Facilitating a sustainable future

DESALINATION IN THE CONTEXT OF POWER-TO-X

- Sea water desalination is an energy intensive process which produces as a by-product, highly concentrated saline water called brine
- Brine is often disposed untreated back into the ocean where it causes harm for the marine and coastal ecosystems, therefore appropriate brine management and brine disposal regulation are essential to protect marine and coastal ecosystems
- Particularly, in water scarce countries, with limited access to fresh water for hydrogen production, an overall efficient and economical use of fresh water should be prioritised.
- In general, sea water desalination should not be seen as an ultimate solution to satisfy a growing global water demand but rather as a tool to close the supply and demand gap

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Developments and chances

Water is a major feedstock for hydrogen production. For one kilogramme of hydrogen from electrolysis, a minimum of 9 and up to 30 litres of fresh water are required. In 2022, the total global hydrogen production reached 95 Mt. Net zero scenarios by the International Energy Agency (IEA) predict an increasing hydrogen production, reaching 150 Mt by 2030 (IEA, 2022). Further studies predict a future global demand of up to 2.3 Gt annually (Olivera et. al., 2021). Hence, the question arises as to how water will be provided for a global Power-to-X (PtX) economy.

Water makes up 71 % of the world's surface. 97 % of which is salt water in the ocean while the remaining 3 % is freshwater. For the production of hydrogen, currently only purified water can be utilised. Which leads to the assumption that an ever-increasing water demand based on the expansion of hydrogen production in the long term can only be satisfied by additional water sources or by new technologies that can utilise wastewater. Given the widespread availability of saltwater, desalination can be such an additional water source. This briefing paper will address the opportunities and challenges associated with desalination primarily focusing on seawater desalination (SWD) for hydrogen production. Aiming to provide decision makers, project managers and investors with an overview of the concerns, challenges and possible solutions associated with desalination for hydrogen production.

The SWD is a well-established technology. The first large-scale SWD-plant was built in the 1930s. Currently over 16,800 desalination plants[1] are operating in 150 countries supplying fresh water for over 300 million people. The global cumulative desalination capacities have reached 97.2 million m³/day in the year 2020 (Eke et. at., 2020). Globally, the allocation is not distributed evenly. 48 %[2] of the global desalination capacity is in the Middle East and North Africa (Jones et. al. 2019).

Though the operating principle of the desalination process may vary, they generally encompass six main stages: construction, water abstraction, pre-treatment, desalination, post-treatment and the discharge of effluent (ONG FIMA, 2023). Desalination technologies can be divided into two main categories: thermal and membrane desalination processes, distinguished by the primary energy source utilised – heat or electricity – to separate salt/minerals from water. While various technologies of thermal desalination exist, multistage flash distillation (MSF) and multi-effect distillation (MED) are common technologies for large scale thermal desalination plants. The thermal desalination process also varies depending on the applied technology, nevertheless the applied principles are based on evaporation and condensation. Water is heated and the vapour, which is free of salt/minerals, is collected by condensation. Until the 1980s, thermal desalination was the most sought-after method. One of the main disadvantages of thermal desalination is the high energy demand required to heat large quantities of water. On average an electrical energy equivalent of 10-15 kWh/m³ (Shatilla, 2020) is required. Even though the energy demand can increase up to 40-80 kWh/m³ depending on the technology used, the efficiency of the desalination plant depends on the salinity content of the input water (Gohil et. al., 2023).

Bodies of water can be classified based on their salinity ranges. Measured is the sodium chloride content in parts per thousand (ppt).

Table 1: Classification of water bodies based on salinity ranges (Akankali & Elenwo, 2015)

Fresh water	Brackish water	Saline water	Brine
< 0.05 ppt	0.05-3 ppt	3-5 ppt	> 5 ppt

[1] In 2020 16,876 desalination plans have been installed. Including other desalination projects 20,971 desalination projects are in place.
[2] The available data varies. According to the International Desalination Association, 53.3 % of desalination plants are located in the middle east.

