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Subsea desalination – significant energy savings and greatly reduced environmental impact

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ABSTRACT

Seawater reverse osmosis (SWRO) is the dominant desalination technology in the world today. However, terrestrial SWRO is energy- and land intensive and more than 50% of the process is typically related to pre-treatment, not the RO process itself. Today's plants also have a negative impact on the local land and marine environment. This paper describes the design of a subsea SWRO system, Flocean, and its vast life-cycle benefits, including lower energy consumption, reduced cost of water, improved reliability, and enhanced environmental sustainability. Installed in water depths of 300–600 m, this approach brings several key advantages that result in significant cost and environmental savings through simplifications in design and operation: (1) In the disphotic zone from 200 m, less than 1% of sunlight reaches the system. This results in a high and consistent feed water quality as no plants grow and therefore there is significantly less life including algae and bacteria. Consequently, the need for pre-treatment is significantly reduced and, in some cases, even eliminated. (2) The system uses ambient hydrostatic pressure to reduce overall energy consumption by 30%–50%, even compared to modern SWRO systems with energy recovery systems. One of the many environmental benefits of the subsea desalination system is the brine discharge which has far less impact on marine life than current terrestrial SWRO systems. Access to high-quality, high-pressure feed water allows for chemical-free pre-treatment and low recovery operation without significant impact on the cost of water. The result is not only an energy-efficient system, but also a chemical-free brine that matches the salinity of the surrounding ocean. In addition, the brine is dispersed at deep sea in areas of low biological productivity. It all adds up to a green discharge product that is ideal for preserving the marine environment. The system was initially proven for oil and gas subsea water treatment applications and based on four decades of subsea technology experience in Norway.

Keywords: Subsea desalination; Green brine; Low energy; Eco-friendly; SWRO; Flocean

1. Introduction

With nearly 40% of the world's population living within 100 km of an ocean or sea [1], seawater desalination becomes an important tool in combatting the world's water scarcity in support of the challenge of access to safe water.

Seawater desalination can be divided into two main categories: thermal desalination and seawater reverse osmosis (SWRO) desalination. Of these two methods, SWRO is the dominant technology accounting for around 70% of the global desalination capacity in 2019 [2]. The prevalence of this technology continues to increase compared to thermal desalination technologies [3].

Research shows a trend where SWRO plant capacities are growing [4] with a sense of competition to be the next big desalination plant to be announced. One reason for the increasingly larger plants may be that the cost of water appears to be inversely proportional to the production capacity [5,6]. However, subsea desalination through reverse osmosis (RO) completely changes the playing field and adds

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a perfect complement to the large terrestrial plants with vast benefits on economy and environment and where size is not an equally important factor.

This paper presents the design of a subsea desalination technology, Flocean Desal, hereafter referred to as Flocean, highlighting the advantages of installing a SWRO plant in the deep sea. The paper pays particular focus on one of the many environmental benefits of the subsea desalination system which is the brine discharge which has far less impact on marine life than current terrestrial SWRO systems.

2. Subsea SWRO design and its benefits

The design of the subsea SWRO system, for installation at 300–600 m water depth, contains the same main functions as a terrestrial counterpart but with large simplifications in every step of the process due to advantages gained from the deep sea and how the system operates.

2.1. Water chemistry

When going below 200 m water depth, into the dysphotic zone, also known as the twilight zone, the quality of the water improves and is seasonally consistent. As only a small portion of sunlight penetrates to this depth, photosynthesis is no longer possible or becomes greatly reduced. The lack of photosynthesis results in significantly lower levels of bacteria, organics and colloidal/particulate matter which greatly simplifies the design of the SWRO system, particularly the pre-treatment system. In its simplest form, inlet pre-treatment can be expected to include an inlet screen and possibly a non-back washable guard filter.

Another water quality benefit of being deep is the inherent consistency in the water quality. At the depths involved, the system will not be sensitive to seasonal variations, weather anomalies such as storms or heatwaves or to contaminations from rivers and other sources. This allows for designing the pre-treatment system and the rest of the plant for a highly well-defined feed water quality and "oversizing" for rare events is not necessary.

Apart from the obvious benefits of a simple, yet effective, pre-treatment system, the water quality in the dysphotic zone will have a combination of a lower (more stable) temperatures and no UV light (no photosynthesis) resulting in significantly lower levels of naturally occurring bacteria, organics and colloidal/particulate matter. Therefore, a significant reduction in the cost of maintenance linked to bio-fouling can be expected.

