Comparing seawater desalination technologies for green hydrogen production: Reverse Osmosis and Multi-Effect Distillation

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Preface

This study was conducted as the thesis for my Master of Science in Chemical Engineering from Lund University. The project was in collaboration with Alfa Laval, and their Energy Division.

I would like to express my gratitude to Frank Lipnizki, as my supervisor at Lund University's Faculty of engineering. Thank you for support and endless membrane knowledge! I would also like to thank everyone in the Green Hydrogen group at Alfa Laval for their helpful insights and support in navigating the complex world of desalination. And I would especially like to thank my supervisor Luciana Mendes, whose continuous support and enthusiasm has made this project an incredible experience.

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Abstract

Due to increasing global energy demands and a need to move away from non-renewable energy sources, green hydrogen is now being considered as a possible replacement for fossil-based energy sources. Especially in “hard-to-abate” sectors, such as steel and petrochemical production, and long-distance transport, where the change to renewable electricity is more difficult. Green hydrogen is produced through electrolysis of water and powered by renewable energy sources. The water quality demand for the electrolysis feedwater is high, and water of very high purity is required. Meanwhile, there are also challenges with water supply and demand in many regions of the world, but by using desalination to purify seawater for electrolysis it is possible to avoid the need to compete for groundwater with other water-demanding sectors.

The most common desalination technology on commercial scale is the membrane technology Reverse Osmosis (RO), due to its relatively low energy demand and high reliability. Thermal desalination technologies such as multi-effect distillation (MED) are used less, due to high thermal energy demand. The electrolysis process does however produce waste heat, and Alfa Laval would like to utilise this heat to power their MED system HyDuo and simultaneously provide cooling to the electrolysis systems.

Thus, this study aims to investigate and compare the Alfa Laval HyDuo system with RO system, to evaluate whether the HyDuo can compete with the established RO systems considering costs and process requirements.

Sammanfattning

Grön vätgas har lagts fram som en lösning på en av vår tids största utmaningar: Att klara av världens energiförsörjning samtidigt som de fossila bränslena avvecklas. Framför allt i sektorer som industriell kemikalieproduktion och långdistans-transport, där övergången till förnybar elektricitet är svårare.

Grön vätgas produceras genom elektrolys, där en elektrisk ström driver den annars icke-spontana spjälkningen av vatten till syre och vätgas. Kraven på vattenkvalitén för denna process är mycket höga, och för att produktionen ska räknas som ”grön” behöver elektriciteten vara förnybar. Samtidigt så finns det många regioner i världen som har hög produktionskapacitet för förnybar el, men en brist på grundvatten. För att undgå detta problem undersöker man nu möjligheten att avsalta havsvatten för grön vätgasproduktion.

Reverse osmosis (RO) är den nuvarande marknadsdominerande avsaltningstekniken, och står för över 80% av global avsaltning av havsvatten. Processen är dock inte felfri, delvis används mycket kemikalier i RO avsaltnings-system och elektrolys-processen producerar även restvärme. Alfa Laval undersöker nu möjligheten att ersätta RO tekniken med deras multi-effekt distillationssystem HyDuo, som skulle kunna utnyttja restvärmen från elektrolys för att avsalta havsvatten samtidigt som det bidrar med kylning till elektrolyssystemet.

Denna rapport har syftet att jämföra HyDuo systemet med RO avsaltning, för att se om Alfa Lavals enhet har möjlighet att konkurrera med de marknadsdominerande RO systemen. Olika för- och efterbehandlingstekniker har också utvärderats, för att få en överblick på hur dessa system skulle se ut i stor skala. HyDuo systemet visade sig sannolikt behöva förbehandling med filter, desinfektion med klor samt efterbehandling med en EDI (Elektrodejonisering) enhet. Fler pilottester behöver dock genomföras för att bekräfta detta.

Även kostnaden för de två systemen utvärderades, med resultatet att HyDuo systemet krävde en större investeringskostnad, men en lägre driftskostnad än RO systemet, men att detta resultat kunde påverkas beroende på vilken för- och efterbehandling som användes. RO systemet krävde dock mer kemikalier, vars toxicitet bör utvärderas i framtida studier. HyDuo systemet har även fördelen att vara mer robust, både i förmågan att anpassa sig efter elförsörjning samt ha lägre krav på vattenkvalitét in i systemet, vilket som en följd innebär mindre krav på förbehandling. Som en slutsats konstaterades att HyDuo systemets förmåga att avsalta havsvatten för elektrolys var lovande, men kräver mer pilottester för att bekräfta denna prognos.

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1 Introduction

In 2015 at the UN Climate Change Conference (COP21), 196 parties agreed to adopt The Paris Agreement, a legally binding international treaty on climate change. The overall goal for the treaty was to hold “the increase in the global average temperature to well below 2°C above pre-industrial levels” and pursue efforts “to limit the temperature increase to 1.5°C above pre-industrial levels.” The reason for wanting to limit the temperature increase to 1.5°C is because the UN’s Intergovernmental Panel on Climate Change (IPCC) indicates that crossing the 1.5°C threshold will result in acute climate change consequences, such as more frequent and severe droughts, heatwaves, and rainfall. To prevent these changes from occurring, greenhouse gas emissions must peak no later than 2025 and decline 43% by 2030 [1].

Solutions that only reduce a small amount of greenhouse gas emissions will now be inadequate and solutions that provide drastic emission reductions are necessary. Clean hydrogen has emerged as a viable option in combating climate change, especially in “hard-to-abate” sectors, such as steel and petrochemical production, and long-distance transport. [2]. Hydrogen has high energy density (120 MJ/kg), making it an excellent energy carrier. Pure hydrogen does however not exist readily available on earth, instead the atom is found in chemically combined forms, e.g. in water, biomass, fossil fuel etc. Meaning that the main challenge for hydrogen is to separate it from these naturally occurring compounds in an efficient and economical way [3].

Hydrogen production is currently dominated by non-sustainable production pathways, and to comply with the 1.5°C scenario, it must undergo a transformation to renewable pathways. And the technology for these pathways does exist. Green hydrogen can be produced through electrolysis of water with renewable electricity. However, large-scale hydrogen production is a relatively new phenomenon and there are still challenges that need to be overcome before green hydrogen can overtake - one of which is the water demand [2].

All hydrogen production requires water for cooling and/or as feedstock and with green hydrogen it is important that the used water is obtained sustainably, for the production to be considered sustainable. To avoid water stress and competition with other water demanding sectors, using desalinated seawater in hydrogen production is incentivized. Particularly in arid regions, close to the coast, where the lack of freshwater would otherwise prevent the building of potential hydrogen electrolysis plants, the use of desalination opens a new energy sector [2].

The use of seawater does however have implications on both environment and economy. Desalination is an energy-intensive process, and expenses for both construction and operation are increased for an electrolysis plant that utilises seawater. The main environmental concerns are related to the brine and thermal pollution [2]. Implications should be investigated.

