energy generation [14] and use in evaporation ponds to produce salt or chemicals for industry. Nevertheless, more investigation is needed to reduce brine quantity and to allow recovery and reuse of brine. In this review, current and emerging technologies are analyzed according to their origin, the maturity of the technologies and their final goal.

2. Technologies for reducing and eliminating brine disposal

2.1. Solar evaporation

Solar evaporation consists of leaving brine in shallow evaporation ponds, where water evaporates naturally thanks to the sun's energy. Salt is left in the evaporation ponds or is taken out for disposal [15]. Evaporation ponds are relatively easy to construct, while requiring low maintenance and little operator attention compared to mechanical systems. In addition, no mechanical equipment is required, except for the pump that conveys the wastewater to the pond, which keeps low operating costs [16]. Nevertheless, evaporation ponds for disposal of concentrate from desalination plants need to be constructed as per the design and maintained and operated properly so as not to create any environmental problem, especially with regard to groundwater pollution [16]. Liners are the most important feature of an evaporation pond and one of the major components in the construction cost. They should be impermeable to avoid brine leakages and mechanically strong to withstand stress during salt cleaning [16]. Common materials for pond liners are: polyvinyl chloride, high-density polyethylene, butyl rubber and Hypalon [17]. However, many agricultural evaporation ponds have clay liners. The use of clay liners with low permeability will substantially reduce the cost of construction, although a small number of leakages are to be expected.

Solar evaporation is a suitable technology to be used in arid regions where land is available [18]. Land is crucial because shallow ponds (ranging from 25 to 45 cm) are optimal for maximizing the rate of evaporation [16]. However, due to the quantity of terrain needed to treat large volumes, evaporation ponds have limited use, especially in wet areas, where land purchase can dramatically raise capital costs. For instance, only 6% of the installations in the US used this method of concentrate disposal up to 1993 and only 2% after 1993, always for small plants [19]. Further research is appropriate to develop new materials (such as waste products from cement factories) for lining evaporation ponds. In addition, the permeability of the clay materials should be determined under different levels of compaction and over extended periods of time under a highly saline water environment. More research in recovering salt as pure as possible is also recommended.

Wind aided intensified evaporation technology (WAIV) was patented as an alternative to evaporation ponds. This method uses wind energy to evaporate wetted surfaces, previously sprayed with brine, that are packed in high density per footprint. By deploying such surfaces in arrays with large lateral dimensions, significant height and minimal depth (e.g. 3–4 m), the wind can be exploited while it is still less than saturated with vapor and the driving force is maintained [18]. Gilron et al. [18] carried out experiments in a pilot plant and demonstrated that the evaporation ratio ($L/m^2 \cdot day$) can be improved between 50% and 90% compared to evaporations ponds. Katzir et al. [15] estimated that using WAIV technology increases the evaporation rate 10-fold over natural evaporation, which allows evaporation ponds to be 10 times smaller. They also studied WAIV technology possibilities for recovery of salts and their use as raw materials. For this purpose, RO and electrodialysis concentrates from brackish groundwater were used as feedwater. Lesico CleanTech is already exploiting WAIV technology at four different sites in Mexico, Australia and Israel [20]. In Israel, a WAIV unit with 500 m^2 of wetted surface was able to evaporate hypersaline brines at a rate of 0.55–1.7 m^3/h in a preliminary study run for over 6 months. This worked out to a 300–1000 $m^3/(day \cdot hectare)$ WAIV footprint.

WAIV technology reduces soil requirements compared to traditional evaporation ponds. Furthermore, energy needs are relatively low since the main driving force is wind dryness, which allows WAIV technology to have low operating costs and makes this technology especially suitable for areas where energy costs and air dryness are high. Although WAIV technology has advantages compared to evaporation ponds, it can also pollute groundwater, and experiments at industrial scale are necessary, especially due to the expected drop-off in efficiency relative to open-pan evaporation as one goes from isolated vertical evaporation surfaces to those in a closely packed array of surfaces [21]. Further research is needed to develop new materials that have a balance between being hydrophilic enough to allow spreading but not so hydrophilic as to reduce the effective vapor pressure. Packing should also be optimized so that it is sufficient for good enhancement of evaporation capacity per footprint without unnecessary blocking of the wind [22]. Finding new possibilities of salt recovery is also necessary.

2.2. Phytodesalination

The application of brine for crop production is limited due to low salt tolerance of most plants. However, approximately 1% of angiosperm species have evolved high salt tolerance, such that some are capable of growth and reproduction with salinities exceeding seawater [23]. These plants, usually called halophytes, allow crop production based on pure RO brine or mixtures with fresh water. Potential products that may be derived from these halophytes include oilseeds, forages, and biofuels [23]. Nevertheless, when soils are irrigated with brine, excessive sodium can limit water infiltration, drainage and evaporation, making it more difficult for plants to absorb soil moisture.

Jordan et al. [23] irrigated the halophyte forage shrub *Atriplex lentiformis* with brine from a brackish water RO plant in an agricultural