Subsea water pre-treatment has been developed and proven over the last 20 y and can now, at a high technology readiness level (TRL) of [7,8][1], reliably include inlet screens, gravitational settlement, enhanced gravity separation, filtration (back washable and non-back washable) and chemical (chlorine) generation on the seabed via electrolysis [8][2].

[1] TRL value in 9 level scale, for example, used by NASA, between 1 (basic principles observed) to 9 (proven in operating environment). https://en.wikipedia.org/wiki/Technology_readiness_level

[2] Note that TRL level in cited report uses the API definition with a 7 level scale.

2.2. Ambient pressure

The second benefit of installing the SWRO system in deep water relates to the surrounding hydrostatic head of the sea. The benefit is largest when the water depth corresponds to the osmotic pressure, hence a typical installation depth target is around 500–600 m. By using the natural ambient hydrostatic pressure, the overall energy consumption is reduced by 30%–50%, even compared to modern SWRO systems with state-of-the-art energy recovery systems.

The installation depth allows for placing the high-pressure pump downstream the RO membranes, on the permeate side, and drawing water over the membranes as opposed to pushing it. This means that energy is focused to the product water only, and not to the feed water. However, despite the available hydrostatic head, a low pressure high flow cross-flow pump is used to enable system start-up and crossflow over the membranes.

This approach does not only yield benefits to the energy consumption but also to the design of the permeate pipeline, comparable to the intake pipeline of a terrestrial system. In terrestrial systems, the intake pipeline, typically HDPE or similar, must be designed to withstand collapse as it operates at negative differential pressure across its walls. The subsea desalination design takes advantage of the structural strength of the pipeline's cylindrical shape, utilizing its tensile properties, rather than exerting it to bending and buckling loads and related bending stress along the wall. This falls out as a result of the subsea approach operating at a slight overpressure which greatly reduce pipeline manufacturing and installation cost.

2.3. Marine ecosystems

The deep-sea installation significantly reduces impact to the marine environment.

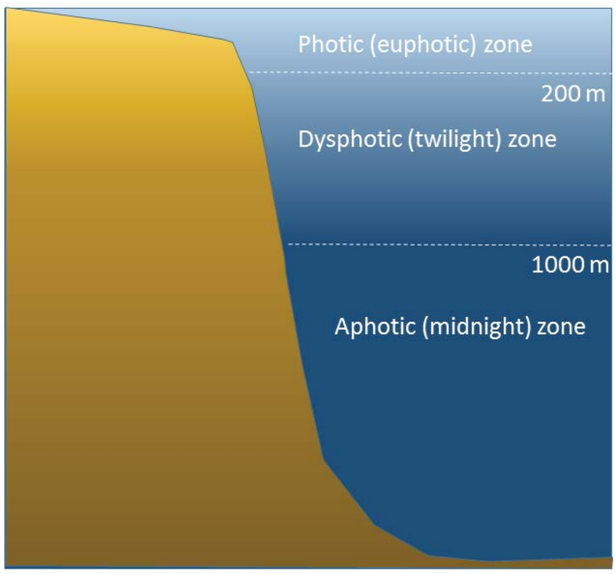

Fig. 1. Zones of the water column as defined by the amount of light penetration [7].

2.3.1. Intake design and marine life impact

The large recognized environmental impact of any surface intake system related to marine life impingement and entrainment is addressed in many places in the literature [9]. As described by Hogan et al. [10], there are a few design aspects that determines the impingement and entrainment impact magnitude where one important is the intake location (issue of biological productivity).

Missimer discusses the concept of deep-water intake systems and their expected reduction in environmental impact because of the lower concentration of living marine organisms and ichthyoplankton. It shall be noted that “deep” in this context is a range of 20–35 m below surface [11] and in some cases at depths >100 m [12]. The Flocean system is anticipated to be installed at 300–600 m depth with anticipation on closely eliminating the impingement and entrainment impact. The effect of real deep-water intake, >200 m, should be researched further in the future.

2.4. Design summary

Fig. 2 depicts a standardised Flocean treatment module and its components.

The module within the solid black line, referred to as a pod, feeds product water either to a central hub, connecting several pods, or directly to the receiving facility. The modularity of the system allows for installing the desired capacity by multiplying the number of pods as needed. It also allows for efficient staged development with gradually increased capacity over time.

The pod design, which is easily retrievable, builds on five decades of development of subsea processing technology for the oil and gas market, most notably on the development and successful qualification of the world’s first subsea water treatment technology [13], and equally important, the experience from Norway’s long history of supply of subsea pumps for deep-water operations [14].