Electrolysers require high water quality, and there are a multitude of technologies that can be used to achieve this. Desalination technologies are divided into two broad classes: Thermal and membrane techniques. Where the membrane technique Reverse Osmosis (RO) is the market dominating desalination technology, since it only requires electrical energy, resulting in a low energy demand. Meanwhile, thermal desalination techniques require both electrical energy, as well as thermal energy to overcome the thermal change of phase, resulting in an overall higher energy demand [4].

The electrolysis process however produces waste heat, around 20-40% of the energy used becomes waste heat [5]. If properly utilised, this heat could be used to power evaporation as a thermal desalination technique, which would lower both the energy- and water demand, as well as overall cost for the process. Alfa Laval is currently investigating the possibility to build such thermal desalination integrated electrolysis systems, by utilising one of their multi-effect distillation units – The Alfa Laval HyDuo.

1.1 Project description

The objective of the project has been to analyse and compare two different desalination technologies to produce water for green hydrogen production: Reverse osmosis and multi-effect distillation. The technologies were compared considering several aspects, including overall technology assessment, investment- and operational costs as well as environmental impact. A literature study was conducted to gather information and to gain better understand of the two technologies. Furthermore, calculations of the investment- and operational costs were performed in Excel.

A complete desalination system was designed and evaluated for each technology, from the seawater as feed source, to the ultra-pure water outlet, ready for electrolysis. This also included any required post- and pre-treatments to complement the main desalination technique. In order to understand the type of post- and pre-treatment required for each system, water quality specifications and possible impurities in each inlet and outlet were investigated.

1.2 Aim

The aim of the project has been to reach a better understanding of the two different desalination technologies: Reverse osmosis (RO) and multi-effect distillation (MED). This includes evaluating different pros and cons with each technology, and by doing this then being able to predict if MED can compete in the future with the currently market dominating RO.

1.3 Scope

The scope of this project is limited to a theoretical study - a literature reviews and a data analysis. No practical lab or pilot tests were conducted during this study. The literature review was conducted to gain a better understanding of the relationship between water purity and electrolysis, as well as the type of pre- and post-treatments desalination plants may require. Data from previously conducted pilot tests with Alfa Laval HyDuo systems was also analysed to better understand the desalination potential of MED, and what additional treatment techniques may be necessary to accompany the MED. Then the two desalination technologies RO and MED are compared based on selected key characteristics including cost, environmental impact, and overall technology assessment.

2 Background

To understand the requirements and the capacities of both desalination technologies, a literature review was conducted, as seen below. It covers different electrolysis technologies and their water requirements and waste heat they produced. Then the two desalination technologies are investigated, the cost model used is briefly introduced, and different pre- and post-treatment typically used for RO are included.

2.1 Water and electrolysis

Green Hydrogen is produced through electrolysis, where an electrical current is used to drive the otherwise non-spontaneous reaction of water (H_2O) splitting into oxygen (O_2) and hydrogen (H_2). There are multiple pathways that this reaction can take, and depending on electrolyser, operating conditions, and ionic agents, they can generally be grouped into 4 main categories: Alkaline water electrolysis, anion exchange membrane (AEM) water electrolysis, polymer exchange membrane (PEM) water electrolysis and solid oxide water electrolysis (SOEC) [3]. Alkaline and PEM electrolysers are currently the most established categories on market-scale [6] [7] and therefore this report will only focus on these two types.

The water purity requirements for both alkaline and PEM electrolysis are high, to ensure an effective reaction and low tear of the membranes. ASTM International, an internationally recognised standards organisation, have published a set of international standards for water quality that are often used to describe water quality requirements for electrolysers. These standards, known under the name ASTM D1193 Type I, II, III and IV, cover conductivity/resistivity, chloride, sodium, silica, and total organic carbon (TOC) of the water. Although these standards include some of the most important aspects of water purity, they are often insufficient to properly cover all the water quality requirements for electrolysers, and other impurities than the ones described by ASTM are often considered as well. These additional impurities which might need to be considered dependent on many different factors, including electrolyser type, feedwater composition, and water treatment technologies. [8]

2.1.1 Alkaline electrolysis

Alkaline water electrolysis is characterized by having two electrodes operating in a liquid alkaline electrolyte, typically highly concentrated potassium hydroxide (KOH). The electrodes are separated by a diaphragm, as anode and cathode, and hydroxide ions (OH^-) work as the ionic carrier. The electrochemical water splitting process consists of two half reactions, one on each side of the diaphragm, as illustrated in Figure 1. A comparison of alkaline and PEM electrolysis characteristics can be found in Table 1 [9].

Alkaline water electrolysis is a well-established technology, and functional on a commercial scale for industrial applications. The electrocatalysts are also noble-metal free, unlike PEM electrolysis that often uses platinum-based catalysts, and the technology has long-term stability as well as relatively low cost. It does however suffer from lower current density compared to PEM electrolysis, and crossover of the gasses in the membrane. The highly concentrated liquid electrolyte also is also corrosive [3].

Alkaline electrolysis is generally less sensitive to impurities than PEM electrolysis, although both require high quality water for long-term stability and membrane life [10]. Alkaline electrolysis is however sensitive to carbon dioxide contamination, but this can be resolved by degassing [11].

2.1.2 PEM electrolysis

Unlike in alkaline electrolysis, there is no need for a liquid electrolyte in PEM electrolysis, as the ion transport happens within the PEM. The electrodes are separated by an electron-insulating solid electrolyte, called a solid polymer electrolyte (SPE) [9]. An overview of the PEM cell can be seen in Figure 1, and a summary of some of the most important components and operating conditions can be seen in Table 1.

Poor water quality is the main reason for stack failure for PEM electrolysers, as both the membranes, catalysts and the porous transport layer are all sensitive to impurities [9]. PEM membranes particularly are sensitive to cations, e.g. Na^+, Ca^{2+} and Mg^{2+}, as well as chlorine [11].

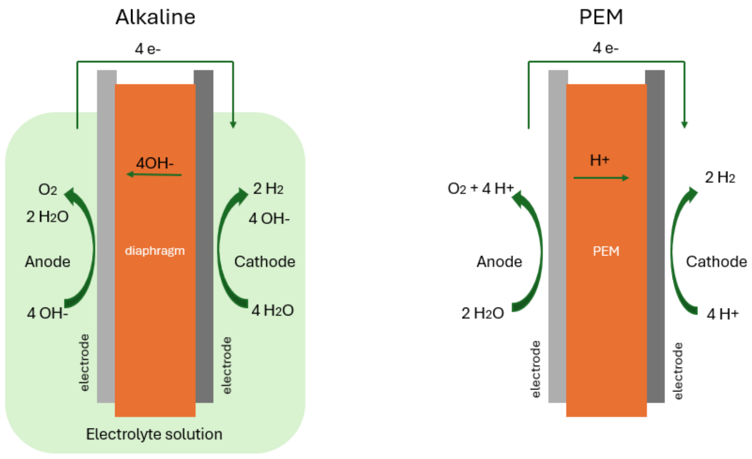

Figure 1: Overview of Alkaline (left) and PEM (right) electrolyser cells, adapted from the International Renewable Energy Agency [9].

