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Reuse and minimization of desalination brines: a review of alternatives

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ABSTRACT

Desalination is currently one of the available solutions to the problem of the lack of water present in most countries due to the global increase in water demand. One of the desalination plants main problem is the large amount of reject brine produced, which can very often severely damage the receiving environment. Nowadays, the management of this residue is based mainly in the dilution prior to the discharge. However, there are many emerging alternative technologies that can be combined to achieve a minimization and valorization of brine and thus an appropriate management. This article introduces and describes briefly the set of available techniques. Each alternative has been assessed in terms of technology, economic and environmental merits, resulting in a numeric table.

Keywords: Discharge; Valorization; Zero-discharge; Brine; Reverse osmosis; Reduction

1. Introduction

Desalination is the process of separating the salts dissolved in brackish or seawater to make them suitable for human consumption, irrigation or industrial use. This process entails the generation of a saline by-product: brine. It presents a lower volume than that of the fed water but a much higher salt content.

Seawater desalination plants produce a considerable amount of brine that is usually disposed of in the sea. This can result in ecological effects in receiving waters. These arise from an inadequate brine dispersion, which causes sudden changes in the environmental conditions, affecting marine flora and fauna. An example of this may be found in the Mediterranean Sea, where there are large extensions of sea grass which are highly sensitive to salinity variations. Some of these are protected as, for instance, *Posidonia oceanica* or *Cymodocea nodosa* (European Council Directive 92/43/EEC) [1,2].

In the case of brackish water desalination plants, often located inland, well away from the coastline, the problem is more complex as the distance to the sea hinders its disposal at the coast. This makes its management more difficult or expensive and it becomes necessary to search for other alternatives. In this case, the problem is sometimes reduced by the fact that the volume of brine produced is usually smaller.

The study on alternatives to the direct disposal at sea of reject desalination is of great importance from an economic point of view since not only a minimization of the disposal is achieved, but also an appraisal where, in some cases, by-products of economic interest may be obtained.

The aim of this revision of the state-of-the-art is to identify and analyze the current status of the several

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alternatives to the direct discharge of brine by means of its management or reuse. This shall be done considering the different brine reuse or minimization options. At the same time, an assessment of the relevance provided by every proposed technique from the technological, economic and environmental point of view shall be carried out.

2. Methodology

To fulfill this objective, databases and other sources have been revised and the most relevant documentation has been identified. Databases searched included ISI Web of Science, Springer, Current Contents, and ACS, as well as grey literature. Three basic indicators were set to carry out the assessment of t he alternatives: indicators are related to the technological, economic and environmental characteristics. Within these indicators were considered various aspects. For instance, the technological factors considered were: current state of the technology, application range, efficiency and number of literature references. The economic indicators consisted of the availability in the market and the cost. Lastly, the environmental characteristics included in the study covered the environmental impact of the alternatives, including risks of pollution, space requirements, volume of brine that can be treated, etc.

Those alternatives considered of interest and included in this paper were classified in three different groups, depending on whether the brine is simply discharged into a receiving body or it is valorized-minimized: disposal, direct use and indirect use.

The set comprising all existing alternatives and the results obtained from the evaluation carried out, is summarized and described in the following section.

3. Analysis of the present state

After the bibliographical revision, the set of alternatives obtained was organized in three different blocks: disposal, direct use, and indirect use. This classification makes a distinction between those options that consider brine as waste (discharge), or those that assess or minimize it, giving it either a direct or indirect use.

By ‘disposal’ we refer to the brine discharge in specific places and under certain conditions without making any assessments. Within this alternative we can find the techniques of deep-well injection and previous dilution (with wastewater or seawater).

‘Direct use’ will be referred to the brine valorization with or without slight adjustments. This can include the elimination or addition of some components. In this category we can find the following alternatives:

- Hydrotherapy uses
- Heat carrier fluid: in solar ponds or as a cooling fluid
- Wetlands regeneration
- Aquaculture
- Growth of halophilic species
- Capacitive deionization
- Membrane distillation
- Electrodialysis
- Nanofiltration
- Osmotic power

Finally, we refer to indirect use when we talk about those alternatives which purpose is that of obtaining or extracting some or all brine components:

- Evaporation ponds: by natural or induced means
- Zero-discharge
- Selective precipitation
- Electrolysis
- Freezing-melting process
- Rapid-spray evaporation

Fig. 1 shows an outline of all the alternatives studied. The first level of classification is the distinction between brine disposal (considering it as waste), or its assessment or minimization, giving it either a direct or indirect use.