It has been developed based on standard engineering principles with a subsea philosophy mindset (e.g., subsea modularization-, operation-, maintenance-, redundancy-, and material philosophies). The development is also aided by the Flocean digital twin that allows for adjusting settings and simulating the process effects [15]. The digital twin offers a tool for optimizing the design on a range of parameters:

- Optimisation of process equipment and sizing
- Concentrate valve regulation over membrane lifetime
- Crossflow- and product pump operational characteristics
- Seawater temperature and quality changes and more

Ultimately, the digital twin is used to tune the design to the conditions relevant to a specific application.

The Flocean system has a typical capacity of 5,000 to 60,000 m^3/d depending on the configuration and with a specific energy consumption (SEC) of around 2–2.5 kWh/m^3.

The low SEC is pivotal for the technologies’ low CO_2 footprint but as mentioned above, it has large environmental advantages on many aspects as compared to terrestrial plants.

Offshore installation and maintenance costs are falling in the face of increasing activity in maritime installations, where more and more players and industries are turning to the ocean to grow their business. Recent trends in the development of ROV and AUV technologies, as well as the aforementioned increase in marine installations, for example, related to renewable energy systems (offshore wind, floating solar, tidal, wave power), underwater data centres, subsea energy storage and more, are helping Flocean reduce risks, project durations and costs.

3. Green discharge in deep sea outfall

As mentioned, this paper shines light on the discharge and outfall design aspects as one of the many benefits of subsea desalination system.

SWRO facilities generate an average of 1.5 m^3 of brine, a highly saline by-product, for every m^3 of permeate they produce. Although alternative methods like evaporation, crystallization, and deep well injection can be utilized for brine disposal, approximately 90% of global desalination plants opt for direct discharge of brine into the sea, a process referred to as “surface water discharge” [16].

The primary environmental impact of brine stems from its high salinity, which ranges from 55–80 g/L, approximately double that of seawater, thereby affecting certain plants and animals. Nonetheless, the slightly elevated alkalinity of SWRO brine, along with the presence of chemicals employed for scaling and biofouling control, as well as trace metals originating from the plant’s pipes and pumps, also pose concerns, albeit to a lesser extent.

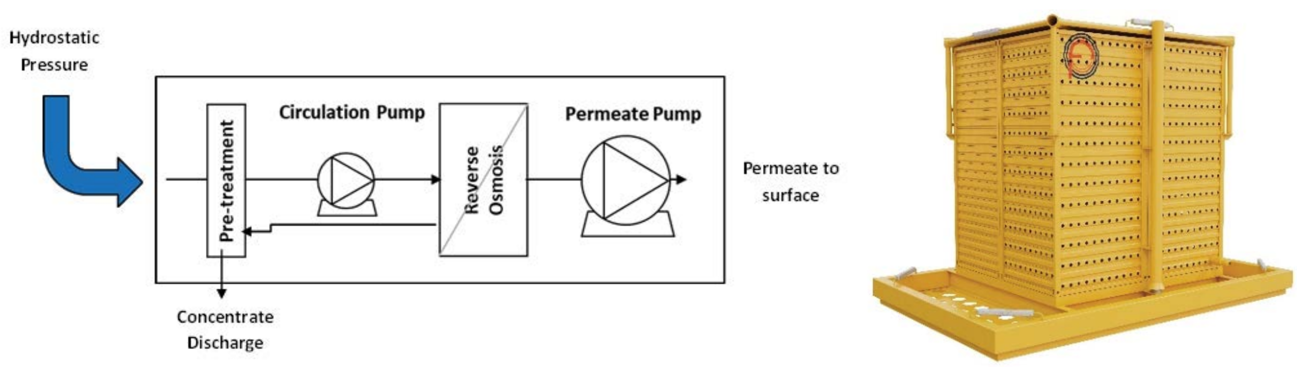

Fig. 2. Flocean process schematic (left), and a pod illustration (right).

The disposal of brine is particularly crucial within benthic (seafloor) ecosystems situated in areas with limited circulation, indicating poor hydraulic connectivity to the open oceans. Numerous regions where SWRO is prevalent, such as the Mediterranean Sea, the Arabian Gulf, and the Red Sea, fall into this category.

3.1. Conventional outfall design and concentrate management

Conventional outfall systems discharge concentrates directly to marine surface-water bodies, typically at shallow water and near the coast. The environmental impact of disposal of concentrate is discussed in length in the literature. Missimer and Maliva [9] lists the primary impacts associated with discharge of SWRO concentrate to include:

- increases in the salinity of receiving water bodies, particularly restricted circulation bodies,
- local impacts of hypersaline brines on marine benthic communities at and near the point of discharge,
- discharge of chemicals used for pre-treatment and membrane cleaning,
- discharge of metals from corrosion (Cu, Fe, Ni, Mo, Cr),
- aesthetic issues (visual impacts),
- impacts to aquifers from leaks from brine pipes,
- temporary damage during construction,
- temporary damage during maintenance,
- permanent damage from emplacement of infrastructure (pads, pipelines, etc.).