Membrane based technologies and in particular reverse osmosis (RO) is with a market share of 69 % the market dominant desalination technology. Here water flows under high pressure (typically 52-82 bar) through a semipermeable membrane to separate the salts and minerals from the water (Shatilla, 2020). With an energy demand of 2.5-4.5 kWh/m³ RO remains a highly energy intensive process, even though compared to thermal desalination, RO is more energy efficient. Independent of the technology used for the desalination process, a higher salinity is correlated with a higher energy demand (Schunke et. al., 2020; Kim et. al., 2019). Consequently, the process of desalinating brackish water generally demands a lower energy input compared with the energy requirements of SWD. The energy demand of brackish water ranges from 0.013 to 2.99 kWh/m³ (Reverse Osmosis Brackish Water Desalination) depending on the salinity content of the brackish water and the degree of salt removal (Patel et. al., 2021).

In recent years efficiency improvements in the SWD process have been achieved. Nevertheless, the current efficiency remains around 50 % (Alanezi et. al., 2020). Meaning that of two litres of water intake, a maximum of one litre of fresh water can be generated. The leftover water is called brine. The brine has an increased salinity content and can contain chemicals which were used during the desalination process. While technical options for brine treatment exist, in many cases the brine is disposed untreated back into the ocean.

Operational desalination facilities by feedwater type (2019)

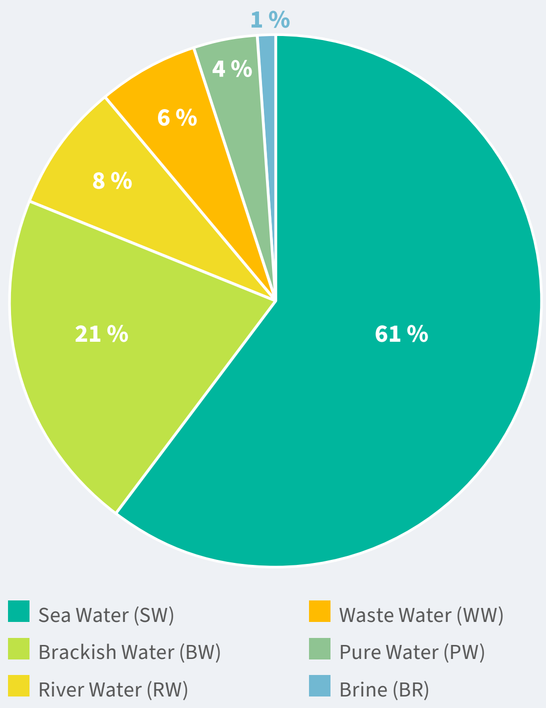

Figure 2: Based on Jones et. al (2019)

Operational desalination facilities by technology (2019)

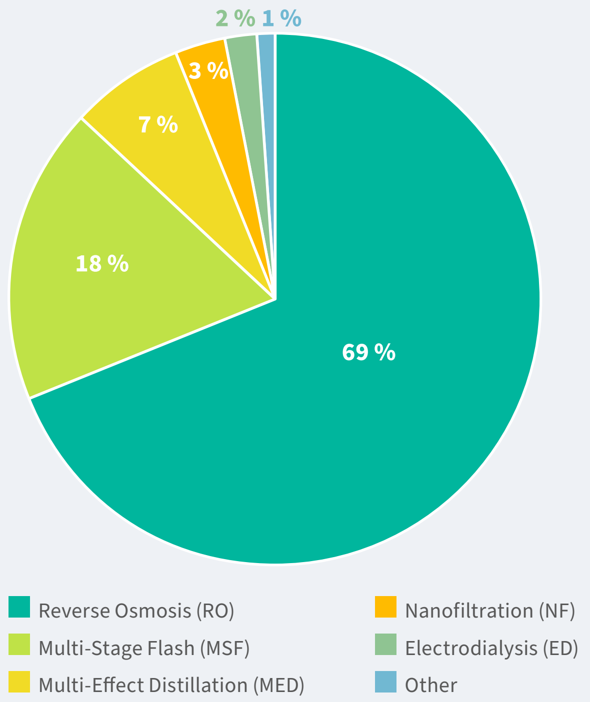

Figure 1: Based on Jones et. al (2019)

Realising opportunities

PtX has emerged as a transformative solution for the transport and storage of energy sources. Nevertheless, alongside its numerous advantages, there are issues regarding the SWD process for the hydrogen production. This chapter addresses the environmental, economic, and social acceptance issues associated with this technology and provides possible improvements or solutions.