Table 1: Summary of operating conditions and most important components of Alkaline and PEM electrolysis, adapted from the International Renewable Energy Agency [9].

	Alkaline	PEM
Operating temperature	70-90 °C	50-80 °C
Operating pressure	1-30 bar	< 70 bar
Electrolyte	Potassium hydroxide 5-7 mol/L	Perfluoroacidsulfonic membranes
Separator	ZrO_2 stabilised with Polyphenylene sulphide (PPS) mesh	Solid electrolyte (above)

Electrode/catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium oxide
Electrode/catalyst (hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black
Porous transport layer anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium
Frames and sealing	Polysulfone (PSU), Polytetrafluoroethylene (PTFE), Ethylene propylene diene monomer rubber (EPDM)	Polysulfone (PSU), Polytetrafluoroethylene (PTFE), Ethylene Tetrafluorethylene (ETFE)

2.2 Electrolysis and renewable energy

Renewable energy sources such as solar and wind power produce electricity intermittently, depending on season and weather, and combining these intermittent electricity sources with a hydrogen production system has both advantages and challenges. Hydrogen has good long-term storage capabilities, which means it can be used to improve power grid systems that struggle with stability, e.g. systems that rely on renewable intermittent energy sources [12]. The energy density for hydrogen is also around 200 times larger than for a lithium-ion battery, resulting in a smaller footprint which may be preferable for e.g. offshore applications [13]. Electrolysis systems however also struggle with the intermittent energy supply, as current electrolysers are designed to operate under steady state conditions. The fluctuation in power may cause start and stop cycles of the system, which can damage electrode materials, decrease durability, and increase maintenance costs for electrolysers, meaning system designs must be adapted to avoid this. It has been suggested that increasing the number of stacks and splitting the power between them could maximize safe and stable hydrogen production [13]. Integrating the system with the grid, an energy-storage system or hybridization with another renewable energy source could also be implemented to support this.

2.3 Electrolysers and waste heat

Since the electrolysis process is not 100% efficient, waste heat is produced as a by-product during the process (both PEM and alkaline), and to keep the system temperature stable the heat is dissipated by either dry or water coolers. In studies so far, the utilisation of this electrolyser waste heat has been largely overlooked, likely due to its relatively low temperature (50-80°C). It could however be utilised to power low temperature MED [10].

The major reason why membrane desalination is preferred over thermal desalination is the energy consumption, where a conventional MED desalination system requires between 14.45-21.35 kWh to produce 1 m^3 of freshwater from seawater, depending on system design. Meanwhile RO systems require only 2-4 kWh for 1 m^3 of freshwater from seawater. For RO systems the consumption depends both on system design as well as salinity, where a higher salinity content in the seawater requires more energy [14]. However, if waste heat from the electrolyser stack could be utilised for thermal evaporation, its energy demand would drastically decrease.

According to a report by the International Renewable Energy Agency (IRENA) the system efficiency of a typical alkaline electrolyser is between 50-78 kWh/kg H_2 and for a typical PEM electrolyser 50-83 kWh/kg H_2 [9]. Meaning that if 20-40% of the energy used is waste heat [5] there is for an alkaline system 10-31.2 kWh and for a PEM system 10-33.2 kWh heat available per kg produced H_2. It is worth noting that stack efficiency changes over time, and an electrolyse system will produce more waste heat over time as the system degrades [10]. Furthermore, the system operates at high stack temperatures (>75 °C), much of the produced heat might be lost through the product streams - water vapour - meaning that lower temperatures are preferred [10].

2.4 Desalination techniques

All hydrogen production technologies require water as an input, not only for production but also for cooling. In 2023, 2.2 billion m^3 of freshwater was used for hydrogen production, which accounted for 0.6% of the energy sectors total freshwater withdrawal that year and with an increase in global hydrogen production, the water demand is could more than triple by 2040. Due to this, it is important that the water for hydrogen production is obtained sustainably [2].

According to the International renewable energy agency more than 35% of all hydrogen productions, both in operation and planned, are located in water stressed areas and even if hydrogen production would only represent a fraction of the total freshwater consumption of all industries globally, it may still results in significant local water demands [2]. By instead using desalinated seawater as a feed source for the hydrogen production, green hydrogen plants could be built in areas that have low or no access to freshwater.

To achieve desired water purity for the electrolysis feedwater two main categories of desalination methods are currently commercialised, membrane, and thermal technologies. Membrane technologies currently hold a large majority of the market, with RO being the most common membrane desalination technique.

2.4.1 Multi-effect distillation (MED) desalination

Thermal distillation is a physical separation process driven by thermal energy and a difference in volatility between components. By adding thermal energy to a liquid solution, the more volatile components in the solution will evaporate and separate from other less volatile components. In seawater desalination thermal distillation is used to evaporate the water, while impurities and dissolved solids remain in a liquid state and will be discharged as a brine. Cooling water is used to condensate the then pure water vapour into a liquid distillate. Although this process can produce water purity sufficient for drinking water standards, some impurities may evaporate with the water and further purification might be necessary to produce feedwater with a purity sufficient for electrolysis [14].

There are different kinds of thermal desalination technologies available on the market, with multi-stage flash desalination (MSF) and multi-effect distillation (MED) and vapour compression distillation being the most common ones [14]. The Alfa Laval system investigated in this study is based on MED, therefore the review will focus on MED desalination.

Multi-effect distillation (MED) systems are designed with multiple effects, where each stage essentially reuses the energy from the previous stage, with successively lower pressures and temperatures after each effect. Thermal power is supplied by an external source for the first effect, which heats up and evaporates the inlet feed. This vapour is then used as the energy source for the second effect, and condensates into pure distillate once the heat has been transferred. The vapour from the second stage then continues to the third to evaporate the feed there, and so it continues in order across the subsequent effects. There are many different configurations of multi-effect distillation, depending on external heat source, vapour flow direction, design arrangements of the tubes etc. [14].

2.4.2 Reverse osmosis (RO) desalination

Osmosis can be described as the spontaneous movement of water across a semipermeable membrane from a region of low solute concentration to a region of high solute concentration. The semipermeable character of the membrane allows water to pass through but not the solutes, and the migration continues until a state of osmotic equilibrium is reached and the chemical potentials across the membrane are equal. This reaction occurs naturally, but when external pressure is applied it can be stopped or even reversed. The flow of the water molecules will reverse if the applied external pressure is greater than the osmotic pressure across the membrane. This process is then called reverse osmosis (RO) and can be used to separate water and solutes, creating a pure permeate water stream. [15]

Despite only being commercialised 50 years ago, reverse osmosis has gone through several optimizations to become a well-developed technology for desalination [15]. Due to low energy demand and high reliability, RO has replaced thermal desalination methods and in 2013 65% of installed worldwide desalination technology was RO [16], and in 2019 the number had increased to 80% [17].

A RO desalination system has four subsystems, as illustrated in Figure 2: A pre-treatment section, a high-pressure pump with energy recovery (turbine), a membrane and finally a post-treatment section.