Next, we will describe briefly each of the alternatives mentioned earlier together with their objectives, the results and discussion obtained from this study.

4. Results and discussion: disposal alternatives

4.1. Deep-well injection

This method consists in the transport and confinement of brine in subsoil formations having the natural capacity for containing and isolating it. Although at the beginning it was used in oil extractions, this technology is currently applied both for industrial and urban waste and for reject from desalination plants when the volume of treated water is low.

This technology has been mostly developed in the US, though, in Spain, there are examples of its use in the reverse osmosis desalination plants in Benferri (Alicante) and Campo de Cartagena (Murcia) [3].

Deep-well injections require a waterproof formation that keeps brine confined. Moreover, the general process of injection must not jeopardize other important resources. It is a well known technology and the control of the operations is highly sophisticated; however, its cost is significantly high. Thus, in the design of the casing and cementation of an injection survey it is necessary to consider several aspects: the materials used, especially in the case of brine due to corrosion problems, the quality

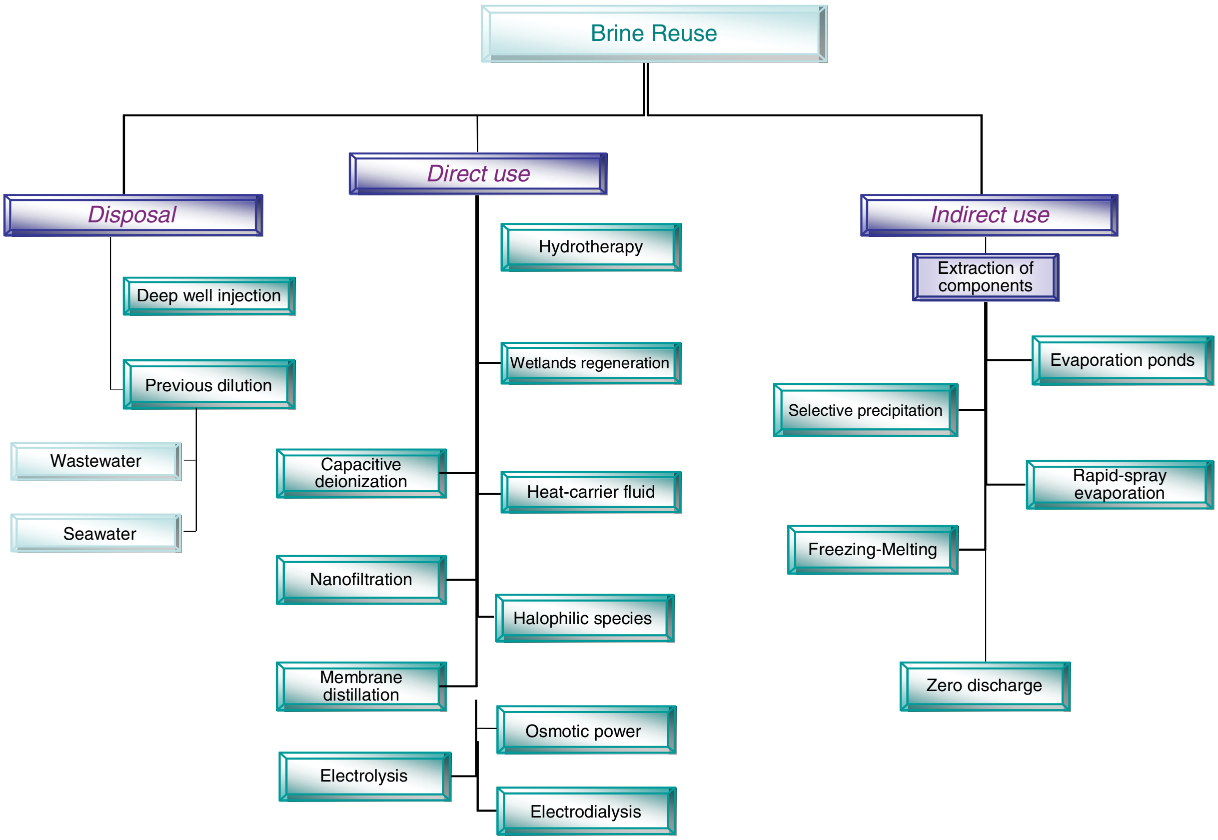

Fig. 1. Alternatives for brine reuse [25].

of the subsoil, the characteristics of the injected brine, the life expectancy of the formation, the probability of migration, regular checks, etc. Sometimes it is necessary to drill a research well in order to obtain the necessary information on the subsoil. Its environmental effect is considerable since it does not eliminate the residue [4,5].