Unveiling environmental concerns

SWD is an energy intensive process. From an energy efficient perspective, reverse osmosis emerges as the most advantageous technology. In many cases, however, the SWD-facilities are operated by using fossil fuels, resulting in the emission of CO_2 (see table 1). Increased utilisation of additional renewable energy sources has the potential to effectively reduce the CO_2 emissions of SWD.

Table 2: CO_2 emission of desalination (kg CO_2/m³)

	Reverse osmosis (kg CO_2/m³)		Thermal desalination (kg CO_2/m³) Average scenario		Thermal desalination (kg CO_2/m³) High scenario	
Energy source[1]	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Lignite	0.95	1.72	3.83	5.74	15.32	30.64
Hard coal	0.83	1.50	3.35	5.02	13.4	26.8
Natural gas	0.50	0.90	2.01	3.01	8.04	16.08
Raw petrol	0.91	1.63	3.64	5.46	14.56	29.12
PV[2]	-	-	-	-	-	-
Wind[2]	-	-	-	-	-	-

In addition to CO_2 emissions, brine discharge is an environmental concern associated with the impact of desalination plants. The brine as a residual product of the desalination process contains a high salinity content. Moreover, brine can contain chemicals such as antiscalants, coagulants, antifouling agents, biocides, and antifoaming agents, which are used for the pre-treatment and membrane/filter cleaning processes. In the case of thermal desalination, the brine is disposed at an elevated temperature compared to the receiving seawater which leads to an overall increasing water temperature. Due to high quantities of brine disposal, which is the case in industrial desalination plants, the marine and coastal ecosystems suffer increased stress. The specific impact on marine and coastal ecosystems is hard to quantify due to the fact that individual factors such as wave exposure, current and tides have to be considered.

However, consequences of untreated brine disposal can be a reduction of abundance and diversity of benthic communities[3], negatively affecting fish larvae, seagrasses, plankton or bacterial activity in the ocean (benthic) bottom (Sola et. al., 2020). This can lead to a less resilient ecosystem with a negative impact on the whole food chain.

Brine management represents a significant and paramount consideration for mitigating the environmental impact and addressing environmental concerns associated with desalination. While minimisation reuse or disposal of the brine should be managed, the implemented measures should always be customised to the specific needs of a desalination plant and the local conditions. As shown in Figure 3, a multitude of brine management varieties are applicable.

(1) Exclusively direct emissions CO_2 have been considered. Calculation based on CO_2-Factors (kg CO_2/kWh). Lignite: 0.383; Hard coal: 0.335; Natural gas: 0.201; Raw petrol: 0.364

(2) Exclusively direct emissions CO_2 have been considered. Including the upstream emissions, a CO_2-factor of 0.055 for PV and 0.016 wind onshore (kg CO_2/m³) can be assumed.
Own elaboration based on Shatilla (2020); Gohil et. al. (2023); Schunke et. al. (2020); BAFA (2022); Kim et. al. (2019); Lauf et al. (2021)