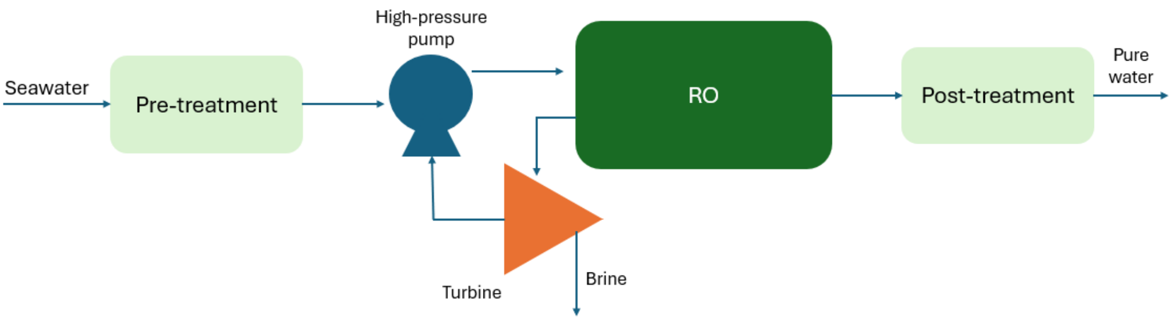

Figure 2: Illustrating an overview of a general RO system, adapted from Okampo and Nwulu [14].

Figure 2 shows a typical RO system, but the concept can be optimised to match specific permeate qualities. The terms “stage” and “pass” are introduced to explain different RO configurations, where a system can be configured in single or multiple stages, single or multiple passes, or a combination of both. In a multiple stage system, the concentrate exiting the first RO stage then continues on to be treated in another RO stage, producing a larger quantity of total permeate. In multiple pass RO, the permeate from the first pass continues to be treated in another RO pass, producing a higher quality permeate. The addition of a second pass increases the rejection of solutes and it used for the pure of ultrapure water, e.g. water for injections in the pharmaceutical industry.

2.5 Pre- and post-treatment in desalination systems

Pre-treatment is considered a critical step for both RO and MED desalination. In MED fouling creates heat losses on evaporation surfaces and requires cleaning. And in RO desalination, scaling it has a direct effect on membrane fouling and operation. Fouled membranes lead to lower membrane lifetime, as well as increased operating and maintenance costs due to cleaning, and the feed pressure must be increased to maintain water flux. The selection pre-treatment process is not always straightforward, as it depends on several factors such as feed water quality, facility footprint, desired permeate quality, scale, costs etc. [18]. However, most systems tend to include physical pre-treatment step with pre-screening and sedimentation to remove larger impurities. The physical pre-treatment is then followed by one or multiple more pre-treatment steps, including coagulation-flocculation, media filtration, dissolved air flotation (DAF), acidification, hardness removal, scale inhibition or disinfection. There are also membrane-based pre-treatments technologies, which include microfiltration (MF), ultrafiltration (UF) and nanofiltration (NF). MF, UF and coagulation-flocculation are considered as the most widely used pre-treatment techniques, and normally combination of pretreatments is utilized [15] [17].

Both MED and RO desalination systems might also need post-treatment, to improve purity or remove any impurities that electrolysers might be particularly sensitive to. This could include e.g. a final polishing step to remove ions, or additional disinfection to prevent microbial growth.

2.5.1 Coagulation-flocculation

Coagulation-flocculation is a pre-treatment technique that removes particles that with low molecular weight which cannot be removed with gravitation in the initial sedimentation step. These particles include colloidal foulants, organic matters and other aqueous particulates. Coagulating chemicals are added to the feedwater to aid sedimentation. Examples of coagulating agents include aluminium sulphate, powdered activated carbon, ferric sulphate, ferric chloride, cationic polyacrylamide, and poly-aluminium chloride. For seawater coagulation, ferric coagulants are preferred as aluminium coagulants are too soluble in seawater and would carry over to the RO membrane and create scaling [19]. Once coagulated, a slow mixing of the water forms chemical-impurity flocs, that then can be removed through sedimentation, flotation, or filtration. [15]

2.5.2 Media filtration

Media filtration is also used to remove suspended impurities, as coagulation-flocculation often fails to remove 100% of these. It can sometimes also be used to remove the flocs created during coagulation-flocculation In this pre-treatment, impurities are removed by passing feed water through a filter bed, where impurities are absorbed onto the surface of filter media grains and trapped in pores. The water continues through the media without being absorbed and is separated from the previously suspended impurities. Different types of granular media can be used for conventional packed-bed filters, including gravel, sand, diatomaceous earth, sponge, cotton, activated carbon (AC) or anthracite. These filter media have the advantage of being able to be regenerated through hydraulic backwashing. Often more than one type of medium is used, this is then called dual media filtration (DMF), e.g. a sand layer covered by a thinner anthracite layer. By using DMF soluble organics removal can be increased. If chlorination is used as a pretreatment step, AC can be used in a media filtration step to remove free chlorine, which otherwise could damage the RO membrane. Granular media filtration, single or dual, is a popular conventional pretreatment in large scale seawater RO plants due to low costs. [17]

2.5.3 Dissolved air flotation (DAF)

DAF is presented as an alternative to conventional sedimentation, where instead of utilizing gravity to separate hydrophobic suspended particles pressurized air is introduced to create air bubbles, which assist in the particle removal. The idea is that the air bubbles adhere to the suspended matter, causing it to float to the surface of the water where it can be removed with some kind of skimming device. DAF has shown an increased ability to remove natural organic matter (NOM) in comparison to conventional sedimentation, with 90-99% algal cell removal with DAF in comparison to 60-90% for sedimentation. This is important as algae can lead to clogging of granular media filters and are difficult to remove with conventional sedimentation. [17]

2.5.4 Disinfection

Disinfection is a critical pre-treatment step to remove microorganisms responsible for biological fouling, where a buildup of microbes on the membrane or heat exchanger surface results in the formation of a biofilm. The biofilm severely deteriorates membrane performance in RO systems, both in terms of selectivity and permeate flow, and biological fouling is estimated to contribute to > 45% of all membrane fouling [17]. There are several disinfection techniques currently used for pre-treatment, mainly chlorination, ultraviolet irradiation, ozonation, ultrasound and potassium permanganate dosing. Chlorination is the most widely used disinfectant technique, where chlorine is dosed into the water, and reacts to form hypochlorous and hydrochloric acids that destroy the microorganisms [15]. The most common RO membranes for electrolysis feedwater do exhibit sensitivity to free chlorine, as the chlorine exposure alters the physiochemical properties and deteriorates performance of membranes through oxidative reactions [20]. To avoid this, either dichlorination technology needs to be used, such as activated carbon pre-filters [20], or alternative disinfection technologies must be investigated. Chlorine in contact with organic matter does also form various disinfection by-products (DBPs) e.g. trihalomethanes (THMs), haloacetic acids (HAAs) and haloacetonitriles (HANs) [21]. The type of DBPs formed depends on several factors, including type and amount on disinfectant used, the organic and inorganic components in the water, contact time, temperature, and pH, and many of them cause issues with toxicity [21].