Lattemann and Höpner [17] discuss the negative environmental impact of SWRO discharge and how the impacts depend on both the physico-chemical properties of the reject streams and the hydrographical and biological features of the receiving environment. Lattemann continues to discuss that enclosed and shallow sites with abundant marine life can generally be assumed to be more sensitive to desalination plant discharges than exposed, high energy, open-sea locations, which are more capable to dilute and disperse the discharges.

To mitigate the potential impact of brine on marine ecosystems, designers of SWRO plants employ a range of strategies:

- Careful selection and cautious use of chemicals for pre-treatment.
- Utilizing multi-port diffusers to enhance dispersion. This allows for the brine to be spread over a larger area, reducing localized impacts and promoting dilution within the receiving water body.
- Exploring alternative discharge methods such as brine injection wells or the utilization of beach and offshore galleries and trenches. These methods provide additional pathways for brine discharge, which can help distribute the brine more effectively and mitigate its potential environmental effects.

By implementing these strategies, SWRO plant designers aim to minimize the ecological consequences associated with brine discharge and ensure the protection of marine environments.

A third strategy that is used in the design of the discharge is to look at the best positioning of discharge pipes meaning that discharge pipes are carefully located away from environmentally sensitive areas, and preference is given to regions with improved water circulation. This helps to minimize the direct impact of brine on vulnerable ecosystems. This third design option, the selection of a proper site for discharge, is considered equal or more important than technical options [17] and is also addressed by [9] who discuss discharge at deep water to reduce the environmental impact of the outfall. Again, in the case of Flocean, the word "deep" refers to waters down towards, or even beyond, 500 m. This is far below most known sensitive eco-systems.

Many of the discussed challenges are naturally resolved by the subsea desalination approach.

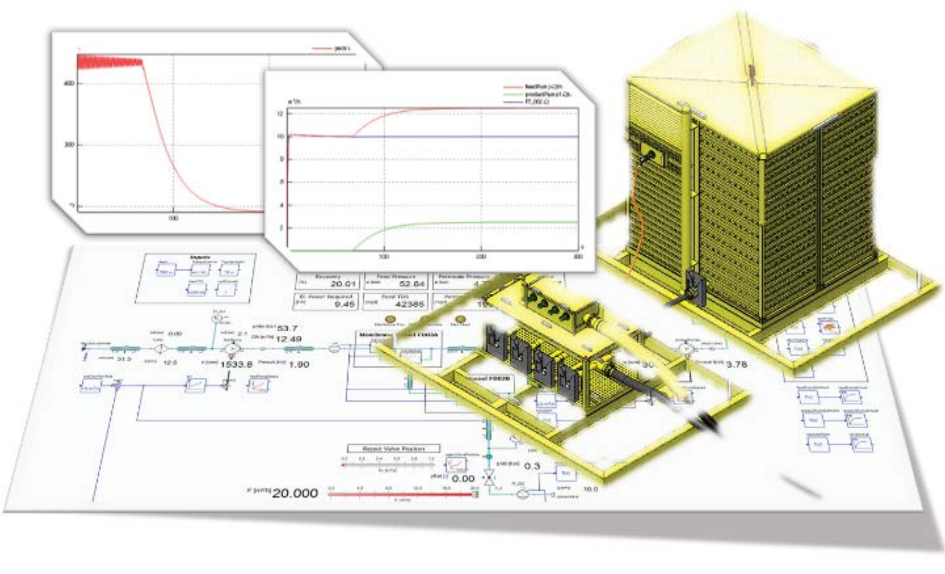

Fig. 3. Illustration of Flocean digital twin.

3.2. Subsea desalination outfall design and concentrate management

The design of the subsea desalination system described in this paper positively addresses discharge salinity levels, chemical use, discharge of metals, visual impacts, outfall location and more.

Subsea desalination systems allow for operation at a low recovery without significant impact to energy consumption or total cost of water. This stems from the feed water being freely available at high pressure, removing the incentive to maximize the utilization of the feed water and by so allowing for economic low recovery operation. The system is designed to operate at a typical recovery rate of 15% meaning the salinity increase in the discharge stream is only 15% higher than the surrounding sea.