Brine management technologies

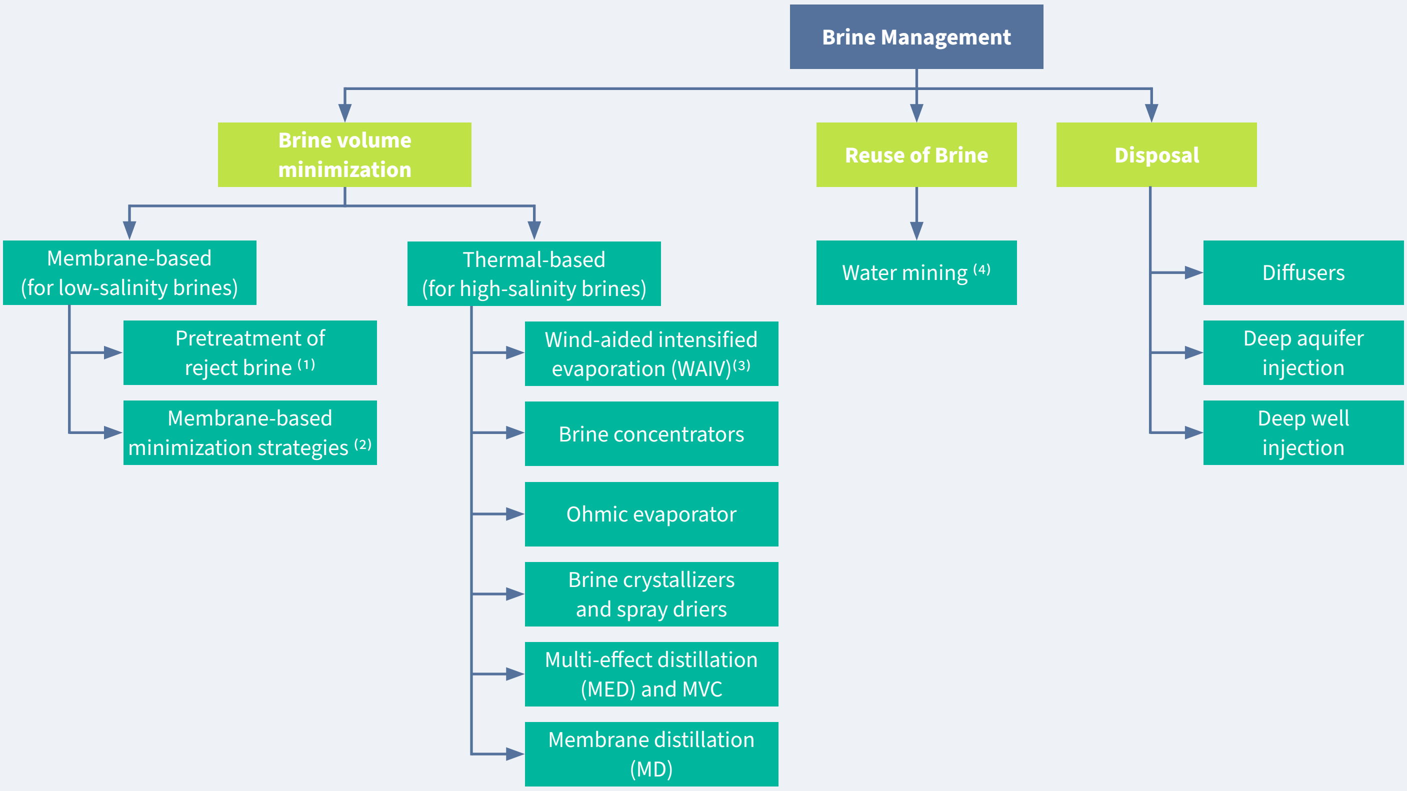

Figure 3: Own elaboration based on Giwa et al. (2017)

(1) Including: Chemical pre-treatment, Electrokinetic treatment and ion exchange, biological techniques
(2) Including: Vibratory shear enhanced processing (VSEP), ED, EDR and electrodialysis metathesis (EDM), Forward osmosis (FO)
(3) Evaporation ponds can also be used; WSIV reduces land requirements
(4) Production of minerals e.g., salts, metals or valuable chemicals. Common methods are crystallisation, evaporative cooling, membrane-based technologies e.g., chemical precipitation, adsorption, membrane and electrokinetic processes, crystallisation and evaporation