Alternative disinfection technologies to chlorination include ultraviolet (UV) irradiation, ozonation and ultrasound treatment. UV treatment is the most alternative method, and also a non-chemical disinfection method. In UV treatment the water is exposed to UV radiation which denatures microbial DNA, inhibiting microbial activity [22].

Ozonation of water produces hydroxyl radicals (OH^-), which can increase biodegradability of dissolved organic matter (DOM). It can also remove iron and manganese from water, forming a precipitate that can be filtered. Although DBPs are formed during ozonation they are generally less toxic than the DBPs from chlorination, the technology does however suffer from higher costs than chlorination [17].

Ultrasound treatment can be used to break down bacterial clusters in water, by creating high frequency waves that travel through the water, causing waves. These pressure waves are alternated to create bubbles, that grow and then implode. Due to pressure and temperature buildup in the bubbles, they release a large amount of energy once imploding. These shocks can break organic matter, preventing further microbial growth. Ultrasonic treatment can also reduce turbidity in water [23].

2.5.5 Scale inhibitors

To avoid scale growth, scale inhibitors such as polyacrylates, organophosphonates, and sodium hexametaphosphate can be used [15]. Also, barium sulphate, silicates and calcium carbonate are commonly used [17]. Scale inhibitors reduce inorganic fouling by modifying the physical and chemicals characteristics of the fouling ions to prevent them from precipitating on the membrane/evaporator surface. [17]

2.5.6 MF, UF and NF

MF, UF and NF are membrane-based pre-treatment techniques. These membrane filters have a larger pore size than RO membranes, and by running the feedwater through one of these before RO, the feedwater quality is improved. All three membrane processes provide numerous advantages over conventional pre-treatment techniques, including but not limited to flux, chemical costs, operating costs, and water quality. These however come with the compromise of higher energy requirements and capital costs than conventional methods, although the costs can be substantially reduced with advances in technology development. Similarly with RO membranes, MF, UF and NF membranes are also sensitive to highly turbid feed waters, which can cause fouling issues, and conventional pre-treatments might be preferred in such cases. Hybrid systems with both conventional and non-conventional are also an alternative, where e.g. coagulation, chlorination and DAF could be used as initial pre-treatment, before a MF unit. [15]

2.5.7 Electrodeionization (EDI)

Electrodeionization is a water treatment technology often used as post-treatment following a RO step. It is a self-regenerating, chemical-free technology, that employs direct current (DC) to remove dissolved ionizable components, such as acids, bases, and salts. It can also remove weakly ionizable components such as dissolved silica and carbon dioxide (CO_2). The technology utilizes ion exchange membranes for the separation of negatively and positively charged components from the water, and ion exchange resin to act as the medium for the ion transport. The EDI unit regenerates itself continuously by creating H^+ and OH^- ions through electrolysis, power supplied with the DC, which removes the need to dose any chemical regenerants. [24]

2.6 The Alfa Laval System

The Alfa Laval HyDuo is a thermal evaporation MED system designed to supply an electrolysis system with two processes at the same time: Water purification and electrolysis cooling. The principle behind the technology is to use the waste heat produced by the electrolyser to evaporate sea- brackish- or river water. The evaporated vapour can then be cooled and used as a feedwater for the electrolysis. By combining the two processes, energy can be saved on both heating and cooling. And due to the robustness of a thermal evaporation system in comparison to membrane desalination, less chemicals could be used during the process. The HyDuo system utilises Alfa Laval plate heat exchangers for the evaporation, which ensure a higher thermal efficiency and also take up less space than the conventional tubular heat exchangers [5].

A general flowsheet of the planned HyDuo/Electrolyser system can be seen in Figure 3. Much like RO, it might be necessary to add pre- and post-treatment to reach desired water purity. It has been theorised that both disinfection and EDI might be necessary.

Figure 3: General overview on an Alfa Laval HyDuo/Electrolyser combined system.

2.7 Cost calculations

The cost of each distillation system can be split into two categories, capital expenses (CAPEX) and operational expenses (OPEX). CAPEX are the major long-term expenses, including physical assets such as infrastructure, equipment, or machinery. OPEX are the variable day-to-day costs, such as employees' salaries, electricity costs, chemical costs, or repair costs.

3 Materials and methods

Two different systems were designed to represent the three different investigated desalination technologies: RO, and the Alfa Laval MED system HyDuo. Both systems included complete pre-and post-treatment necessary to achieve desired water quality. Then they were compared based on several different characteristics including CAPEX, OPEX, energy demand, use of chemicals and overall impact on environment.

3.1 Desalination system designs

It should be considered that there are many different ways to design both of these systems, and the designs used in this report were created based on a combination of the literature review and testing, as well as industrial expertise.

3.1.1 MED system design - HyDuo

In order to understand what kind of pre- and post-treatment would be necessary for the HyDuo system to reach required water purity, water impurities of concern were investigated. Data from different Alfa Laval pilot tests conducted before this study were summarized, and compared to water purification demands for different electrolyser suppliers. Based on whether the HyDuo reached required removal efficiency of specific impurities, conclusions could be drawn on whether, and if so which kind of, pre- or post-treatment would be required.

3.1.2 Reverse osmosis system design

Being the dominating desalination technology on the current market, there were many alternative ways to design a RO system for desalination, particularly regarding the different pre- and post-treatment techniques. Available data was considered, and a complete desalination system was designed. Pre- and post-treatment technologies were selected with the purpose of keeping chemical usage low and ensuring high quality of permeate.

3.2 Comparison between MED and RO

The two different desalination technologies were compared to one another based on a number of different characteristics, where the main areas of interest are detailed in the following subsections.

3.2.1 Energy demand

The energy demand plays a important role in not only cost, but also stability of each system. Since renewable energy sources are required for the hydrogen production to be considered green, issues with intermittent electricity supply will emerge. The energy demand for each step in the desalination systems was investigated, along with the possible requirement of intermediate energy storage for a stable electricity supply.

3.2.2 Chemicals and environmental impact

Using chemicals in desalination techniques, although undesirable, is inevitable. Whether it is for anti-scaling, disinfection, coagulation-flocculation, or other treatment. Complete chemical usage for each desalination system was investigated, along with cost and toxicity of each agent.

Most chemicals used in the system will end up in the concentrated brine by-product produced in the RO or in MED. The impact of this brine on the environment was also investigated.

3.2.3 CAPEX and OPEX

The compiled data used to estimate CAPEX and OPEX was gathered either through the literature review as part of this study, or through industrial suppliers. The sections below details which parameters were investigated to create the CAPEX and OPEX models for both desalination techniques.

All key parameters identified are listed in Table 2. The cost model was based on a template previously utilised by Alfa Laval for MED and RO comparison, but now updated with new data.

Table 2: All parameters used to create CAPEX and OPEX models for the desalination systems.

Desalination CAPEX	**Desalination OPEX**
Desalination equipment	Thermal energy
Pre-treatment equipment	Electrical energy
Post-treatment equipment	Chemical costs
Cooling	Maintenance costs
Installation	Equipment replacement costs
Commissioning	
Testing	
Training	

4 Results and Discussion

Based on the conducted literature review, pilot tests results and industrial expertise, two different seawater desalination systems for were designed, as seen below.