Therefore, we do not consider the deep-well injection as an appropriate alternative for brine from desalination processes, except for brackish water desalination plants with very small disposal volumes in those situations where the disposal of brine is not achievable by other means.

4.2. Previous dilution

The second alternative to direct disposal is the evacuation of desalination brine by means of previous dilution with any other source as, for instance, wastewater, seawater or cooling water from central power stations. In all cases, the objective is to reduce brine salinity, approaching its amount to that found in the sea, and so minimizing the impact of the disposal at the coast [6,7]. This is especially important when the area has populations of sea grass which is highly sensitive to salinity changes as, for instance, the fields of *Posidonia oceanica* or *Cymodocea nodosa*.

In the first case, the dilution with wastewater achieves not only a reduction in the salinity of the discharge, but also acts as a sanitizer agent in the WWTP effluent, thus improving the quality of both effluents. Another synergy effect occurs in the dilution with cooling wastewater because this combination reduces the disposal salinity as well as its temperature.

The previous dilution of brine is a cost-effective and interesting option. Not only it decreases the salinity of the disposal, but it enables the discharge through a simpler and cheaper outfall.

We can find several examples of these alternatives in Spain, like the combination reverse osmosis treatment plant-WWTP in Adeje and Arona in Tenerife, the mixture of brine with seawater conducted in the desalination plant of Andratx (Mallorca), or Javea or the desalination plant in Sagunto (Valencia) [1–3,8,9].

A limitation for the use of this alternative that must be mentioned is the necessity to have a wastewater treatment plant or a power plant near the desalination facilities. This also has the advantage of diluting contaminants released along with the brine.

5. Direct use alternatives

5.1. Hydrotherapy

Taking into account the therapeutic and healing properties seawater has, it isn't difficult to imagine that brine, which is just a concentrate of seawater, can enhance those properties. In fact, the use of brine can be extended to several activities in Spa centers, particularly in swimming pools with different salt concentrations: salty pools (usually containing a similar salinity to that of seawater), flotation pools (super-salty pools, with 183.3 g/l), or *brine pools*, a new concept that would involve the use of brine in its original state to fill these pools, with intermediate characteristics to those mentioned above [10].

In spite of the fact that the use of brine in these centers does not eliminate the problem of the disposal, it does present a series of indirect environmental advantages, namely the reduction of fresh water consumption. Moreover, from an economic point of view it also reduces both the consumption of fresh water and salt for the preparation of the pools.

On the other hand, this option is valid for the minimization of reduced amounts of brine. For this reason it is suggested for use in combination with any other proposed minimization alternatives.

However, in most places brine would have to be specifically authorized to be allocated for this use, as every source of water used in pools, other than potable water from the mains distribution network, needs a governmental permit.

The use of brine from SWRO desalination plants in hydrotherapy has not been yet introduced. It is mentioned only as a suggestion for further research with utmost caution, particularly from the health point of view.

Currently these pools contain potable water and salt. Table 1 shows the composition of the main ions present in three different water sources proposed for their possible authorization in hydrotherapy pools.

5.2. Wetlands regeneration

Some wetlands and brackish ecosystems suffer a progressive degradation due to drought and to agricultural, stockbreeding and industrial development. Thus, desalination brine could be considered an option to regenerate these wetlands and brackish ecosystems [11]. There are two possibilities: the regeneration of coastal wetlands through brine from seawater desalination or the regeneration of inland wetlands with brine from brackish water desalination processes [12].

Although it can be applied only in certain occasions, its environmental benefits are obvious. Its economic implications depend intrinsically on the desalination plant characteristics together with the wetland we wish to regenerate: the combination of both projects in one would enable both the quality improvement and availability of water resources and, at the same time, the reject would be eliminated, this way making possible the regeneration of natural areas.

Table 2 shows the water composition of different wetlands in Spain compared to that of SWRO brine.

5.3. Heat carrier fluid

Brine can act as a fluid with special characteristics for heat storage and transfer. This is due to its special physical and chemical characteristics, especially its high salinity. Therefore, there are two ways to benefit from brine: using it in solar ponds or as a cooling fluid.