Minimising the overall amount of brine that needs to be disposed of is the most obvious approach for sustainable improvements followed by the reuse of brine. Direct disposal should only be considered if it remains the only practical and economical feasible option (Giwa et. al., 2017). In most cases, the installation of a diffuser in contrast to conventional end of pipe systems can be a first disposal measure. ‘Diffusers are mixing devices that increase discharge velocity and turbulence between brine and environmental seawater’ (Loya-Fernández et. al., 2018). This will lead to an improved mixing process between the brine and the seawater and will reduce the stress on marine and coastal ecosystems. Although diffusers represent a viable technical option to attenuate the impact of brine disposal on the marine and costal ecosystems, they are not standalone solutions. Their effectiveness should be complemented by additional brine management approaches for a more comprehensive mitigation strategy. Zero-liquid discharge (ZLD) is a further brine management option to consider. ZLD aims to minimise or eliminate any liquid waste (Liang et. al., 2021).

Furthermore, the water intake poses a risk for marine life. Due to the under pressure created by the water intake pipe, small and micro-organisms can get sucked in and must be removed during the pre-treatment. A cost-effective enhancement is the installation of a fine mesh covering the water intake, thereby diminishing the likelihood of small organisms being entrained. Mitigating the water intake velocity serves as an alternative effective method. Moreover, the transition of water intake from a surface-level to a subsurface intake configuration can serve as a protective measure for marine life. In this context, the intake is

3 Benthic communities are a diverse group of organisms that inhabit the bottom of aquatic environments, such as the ocean floor, and play a crucial role in the ecosystem such as e.g., clams, worms, mussels or sea stars.

positioned beneath the ocean floor, leveraging sand as a natural filtration medium. This approach potentially reduces the amount of chemical utilised in the pre-treatment processes (Folk, 2022).

Unveiling economical concerns

The foremost economical concern associated with SWD is the substantial energy requirements resulting in elevated production costs for desalinated water. However, in a PtX context, desalination costs are usually small in comparison to the overall PtX project and desalination offers many opportunities to create local benefits. An increased water demand for hydrogen production can lead to high local water prices. The same principle applies to electricity prices which can increase due to the high energy demand. Lastly, operational expenditures (OpEx) and capital expenditures (CapEx) for large-scale industrial desalination plants are high which creates barriers for less economically developed counties. Renewable energies can have the lowest levelised cost of electricity (LCOE), depending on geographic location, resource availability, regulatory environment and advancements in technology (Kost et. al., 2021). Therefore, the utilisation of renewable energies instead of fossil fuels with higher LCOE can reduce the OpEx of desalination plants.

In water scarce regions, SWD might emerge as the sole feasible choice for hydrogen production, despite its higher cost in comparison to utilising of ground/surface water or desalinating brackish water. Nonetheless, in the context of a whole hydrogen project the cost of SWD and brine management represent only a small fraction of the total cost of green hydrogen production. Estimates predict the SWD cost (including treatment & transport) to represent less than 2 % of the overall total costs involved in hydrogen production. The required energy for the desalination process represents about 1 % of the total energy demand (Blanco, 2021). Additionally, Morales and colleagues have determined the energy demand for brine treatment can be less than 3 % of the PEM-electrolysis process. This leads to the conclusion that efficiency improvement in the electrolysis process would have a significant impact in reducing the cost of hydrogen production.

An additional income stream can potentially be generated by water mining of brine. Here brine is used to extract minerals/ salts, metals or valuable chemicals. However, the economic feasibility of water mining is not assured and should therefore be evaluated for each desalination facility individually. In the case of utilising further chemicals for the water mining process, the handling of the waste product should be considered as in the case of the overall brine management. High CapEx are currently unavoidable, nonetheless, SWD is a known process and based on reliable technologies that provide a stable freshwater supply and the investment in the infrastructure can generate planning security against fluctuating or rising water prices.

Unveiling acceptance concerns

According to the United Nations World Water Development Report 2023, two billion people do not have access to safely managed drinking water services. Desalination can be one option to increase the supply of domestic water, however, if the desalinated water is used for hydrogen production a conflict of interest between the domestic or industrial utilisation of water is likely. If the desalinated water is not shared with the local communities, acceptance issues can arise. This can become an issue in regions dealing with increasing water stress and water scarcity.