4.1 MED system design – Alfa Laval HyDuo

Designing the Alfa Laval MED system several factors were considered. Firstly, the conducted literature review, where pre- and post-treatment technologies typically used for RO systems were now considered, to see which might be required for the MED system. Secondly, test results of the outlet water from the HyDuo pilot tests were compared to electrolyser inlet demands. By comparing these, conclusions can be drawn on which impurities did not reach the electrolyser inlet demands, and therefore needed further removal.

Based on the results from this investigation, it was determined that the Alfa Laval HyDuo would require pre-treatment with chlorination to remove microorganisms, as well as post-treatment with an EDI unit as an additional polishing step. Initial pre-screening for larger debris would also be used. An overview of the process flow sheet can be seen in Figure 4 .

Figure 4: Flow sheet of the desalination process, using Alfa Laval's MED unit HyDuo, including necessary pre- and post-treatment.

Two different pilot tests were conducted, in 2022 and 2023 respectively. During the 2022 test there was also an EDI added after the HyDuo, to investigate its potential when paired with the HyDuo unit. An simplified overview of this data can be found below, in Table 3.

Table 3: Common parameters for measuring water quality for electrolysers, and if they reach desired levels in the distillation and EDI steps. Green indicates good removal, yellow indicates promising results but more testing is required, and red indicates no test results available to comment.

Parameter	**HyDuo outlet**	**EDI outlet**
Aluminium		
Boron		
Calcium		
Conductivity		

Copper		
Carbonate $CO3^{2-}$		
Carbon dioxide		
Chlorine		
Chloride		
Iron		
Magnesium		
Potassium		
Silica SiO_2		
Sulphate SO_4^{2-}		
Sodium		
TOC		
Total nitrogen		

Table 3 shows for some of the most common impurities in a desalination process if purification is sufficient to meet requirements for the next unit in the desalination process, with some of the most common impurities. First, if the HyDuo removes enough impurities to reach the inlet demands for the EDI unit. And secondly, if the following EDI unit purifies the water enough the reach inlet demands for an electrolyser. Green indicates good results. Yellow indicates that there isn’t enough data to for certain say that removal is sufficient, but based on supplier information and the conducted literature study it is assumed that sufficient removal can be reached, and pilot tests need to be done to confirm this. Red indicates no data available to base any assumptions on. There were no indications of impurities that for certain would not reach the required levels, which is very promising for this system design. However, there were a few measurements with some uncertainty, these are discussed below.

4.1.1 Further testing with EDI

Aluminium, magnesium, sodium, carbonate, silica, and total nitrogen are all expected to reach the required removal for the electrolyser inlet demands, based on EDI supplier’s expectations, but since none of these compounds were tested for at the EDI outlet during the pilot tests, it cannot be said for certain until this is done.

4.1.2 Conductivity

Conductivity measurement showed contradicting results during the pilot test in 2022. The reason being that the conductivity at the HyDuo outlet was very promising at 2.6 µS/cm, as it was well below the EDI inlet demand of 40 µS/cm. However, once the water exited the EDI, the conductivity did not reach the expected level of the supplier, 0.056 µS/cm, but only 0.736

µS/cm. This result would then be too high for the electrolyser inlet demands, which ranges in 0.1-0.5 µS/cm. It was concluded that the higher conductivity was likely a result of copper contamination from the system's piping. More testing is required with different piping to ensure no contamination, to be able to confirm that the expected conductivity levels can be reached.

4.1.3 Total organic carbon (TOC)

TOC measurements after the HyDuo outlet showed a concentration of 0.3 mg/l. The investigated EDI suppliers have TOC inlet demands of 0.2-0.5 mg/l, and investigated electrolyser suppliers have inlet demands of 0.2-1.0 mg/l. With these measurements in mind, it is entirely possible to select EDI and electrolyser suppliers accordingly, to ensure that inlet demands are met. The main issue with TOC is that EDI units do not remove TOC from the water meaning that the TOC level exiting HyDuo needs to be low enough to meet the electrolyser inlet demands without any further removal. As the permitted ranges are narrow, and this discussion is based only on the tests results from the 2023 pilot test (TOC was not tested in the 2022 pilot tests), further testing should be conducted to confirm whether the TOC levels will be within the permitted range or not.

TOC levels in seawater are typically in the range of 2-5 mg/L but can be higher in case of algae bloom or when affected by humic matter from rivers [19]. In the 2023 pilot tests the TOC before the HyDuo was not measured so it is difficult to know unit's TOC removal capacity, and in future tests TOC should be measured both before and after the MED. It should also be noted here that no chlorination was used during the pilot tests, meaning that the TOC levels could decrease once this is added.

If not, it might be worth investigating the need to add additional treatment to further remove TOC. TOC removal is done through disinfection, but since electrolyers exhibit sensitivity to chlorine it is unsolicited to use the most common disinfection method (chlorination) this late in the desalination process. Instead, it could be suggested that another disinfection method should be used, such as UV treatment. This would however add significant costs to the treatment process, and more testing is required to confirm if this addition is necessary or not.

4.1.4 Carbon dioxide (CO_2)

Another contaminant that should be subjected to further testing is CO_2. It may appear counterintuitive that CO2 removal, as shown in Table 3, achieves desired levels in both the HyDuo and EDI systems. The reason for additional testing is the possible CO_2 contamination from air. In a completely continuous, well isolated system, the risk of CO_2 contamination is low, as the pure water has little contact time with air once the desalination has started. If a system however requires storage tanks between different desalination steps or required a storage tank between the finished desalination system and the start of the electrolysis system, CO_2 contamination might occur. Based on the pilot tests in 2023, the CO_2 levels out of the HyDuo reached inlet demands of the subsequent EDI and according to the electrolyser supplier for the EDI, the CO_2 removal for their unit is > 99%, which should put the CO_2 concentrations well below the electrolyser inlet demands. Meaning that even if some contamination did occur, the CO_2 concentration might still be within the permitted range. To ensure this, CO_2 levels need to be tested not only on a pilot scale, but in complete a system including possible storage tanks and any other points where the water might come in contact with air. If CO_2 contamination is defined to be significant, solutions to either isolate the pure water or filter out CO_2 should be investigated.

4.1.5 Chlorine

The membranes in EDI units are sensitive to free chlorine [25] which is therefore included as one of the key parameters in Table 3. However, during the pilot tests in 2022 and 2023 no chlorine dosing was used for disinfection, and no data is available on chlorine levels in the water. Only chloride, which is readily available in seawater, was measured. Subsequently, the HyDuo's ability to remove free chlorine and its disinfection byproducts is unknown.

It is entirely possible that the HyDuo could remove the disinfection byproducts sufficiently, but due to the lack of available test data no statements on this can be made in this report. However, if the HyDuo does not remove these components sufficiently, some additional pre-treatment might be required, e.g. dichlorination after the chlorine dosing or replacing the chlorination with another kind of disinfection technique, e.g. UV treatment. However, it should be noted that the high salinity of seawater has a slightly obstructing quality on the UV treatment [26], and higher intensity UV radiation as well as more frequent cleaning might be necessary to compensate for the salinity. There are however limited studies on using large-scale UV treatment for seawater, so testing is required to determine whether UV could replace chlorination in this case.