Table 1
Composition of possible water sources for their use in hydrotherapy Source: Canaragua

Composition of proposed source waters for flotation pools (mg/l)				
Parameters	Unit	Potable water+salt	Seawater+salt	Brine+salt
Chlorine	mg/l CL-	107920	104370	104527.7
Sulfate	mg/l SO_4^{2-}	815	3740	3977.6
Silica	mg/l SiO_2	41	17	147.9
Calcium	mg/l Ca^{2+}	260	776	3593.5
Magnesium	mg/l Mg^{2+}	299	1008	2398.5
Sodium	mg/l Na^+	73500	72800	67762.4
Potasium	mg/l K^+	204	456	866.4
Nitrates	mg/l NO_3^-	170	147	139.1
TDS		183209	183314	183304

Table 2
Composition of various wetlands and SWRO brine Sources: Canaragua and [13]

Comparison of seawater-brine-wetland water

Parameters	Unit	Sea water	Brine	Cabo de Gata (Almería)	Caravalseca (Basque Country)	Visán lagoon (Galicia)
pH		7.3	7.6	8.23	7.3	7.2
Conductivity	µS/cm	52000	80500	98956	64561	4142
Chlorine	mg/l Cl^{-}	19880	34080	32000	12100	1400
Sulphate	mg/l SO_4^{2-}	2147	3856	3860	22100	169
Silica	mg/l SiO_2	19.6	32.3	0	0.3	6.2
Calcium	mg/l Ca^{2+}	642	952	991	380	63
Magnesium	mg/l Mg^{2+}	1394	2456	2940	1250	66
Sodium	mg/l Na^{+}	10880	17340	14727	15260	897
Potasium	mg/l K^{+}	352	618		62	30
Total hardness	mg/l CO_3Ca	7337	12480			
Nitrates	mg/l NO^{3-}	16.4	28			
Nitrites	mg/l NO^{2-}	<0.02	<0.02	0	0	0
Amonium	mg/l NH_3	<0.1	<0.1	0	0	0

A solar basin is an artificial large shallow salt-water body that captures and stores solar energy. It is divided into three layers: the upper layer, which is thin and with little salt concentration; the lower layer, which contains a high salt concentration and is responsible for the storage of heat; and the intermediate layer, which presents a gradient of salinity and acts as a thermal isolator between the other two.

Solar radiation is absorbed and stored, creating a temperature difference between the upper and the lower layers of 40–70°C. Thermal or electric energy may be obtained depending on the technology used [14].

The efficiency of a solar pond depends mainly on three factors: the environmental climatic conditions, the use of an appropriate isolation and waterproof of the floor, and the use of an appropriate energy recuperation system [15].

From a technological point of view, solar ponds may be considered as a widely studied technique of brine reuse. There are several research and in some cases implementation plants. However, its incapacity to absorb the volumes of reject from large desalination plants together with its low collecting efficiency with respect to other systems has always reduced its options of becoming a definite solution to brine disposal [16–19].

Furthermore, brine may be used as a secondary cooling fluid due to the fact that it can be cooled beyond the freezing point of pure water. There are certain implementations in which a saline preparation is used to obtain a higher degree of cooling, such as some control devices of organic emissions to the air or air conditioning. Nowadays, there are also other options like fast cooling techniques of canned or bottled drinks, based mainly in brine thermal qualities such as suggested in a patent [20].

In any case, the use of brine as a cooling fluid requires a precise study of its characteristics as well as the cooling procedures to determine in each case the appropriateness of substituting the current cooling fluid.

5.4. Halophilic species

Brine can work as a means of cultivation or irrigation of a diverse number of species, both plants and animals, which are especially tolerant to saline concentrations slightly higher than that of fresh water (brine from brackish water desalination), or higher than that of seawater (brine from seawater desalination) [21].