In order to increase acceptance, a conflict of interest between industrial water and energy use and domestic use should be avoided and domestic use should be prioritised. This can be achieved by including the domestic water demand in the capacity planning of a SWD plant, to supply local communities with safe, reliable and low-cost fresh water. In the context of the whole project, the emerging marginal cost of oversizing could be borne by the local government of the company itself as part of a corporate social responsibility strategy. Nonetheless, water efficiency measures and water efficiency policies need to be implemented. Due to water leakages in the pipe systems, up to 50 % of the domestic fresh water can be lost, therefore investments in more efficient pipe systems and maintaining the current ones are necessary. Additionally, over one-third (2.75 billion) of the world's population lives within 100 km from the coast. Desalination plants are usually strategically placed in proximity of the ocean, which is a highly populated area. This can lead to competition for plant sites which need to be addressed by local policies.

As a consequence of environmental implication of untreated brine disposal on the marine and coastal ecosystems, a decline of the fish stock is possible. With the associated loss of livelihood, acceptance issues of local fisher(wo)men and the related value chains are likely. The implementation of the previously discussed brine management method can help to increase the acceptance by reducing the stress on the marine and costal ecosystems.

Ways forward

Desalination presents certain drawbacks. Nonetheless, when executed sustainably, it stands as one viable option for providing water necessary for hydrogen production. Therefore, decision makers and planners should integrate renewable energy such as PV and/or wind in the planning phase of new desalination plants to potentially reduce OpEx while minimising CO_2 emissions. Solar-desalination plants with parabolic mirrors are another option to reduce CO_2 emissions, however, the brine should be cooled down before being disposed into the ocean.

Policy makers, planners and investors should take direct negative effects on the environment and more indirect impacts on local communities or stakeholders into account. Under any circumstances a focus should be put on highlighting potential positive aspects of desalination plants in the context of hydrogen or PtX projects. Most prominently, desalination plants can provide accessible drinking water for local communities.

Lastly, there are no international treaties regarding brine disposal so far. Even the Oslo-Paris Convention for the protection of the marine environment of the North-East Atlantic (OSPAR) does not include the regulation of salt levels. Regional legislation offers an exception as, for example, in California (USA) where brine disposal is partly regulated. Given the expected increase in desalination, policy makers should regulate brine disposal. Under evaluation and consideration of the local circumstances the composition and amount of chemicals, brine temperature, salinity content and the overall amount of the disposed brine should be evaluated and the appropriated brine management measures should be implemented accordingly.

Literature recommendation

Eke et. al (2020): **The global status of desalination: An assessment of current desalination technologies, plants and capacity,**
DOI: https://doi.org/10.1016/j.desal.2020.114633

Gohil et. al. (2023): **Current Status and Advancement in Thermal and Membrane-Based Hybrid Seawater Desalination Technologies,**
DOI: https://doi.org/10.3390/w15122274

Jones et. al. (2019): **The state of desalination and brine production: A global outlook,**
DOI: https://doi.org/10.1016/j.scitotenv.2018.12.076

Giwa et. al. (2017): **Brine management methods: Recent innovations and current status,**
DOI: https://doi.org/10.1016/j.desal.2016.12.008

Sola et.al. (2020): **Sustainable desalination: Long-term monitoring of brine discharge in the marine environment,**
DOI: https://doi.org/10.1016/j.marpolbul.2020.111813

Morales et al. (2023): **Water management for Power-to-X offshore platforms: an underestimated item,**
DOI: https://www.nature.com/articles/s41598-023-38933-w

Futterlieb et. al. (2021): **Limits of High Recovery Inland Desalination: Closed-Circuit Reverse Osmosis – a Viable Option?,**
DOI: https://doi.org/10.1002/cite.202100042

Roberts et. al. (2019): **Design of Seawater Desalination Brine Diffusers,**
DOI: https://doi.org/10.3850/38WC092019-1053;