The economics of terrestrial SWRO plants dictate that high recovery rates of permeate (% permeate vs. % brine reject) are required to maximise their efficiency. Today's plants typically operate at 40%–60% recovery rate. The higher the % permeate produced, the higher the dissolved solids content in the brine reject stream. Environmental organisations are therefore increasingly concerned about the potential for alterations to the community structure (acute and chronic toxicity), under constant discharge of the high concentrations of desalination brines. To operate at high recovery rates is not driven purely by economic interests but also links to a lower CO_2 footprint as the alternative, operation at low recovery rate, greatly increase the energy consumption on terrestrial. This falls out from the fact that low recovery rate operation does not maximize the return of the energy invested in pressurizing large amount of feed water for the RO process.

The severity of the discharge of highly concentrated brines is naturally resolved or significantly reduced by the subsea desalination approach and summarized in the bullets:

- Subsea desalination economics allow for a lower permeate recovery rate from the RO membranes. It follows that the lower recovery factor yields lower salinity levels in the concentrate stream (brine discharge). In addition, some of the energy (flow) from the feed pump can be used to enhance dilution of the already low salinity levels in the discharge stream.
- Concentrate is discharged deeper than most active marine ecosystems. At increased depths (>200 m) the lack of UV light means photosynthesis is no longer possible. This means significantly less impact on benthic communities and less alterations to community structure in, for example, seagrass, coral reef and soft-sediment ecosystems.
- Zero chemical discharge follows the operation at increased depths which gives a combination of a lower (more stable) temperatures and no UV light (no photosynthesis) result in significantly lower levels of naturally occurring bacteria, organics, and colloidal/particulate matter. This in turn means that chemical treatment should not be required to prevent biofouling of the RO membrane elements. Zero chemical discharge is an important benefit of subsea SWRO with "green" concentrate discharge.
- The material philosophy for subsea equipment involves the careful selection and use of materials that can withstand the harsh conditions and challenges of underwater environments with considerations to, for example, corrosion resistance, structural strength, fatigue resistance, subsea coatings and more. As a result, materials are always high-grade stainless steels, typically SuperDuplex, and as such, reduces or eliminates the concern of discharge of metals from corrosion.
- As the discharge occurs right near the station without any piping of the brine from the plant to the ocean, the issue with potential leakage to land and aquifers is eliminated.

The combination of discharge at high energy open and deep-sea locations, in areas of low biological productivity, with the brine being chemical free and close to ambient seawater salinity makes for a design that can operated with far lower environmental impact than that of conventional terrestrial SWRO plants.

4. Conclusion

In conclusion, this paper discusses the design and benefits of subsea seawater reverse osmosis (SWRO) desalination technology, known as Flocean Desal. The paper highlights the advantages of installing SWRO plants in the deep sea, focusing on the environmental benefits, specifically the reduction in impact on marine life compared to terrestrial SWRO systems.

The deep-sea installation of SWRO systems offers several advantages. Firstly, the water quality at depths below 200 meters is improved and more consistent, with lower levels of bacteria, organics, and particulate matter. This simplifies the design of the SWRO system, particularly the pre-treatment process. The deep-sea environment also provides a stable and well-defined feed water quality, eliminating the need for oversizing the system for seasonal variations or contaminations.

Another benefit of deep-sea installation is the utilization of ambient pressure, which reduces the overall energy consumption of the system by 30%–50% compared to modern SWRO systems. The hydrostatic head of the sea allows for placing the high-pressure pump downstream of the RO membranes, resulting in energy savings and simplified design of the permeate pipeline.

Furthermore, the deep-sea installation significantly reduces the impact on marine ecosystems. Surface intake systems in traditional SWRO plants can cause impingement and entrainment of marine life, but deep-water intake systems have lower concentrations of living marine organisms and ichthyoplankton, minimizing the environmental impact. The modular design of the Flocean system, based on subsea processing technology, allows for scalability and staged development, accommodating different capacity requirements over time.

The paper also discusses the design aspects of discharge and outfall management in subsea desalination systems. Conventional surface water discharge of SWRO concentrate can have adverse effects on marine environments due to increased salinity, chemical discharge, and potential damage to benthic ecosystems. To mitigate these impacts, designers employ strategies such as careful chemical selection, multiport diffusers for enhanced dispersion, and alternative discharge methods. The subsea desalination approach, operating at low recovery rates and deep-water depths, inherently addresses many of these challenges and minimizes the environmental impact of brine discharge.

Overall, the subsea SWRO technology presented in this paper offers numerous advantages, including simplified design, reduced energy consumption, and minimized impact on marine ecosystems. The design and operational considerations discussed contribute to the development of sustainable and environmentally friendly desalination solutions, supporting efforts to combat water scarcity and ensure access to safe water resources.

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