Two of the most widely studied options are the cultivation of Artemia (brine shrimp) and Dunaliella salina. The first is a small crustacean not bigger than two centimeters long, which in its natural environment only appears in waters of high salinity (from 70 to 340 g/l), although it can also develop in seawater [22]. The Artemia is very often used as a natural food for larvae or young and adult species of fish and shellfish. Dunaliella salina is a chlorophyta alga which stores large quantities of carotenoids (up to 14% of its dry mass) and contains high quantities of glycerol [23,24]. This makes it a very important natural source of β-carotene, being of much interest for food and pharmaceutical industries. Alongside *Dunaliella salina* there

SWRO brine is an ideal medium for the growth of species such as *Dunaliella salina*, which is of high biotechnological value. Studies show an effect produced due to the adaptation of microalgae to this type of environment. This results in high carotenoid production rates in comparison with the commonly used cultivation media. Although the way in which this type of brine stimulates carotenoid production in *Dunaliella* has not been described yet, it does open up the possibility of using this kind of cultivations as alternatives, especially in those areas where there is high brine production through desalination processes due to the lack of fresh water [25] (*see* Fig. 2.).

Another option is the upbringing of fish species able to live in saline environments. In fact, the rearing of these fish is carried out in some regions where evaporation ponds are used. In general, these species are of significant importance to the food sector and for recreational fishing fields.

In addition, there are certain plant species tolerant to relatively high salinity levels. Some of these species belong to the agricultural sector and, under certain conditions, they can be irrigated with brackish water (up to 8000 mg/l). Examples of these are: beetroot, sugar cane, cotton, dates, barley, spinach, asparagus, or wheat. Another possibility which is being studied and tested nowadays is the irrigation of grass with high salinity water. One of the genus with this tolerance capacity is *Paspalum* [26]. The endured levels of salt depend on the subspecies and other external factors, such as the deepness of the roots or the soil tolerance to the salt.

This alternative has shown a good efficiency in the valorization of brine, although it is able to minimize only small volumes of the disposal. For this reason, its use must be in combination with other alternatives. Besides this alternative as well as others proposed obviously require some form of co-location. The culture facilities should be available near the brine discharge stream.

5.5. Capacitive deionization

It is a desalination technology to make the water flow pass through a module of capacitive condensers composed by several pairs of carbon aerogel electrodes with a high surface area and low electrical resistance. The ions are attracted and adsorbed in the charged surface of the electrodes, polarized by a direct current. When the electrodes are saturated, a stage of regeneration is conducted, where the electrodes have their power cut, and the retained ions are freed. If during this process the electrodes are connected to an external electric circuit, an electric current is produced, like during a condenser discharge.

Fig. 2. Cultivation of *Dunaliella salina* in raceways with SWRO brine [25].

The process has been studied in labs, and prototypes for brackish or seawater have been developed. Its performance is more suitable in brackish water, since it has been proved to be less effective in higher salinity levels. For this reason, it can be an option to treat brine from brackish water desalination plants [27–30].

From a technology viewpoint, the process can yield product water of very low salinity and highly concentrated reject brine, but in lesser volume than membrane technologies. Moreover, the process of cleaning electrodes recovers up to 50% of the energy applied, which reduces costs significantly [31].

The disadvantages for this process are the current state of the technology, which is not fully developed yet, and the restrictions of its applicability only to brackish water effluents and very small volumes at this moment, as reviewed by Orem [32].

5.6. Membrane distillation

It is based on the phenomenon of transporting both the solvent and the solute through a membrane that separates two compartments at different temperatures [33,34]. There are two kinds of transport, depending on whether the solvent flow is encouraged (thermo-osmosis) or the ions are encouraged (thermodialysis). It provides a low salt permeate flow and reduces the volume of brine. This technology has not been well developed yet, due to the relatively low achievable factors of separation. In spite of its apparent limited implementation, its use both as pre- and post-treatment of reverse osmosis desalination is currently under research [35,36].

5.7. Osmotic power

When water with different salt concentrations is mixed, this is transported through a semi-permeable membrane from the side with less salt concentration to the side with a higher salt concentration. This involves an increase in the pressure due to the osmotic potential. This pressure produced by osmosis can be used in several ways, including its use in a turbine [37]. The best process of energy production through this mechanism has been found out to be pressure retarded osmosis (PRO) [38–41]. Fig. 3 shows an outline of how a PRO plant works.

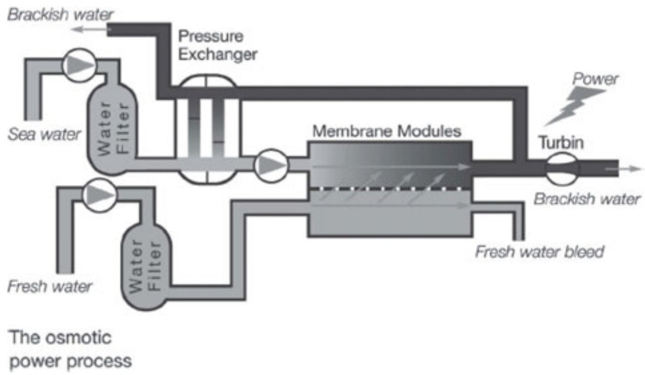

Fig. 3. Outline of how a PRO system works [42].