Loya-Fernández et. al. (2017): **Quantifying the efficiency of a mono-port diffuser in the dispersion of brine discharges,**
DOI: https://doi.org/10.1016/j.desal.2017.11.014

Sharkh et. al. (2022): **Seawater desalination concentrate – a new frontier for sustainable mining of valuable minerals,**
DOI: https://doi.org/10.1038/s41545-022-00153-6

References

Akankali J. & Elenwo E. (2015). Sources of Marine Pollution on Nigerian Coastal Resources: An Overview

Alanezi A., Altaee A., Sharif A. (2020). The effect of energy recovery device and feed flowrate on the energy efficiency of reverse osmosis process, the recovery rate can vary based on e.g., the utilised technology and the water quality

Blanco H. (2021). Hydrogen production in 2050: how much water will 74EJ need?, URL: https://energypost.eu/hydrogen-production-in-2050-how-much-water-will-74ej-need/

Bundesamt für Wirtschaft und Ausfuhrkontrolle (2022). Informationsblatt CO_2-Faktoren

International Energy Agency (2022). Technology deployment, URL: https://www.iea.org/energy-system/low-emission-fuels/hydrogen

Eke J., Yusuf A., Giaw A., Sodiq A. (2020). The global status of desalination: An assessment of current desalination technologies, plants and capacity

Folk (2022). Environmental Impacts of Seawater Desalination

Giwa A., Dufour V., Marzooqi F., Kaabi M., Hasan S. (2017). Brine management methods: Recent innovations and current status

Gohil P., Desai H., Kumar A., Kumar R. (2023). Current Status and Advancement in Thermal and Membrane-Based Hybrid Seawater Desalination Technologies

Jones E., Qadir M., Van Vliet M., Smakhtin V., Kang S. (2019). The state of desalination and brine production: A global outlook

Kim J., Park K., Ryook Yang D., Hong S. (2019). A comprehensive review of energy consumption of seawater reverse osmosis desalination plants

Kost C., Shammugan S., Fluri V., Peper D., Memar A., Schlegl T., (2021). Levelized cost of electricity renewable energy technologies

Lauf T., Memmler M., Schneider S. (2021). Emissionsbilanz erneuerbarer Energieträger

Liang Y., Lin X., Kong X., Duan Q., Wang P., Mei X., Ma J. (2021). Making Waves: Zero Liquid Discharge for Sustainable Industrial Effluent Management

Loya-Fernández Á., Ferrero-Vicente L., Marco-Méndez C., Martínez-Garcia E., Zubcoff Vallejo J., Sánchez-Lizasa J. (2018). Quantifying the efficiency of a mono-port diffuser in the dispersion of brine discharges

Morales Y., Samanta P., Tantish F., Horn H., Saravia F. (2023). Water management for Power-to-X offshore platforms: an underestimated item

Olivera A., Beswick R., Yan Y. (2021). A green hydrogen economy for a renewable energy society

ONG FIMA (2021). Economia en tiempos de Crisis: Perspectivas papa la transición lógicocologica en Chile

Patel S., Biesheuvel M., Elimelech M. (2021). Energy Consumption of Brackish Water Desalination: Identifying the Sweet Spots for Electrodialysis and Reverse Osmosis

Schunke A., Hernandez Herrera G., Padhye L., Berry T. (2020). Energy Recovery in SWRO Desalination: Current Status and New Possibilities

Shatilla (2020). Nuclear desalination, p. 248

Sola I., Fernández-Torquemada Y., Forcada A., Valle C., Pilar-Ruso Y., González-Correa J., Sánchez-Lizaso J. (2020). Sustainable desalination: Long-term monitoring of brine discharge in the marine environment

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→ Briefing #1: Carbon Sources

→ Briefing #2: Desalination

→ Briefing #3: Land use

→ Briefing #4: Benefits for local communities

→ Briefing #5: Skills & Jobs

→ Briefing #6: Stakeholder participation

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