4.2 Reverse osmosis system design

A RO desalination system design was investigated and selected based on the conducted literature study. The design included a pre-screening for larger debris, followed by coagulation-flocculation to remove microorganisms and suspended solids. Followed by UF, RO and an EDI unit. The selection of a membrane pretreatment also minimized chemical demand in comparison to other conventional pre-treatment methods. An overview of the process flow sheet can be seen in Figure 5.

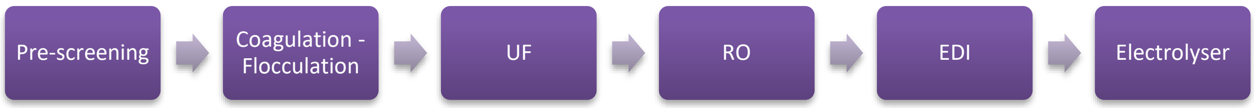

Figure 5: Flow sheet of a desalination process using RO as the main technology, including pre- and post-treatment.

Coagulation-flocculation was selected as the second step of the RO pre-treatment, due to being a well-established technology and having low capital costs. UF was selected to follow the coagulation-flocculation, with the idea that a UF membrane would produce a high quality permeate with lower chemical consumption than conventional alternatives and remove enough microorganisms to avoid the need for disinfection through chlorine dosing. Similarly to the MED system, an EDI was added as a final polishing step. It was deemed that s single-pass RO should be enough to reach desired water quality. The electrolyser also requires cooling, and although not depicted in this flow sheet either seawater cooling or a cooling tower will also be required.

4.3 Comparison of chemical usage in RO vs MED

One of the main reasons why MED might be an interesting competitor to RO is the possibility of lowering chemical usage, as conventional RO desalination and its pre-treatment technologies tend to require more chemicals. However, the selected RO system seen in Figure 5 requires relatively low chemical dosage in comparison to more conventional RO systems, mainly thanks to the UF step. Chemicals are only required for cleaning, for the coagulation-flocculation step, for anti-scaling, and for disinfectant for the cooling tower. The HyDuo system only needs chemicals for anti-scaling and disinfection.

4.3.1 Comparison of chemical requirements

The chemicals used in the RO and the MED systems can be seen Table 4.

4.3.1.1 Acid and alkaline cleaning in the RO system

Both the UF and the RO membrane require chemical cleaning to avoid performance deterioration. The available commercial cleaning agents are often a mixture of different compounds and proprietary, meaning the exact composition is unknown to the public domain. However, for this system the UF membranes requires some kind of alkaline cleaning, and the RO membrane some kind of acid cleaning. The cleaning frequently of the membranes varies from case-to-case, and depends on a number of factors such as feedwater composition, membrane material, temperature, pH etc. Common alkaline cleaning agents for UF include sodium hydroxide (NaOH) and sodium hypochlorite (NaOCl). Acidic cleaning agents frequently used for RO include nitric acid (HNO_3) and citric acid. Due to the large variation in required chemical dosing, this study makes no attempt to estimate concentration and cost of these cleaning chemicals, but their presence is mentioned regardless [27] [28].

4.3.1.2 Coagulant in the RO system

Ferric chloride was selected as the coagulant in the coagulation-flocculation step before the RO system, as it is the most commonly used one for seawater coagulation [19]. It is normally dosed at 1-10 mg/L depending on the raw water characteristics, pH of the coagulation and whether a strong acid will be used after to adjust the pH of the coagulation [19]. For this study, ferric chloride dosing is estimated to be 3 mg/L, which when dosed as ferric chloride hexahydrate is 5 mg/L.

4.3.1.3 Disinfection in cooling towers

The HyDuo system powers its distillation by using the excess heat from the electrolysers. As this also provides cooling for the electrolysers, the HyDuo system will not require any external cooling tower. The RO system will however need this, to avoid overheating electrolysers. Calculations for disinfection requirements were based on available data from cooling towers in other Alfa Laval systems, which normally dosed inline with 0.3 ppm FAC (free available chlorine), with one day off per week. This results in an average dosing of 0.257 ppm FAC. Since pure chlorine is a gas at room temperature, chlorine dosing is done with sodium hypochlorite (NaOCl) dissolved in water instead. With a 12 wt.% NaOCl solution, this results in a dosing of approximately 4.4 mg/L, see **Error! Reference source not found.** for calculation. Since no cooling towers are required for the HyDuo system, only the RO system uses disinfection in this step.

The HyDuo system does however use chlorine dosing before the distillation, as disinfection. This is also dosed as sodium hypochlorite and at the same rate as the cooling tower.

4.3.1.4 Anti-scaling

Anti-scalant is dosed in both the RO and HyDuo systems to avoid scaling, and is assumed to be dosed at the same rate for both systems, at 2 mg/L.

4.3.1.5 pH adjustment

Considering all the dosed chemicals in both the RO and the MED system it is reasonable to assume that some kind of pH adjustment will be required during the processes, to avoid corrosion. However, since the required pH adjustment is entirely dependent on feedwater, temperature, dosed chemicals etc. this study makes no attempt to estimate the required chemicals and dosing, and both systems should be tested before making any assumptions.

Table 4: All the chemicals needed for the RO system in Figure 5, along with which step where they are dosed in and concentration of dose.

RO	**Chemical**	**Dosage (mg/L)**
Before UF	Alkaline cleaning agent	-
Coagulation-flocculation	Ferric chloride hexahydrate	5
Before RO	Acid cleaning agent	-
Before RO	Anti-scalant Alpacon Altreat 400	2
Cooling tower	Sodium hypochlorite NaOCl	4
HyDuo – MED	**Chemical**	**Dosage (mg/L)**
Before HyDuo	Anti-scalant Alpacon Altreat 400	2
Before HyDuo	Sodium hypochlorite NaOCl	4

It should be noted that the dosage of each chemical will vary much depending on the feedwater composition, and seawater composition can heavily vary, depending on location and time of year, especially during heavy algae blooming periods [18].

Overall, both the MED and the RO system require chemicals. In these particular designs, RO requires the additional ferric chloride for the coagulation-flocculation step, as well as additional cleaning for the RO and UF membranes, making its chemical consumption higher than of the MED system. It should however yet again be noted that there are many different ways to design both of these systems. The HyDuo system could for example eliminate its chlorine dosage by utilising an alternative disinfection treatment, e.g. UV treatment or simply utilise another disinfection chemical, with less toxic disinfection by-products than those of chlorine. In this case the anti-scalants would be the only chemicals left to dose in the system.

For the RO system it is more difficult to remove all dosed chemicals, as RO membranes are more sensitive to impurities than the HyDuo is. Meaning that the RO feedwater requires a higher quality, and therefore more pre-treatment before entering the RO unit than the feedwater for the HyDuo would need. Non-conventional pre-treatment methods, such as the UF, appear key to limit chemical dosages in RO systems. Cleaning agents could also be selected with environmental impact in mind, to avoid toxic by-products.