This technology was initially devised to be located in river mouths or at the hydroelectric station exits which are located close to the sea.

The installation costs for this technology are high. Statkraft, a leading company in this technology, estimates that the energy production cost through osmotic power will be roughly the same as the energy production cost through offshore wind turbines for the period 2010–2015 [43].

Nowadays, there is another research area based in the same operation principles to generate energy, but it uses a system of reversed electrodialysis (RED). This system is still in the testing and development phase by several research groups and Dutch companies, where it is called *Blue Energy* [44] (*see* Fig. 4).

Both options can be used for the minimization of all the brine produced in any desalination plant, either from brackish or seawater desalination processes. In this case, brine would be used as the feed for a production process to generate electricity: pressure retarded osmosis or reversed electrodialysis [46]. The disadvantage presented by this alternative is the fact that both techniques are under development, and longer research time will be required before a commercial plant can be built.

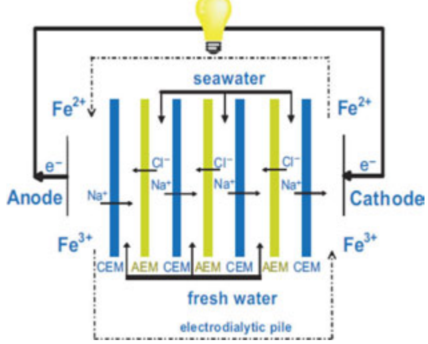

Fig. 4. Scheme of a RED process to obtain energy [45].

5.8. Electrodialysis

Electrodialysis enables the separation of saline mixtures by means of ion exchange through membranes with net charge. Because of its high electric energy consumption it is usually only used with brackish water. However, leaving aside economic considerations, its implementation in more concentrated water is being tested and it can reach seawater brine levels [47]. Furthermore, this technology could be interesting if combined with others for the reuse of brine, as, for example, a stage of concentration prior to crystallization, as reviewed [48].

5.9. Nanofiltration

Nanofiltration can be a previous step to reverse osmosis, since it can retain ions in a similar range. Nanofiltration increases desalination efficiency because its product will have a lower concentration of dissolved salts. This reduces the osmotic pressure required. It is technologically feasible nowadays.

On the other hand, the brine obtained in the first osmosis stage can be treated with a nanofiltration process [49]. This way we can concentrate brine, minimizing the reject volume and increasing the product water volume. Currently, due to the work pressure from the nanofiltration membranes available, (around 41 bar), this technology is considered to be adequate for brackish water desalination brine, although recently nanofiltration membranes for seawater are being developed [50].

Nevertheless, configurations similar in energy and flow rates to a two-stage SWRO desalination facility can be obtained by replacing the second RO stage by a NF module. However, this system is recommended only for brackish water desalination plants, or for seawater desalination facilities in those cases where the product water requires certain quality standards, achievable only through a nanofiltration process; i.e., a product poor in divalent ions, like the electrochemical industry [51–55].

6. Indirect use alternatives

6.1. Evaporation ponds

It is a shallow deposit located in the open air, which allows brine to concentrate by means of evaporation, obtaining sea salt as part of the process. It is normally used in areas suitable for evaporation, in mild and dry climates and cheap and vast lands, because a large exposition surface is required to increase its yield. In Oman, this is one of the most used resources for inland desalination plants with capacities between 50–1000 m^3/d [56].

Furthermore, the evaporation ponds can be used to obtain economical profit combining it with some aquacultural practices (fish, artemia or algae), as in several places in Australia [57,58]. It can also be combined with solar ponds to produce energy, since the settings, which are ideal for both systems, present the same factors.

As to its dimensions, there are some key: for instance, the evaporation rate, which will depend on the local climatic conditions and the amount of salts dissolved in water. Another influential parameter is the surface area: the bigger it is, the more the evaporation. As to its depth, for an optimal evaporation, the basins should not be more than half a meter in height [4].

In general, natural evaporation can be a relatively slow process to enable the treatment of substantial brine amounts. However, evaporation can be forced by means of modifications that make the evaporation rates increase. These can be numbered as: temperature increase, differential pressure between the surface and the atmosphere, wind speed, insufflating air, or reducing the surface tension.

Environmentally speaking, basins reduce the volume of brine and this can provide other commercially derived benefits, including salt production, although large amounts of brine cannot be valorized in this way and large areas are required for a small minimization of the disposal. From the technology point of view, it is a simple fully implementable option [59].

6.2. Selective precipitation

Another alternative to brine desalination is the sequential extraction of the dissolved elements contained in the form of greatly valuable compounds either in crystalline or liquid state. This is known as selective precipitation. It is a process that comprises several evaporation and cooling stages while adding specific chemical reactants to favor the precipitation from of one substance or any other. Apart from sodium chloride, substances such as gypsum, magnesium hydroxide, calcium chloride and sodium sulphate, among others, can be obtained. All of them have a high quality and can therefore be commercialized at a good price [60,61].

The main determining factors in this process are the composition and concentration of the present or added salts, the climate (temperature, humidity, rain, etc.), the energetic cost (especially of the thermal transfers) and the land availability (especially for the evaporation ponds, storage or brine pre-concentration) [62].

Regarding the technological aspects, it is a good alternative for brine, since the salt extraction processes and operations are widely established and well known, since they require evaporation and crystallization installations, among others, it would be necessary to analyze economically whether the energetic cost is too high. In this respect, installation costs should also be considered. However, if the amount of yielded product and its market value are optimal, the sale incomes could cover those costs.

6.3. Electrolysis

The process of electrolysis consists in applying an electric current to a volume, this case being brine which allows the separation of its ions. Electrolysis is used industrially in the production of chlorine gas applying it to a solution of sodium chloride. Apart from chlorine, hydrogen and soda are also obtained. Since desalination reject contains sodium chloride as main salt, its use as raw material to conduct the electrolysis industrial process could be made feasible to obtain the already mentioned products. To reach this goal, a previous concentration of up to 250 g/l would be necessary, together with a study of the possible interferences that the rest of the present ions may cause [63].

The three products obtained in the process are very important commercially and can even be usable in the desalination processes. This is exemplified by: chlorine or soda ash which can be used for a possible brine salt extraction (magnesium hydroxide) by means of selective precipitation.

This alternative has high energy and investment requirements, even though it can process a large volume of brine.

6.4. Freezing-melting process

This process could be used for both sea and brackish water desalination. It is produced by a change of state in the feed fluid. In the case of brine there is no known usage. However, taking into account its characteristics it could be implemented.

The aim of this process is to obtain, on the one hand, a saline solution and, on the other, salt-free ice crystals. For this purpose, a two-stage approach is applied. First, the feed water is frozen and it is physically segmented into the water and salt it contains. Then, the ice crystals are separated mechanically. These carry some salt, so they are washed with the water product previously obtained. This new washed brine can be recirculated and the process may be reinitialized. If the conditions are adequate when melting the washed ice very pure water can be obtained.

One of the advantages this process has is its low energy requirements with respect to other desalination systems. This is due to the fact that the heat latent in the ice melting is 1/7th of the latent heat in the evaporation of water [64]. However, it does involve high initial capital investment, as well as high operation costs in the stage of ice separation.

6.5. Rapid-spray evaporation

It is a relatively new technology, able to treat both sea water and brine obtained in conventional desalination plants. This process was born in the seventies, although AquaSonics International was the private company that developed and patented the process in 2001. It works in a simple way: brine is pumped into vaporization vaults through special injectors that expel it at high speeds and in the form of droplets. The vaporization of the drops is rapidly produced (less than 25 ms), causing a sudden separation of the salt, which falls to the bottom as a dry product. The salt-free vapors are condensed in another vault, obtaining a water product of less than 400 mg/l [65]. Therefore, this process would enable the complete management of reject desalination brine, obtaining pure water product and a commercially attractive salt by-product.

The vaporization index is determined by the size and speed of the drops, the atmospheric conditions and the composition of the feed water. Among the advantages this process offers, the following may be named: the minimum dependence on the amount of total dissolved solids and the total separation costs; its capacity to treat solutions of up to five times seawater salinity; and the possibility of increasing the total water product produced in a desalination facility.

Each rapid-spray evaporation unit is able to process 378.55 m^3 with an estimated cost of 0.40 €/m^3. However, this technology is not yet commercial, since it is still being developed by AquaSonics.

7. Zero-discharge

Zero-discharge is the ideal objective in brine water desalination management, i.e. the permanent elimination of almost the total amount of reject brine. This can be achieved by a specific treatment, combining two or more technologies, or by assessment or minimization procedures such as the ones mentioned above. Several authors have reviewed a range of processes [11,66].

In order to select a good method for the management of brine disposal a number of factors must be taken into account: the amount of brine, the physical location of the discharge, the availability of land at the chosen point, the social acceptance of the method, capital and operating costs and the capacity of the system for future extensions [12,51,53,63,67].

For large desalination plants, most of the alternatives proposed in this paper are partial solutions to the direct discharge due to the low flow rates that can be treated. Unfortunately, all proposed alternatives can only handle small or medium amounts of brine: none of them can treat large amounts of brine as produced by the large plants nowadays in operation. In case of direct disposal, and where no other option is technically and/or economically available, the suggested alternative is the previous dilution of the discharge.

Despite the volume treated, all the alternatives achieve a minimization and/or valorization of brine, obtaining a consequent economic and/or environmental value from what was considered at first instance as a residue. Thus, the adoption of these measures can yield benefits from the use of the sub-product brine in other processes.

In order to have an assessment, even superficial, of the alternatives, a table was prepared by marking a number of criteria for each method. The criteria used were technological (state of development, range of application -in terms of salinity, etc.-, efficiency, amount of available references); economic criteria (commercial availability, costs relative to the conventional process); and environmental (environmental impact, brine discharge reduction). The results are shown in Table 3.

All items were marked in a scale from 1 to 5, from least (1) to most (5) favorable assessment. In the case of cost, the figures should be regarded as cost relative to the cheapest conventional process (direct discharge to ocean). Therefore, costs marked as 1 mean the most expensive, whereas cost marked 5 means similar values to direct discharge to ocean.

Similarly, the brine discharge reduction should be regarded as the amount of brine that can be treated or managed by the proposed alternative, therefore meaning a reduction in direct discharge of brine to the ocean.

In all cases, the marks were assigned to the best of our knowledge and judgment according to the literature and previous works, as a direct assessment. No attempt has been made to perform a mathematical multi-variable optimization.

8. Conclusions

Information has been gathered to provide a structure of the alternatives for brine treatment or management. These alternatives have been described from a technological, economical and environmental point of view. The features for each alternative have been evaluated in a judgment scale from 1 to 5 (most favorable as referred to conventional ocean discharge). The most relevant differences have been observed in the technological perspective, depending on the current degree of development of the technology. However, most mentioned alternatives can be applied immediately and can be very advantageous both for the minimization of reject desalination brine and for its valorization.

Moreover, a detailed study of the specific situation of each desalination plant (brine flow to be treated,

Table 3
Evaluation of alternatives to direct brine discharge

Classification	Alternative	Technological criteria				Economic criteria		Environmental criteria	
		State of development	Range of application	Efficiency	Available references	Commercial availability	Relative costs	Environmental impact	Brine discharge reduction
Discharge	Deep-well injection	4	2	4	5	3	1	2	
	Previous dilution: WWTP effluent	5	2	5	3	5	3	4	4
	Previous dilution: seawater	5	3	5	4	5	2	4	5
	Previous dilution: refrigeration effluent	5	2	5	3	5	3	4	2
Direct use	Hydrotherapy	1	2	5	1	1	5	4	1
	Wetlands regeneration	4	4	3	3	5	5	5	1
	Heat-carrier fluid	3	4	4	3	3	3	3	1
	Halophilic species	4	2	5	3	5	4	3	1
	Capacitive deionization	3	2	3	3	2	3	3	2
	Nanofiltration	5	4	4	5	4	3	3	3
	Membrane distillation	2	1	3	2	2	2	3	3
	Electrodialysis	5	3	3	3	5	3	3	3
	Osmotic power	2	4	5	4	1	2	4	4
Indirect use	Selective precipitation	3	4	4	3	3	2	3	2
	Freezing-melting	3	3	3	2	3	4	3	2
	Evaporation ponds	3	3	5	2	5	5	2	4
	Electrolysis	4	2	3	4	4	2	3	2
	Rapid spray evaporation	3	4	4	1	3	3	5	2
	Zero discharge	3	3	5	3	3	2	5	5

location, environmental sensitivity, etc.) is deemed necessary in order to specify which of the described treatments or combination of treatments are appropriate for each case.

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