4.4 Cost comparison for RO vs MED

A cost model was created for each system to calculate total investment cost, annual capital cost, annual fixed cost, and annual variable cost. These were then used to calculate total cost for 1 m^3 of desalinated ultrapure water. The results for each system can be seen in Table 5 below, and the full calculation sheet can be seen in Appendix B.

Table 5: Results from cost comparison of the RO and MED systems.

RO system		
Total Investment cost	€	1 308 000
Annual capital cost	€	131 000
Annual fixed costs	€	150 000
Annual variable costs	€	172 000
Total annual cost	€	453 000
Total cost for 1 m^3 of desalinated water	€	2.29
MED System		
Total Investment cost	€	2 054 000
Annual capital cost	€	206 000
Annual fixed costs	€	33 000
Annual variable costs	€	77 000
Total annual cost	€	316 000
Total cost for 1 m^3 of desalinated water	€	1.59

The RO system costs were calculated twice, with cooling towers and with sea cooling. Due to the lower capital costs of the system with seawater cooling, it is presented in Table 5. As seen in Table 5, although the MED – HyDuo system has a significantly higher investment cost, the total annual cost is lower than the RO system. This results mainly from a difference in robustness. The RO system is assumed to require more frequent maintenance and spare part replacement, due to the shorter life cycle of the RO membrane. The HyDuo unit is less sensitive to contaminants, and therefore the operational costs are lower. The chemical and electricity requirement is also higher for the RO system, further contributing to the higher total annual cost.

It should however also be mentioned that depending on RO system design, the costs can be lowered, e.g. the UF system selected for pre-treatment has both a high investment costs and adds to the RO system's electricity consumption. If replaced with a conventional filtering technology, costs would decrease. This would however come at the environmental expense of chemical additions, as conventional RO pre-treatment technologies have a higher chemical consumption than an UF unit [15].

4.4.1 Assumptions in the cost model

Certain assumptions have been made for the cost calculation models. All parameters used for the calculations, and their estimated values, are found in Appendix B.

For the cost calculation no infrastructure costs were included, as they are considered to be similar for MED and RO and not necessary for this comparison. Consequently, costs for piping and pumps, as well as storage tanks for the water are excluded. However, it should be noted that pumps in particular are costly for such large-scale water treatment and should be included in future work to improve cost model accuracy.

Brine treatment is also not considered in the cost model but would in reality add both significant capital and operational costs. The HyDuo system does in comparison to the RO system produce a larger amount of brine, but the brine is also less concentrated than in the RO system. For offshore applications in particular brine treatment is a major concern, as large amounts of brine cannot be left untreated, and there are arguments to be made in favour for each technology. RO might be preferred as it produces less brine, and if the recovery rate could be increased further from the currently estimated 50%, the produced brine volume would be even smaller. This would make brine treatment both easier and less costly. The HyDuo does produce a larger volume of brine, however this brine is also more diluted than the RO system brine. It would be worth investigating whether this more diluted brine maybe can be discarded directly into the sea without further treatment, since it is only slightly concentrated in comparison to seawater and also contains less chemicals than the RO system. This does however have to be further investigated before any assumptions can be made, therefore this study makes no attempt to calculate possible brine treatment costs.

Water required for backwashing (the water pumped backwards through filter media to remove accumulated particles and debris) was also not included in the cost model but would in reality increase the amount of desalinated water the system needs to produce, leading to higher energy and cost requirements.

Another cost that could affect the total system cost substantially, but was not included in this model, was the cost for energy storage and integration. Electrolysers depend on a stable electricity supply and cannot be powered by intermittent renewable energy sources only, such as solar or wind. Meaning the system needs to either be supported by an energy storage system, integrated into the grid, or some kind of hybrid solution. RO units are also dependent on a stable electricity supply, whereas the HyDuo is less sensitive to fluctuations in power. So, if e.g. an offshore system were to be built, that would require an electricity storage system, and the capacity of that storage system would be affected by the selection of desalination technology.

Where a RO system would presumably require larger energy storage than a MED. The calculation for such costs does however remain out of the scope of this study but could be interesting to compare in future work.

5 Conclusions

5.1 Overall technology assessment

Based on the literature review and the data collected from previous pilot tests, the Alfa Laval HyDuo shows promise in reaching the desired water purity levels for electrolysis, once complemented by pre-screening, disinfection, and post-treatment with an EDI. Certain parameters, (including CO_2, TOC, chlorine, and concentration of some ions, as well as conductivity) should be further investigated and confirmed in pilot testing to confirm. Depending on results from these tests, it may be necessary to investigate both alternative disinfection technologies such as UV treatment, and CO_2 filters. If additional pre- or post-treatment technologies need to be added, it will affect the system capital and operational costs.

5.2 Cost comparison

Cost calculations showed a higher investment cost for the HyDuo system than the RO system, but a lower operational cost. These costs will vary depending on system design and should be seen more as an overall comparison rather than exact costs. It should also be noted that with continued development of both RO and MED technology, as well as all their pre- and post-treatment technologies, should have a decreasing effect on investment costs.

5.3 Future work

More pilot tests should be done on the HyDuo system to confirm that no more pre- and post-treatment is required, than what is already seen in Figure 4.

One area that this study did not cover, but should be investigated in future work, is the brine from each system. Both the RO and the HyDuo system produce a concentrated brine as a by-product, and this brine needs to either go to further treatment or discharged into the sea. Since the RO system requires more chemical dosing it is reasonable to assume that the RO brine will contain more chemicals, some of which should not be let out directly into the sea. A complete study on brine concentration, components, their toxicity, and impact on a marine system should be conducted.

Another area of interest is the requirement for energy storage and stable electricity supply. Since both the HyDuo, RO and electrolysis units require a stable electricity supply, some kind of integration with the grid, or energy storage solutions is necessary. How large these storage systems would be depending on system design, and how much these possible solutions might affect system cost should be investigated in future studies.

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7 Appendices

7.1 Appendix A

Calculation sheet for NaOCl dosing

Recomennded FAC dose	0,300	ppm, with one day off / week				
Actual FAC dose average	0,257	ppm = g/m3				
M (Cl)	35,450	g/mol				
n (Cl)	0,007	mol/m3				
n (NaOCl)	0,007	mol/m3				
M (NaOCl)	72,440	g/mol				
m(NaOCl) (pure)	0,525	g/m3				
m (NaOCl) 12 wt%	4,379	g/m3				

7.2 Appendix B

Calculation sheet for cost calculations, done in excel. Due to confidentiality, certain data is redacted in this version.

Alfa Laval Desalination Solutions for Green Hydrogen Production 100 MW

Project Data	MEP
Capacity per day	600 m3/day
Capacity per hour	25,00 m3/h
Capacity per year	198 000 m3/year
Feed water inlet (MEP)	75,00 m3/h
Sea water inlet (RO)	50,00 m3/h
Size of Electrolyser	100 MW

Customer Input			Dosage RO (ppm)	Dosage MEP (ppm)	Cooling Tower (ppm)
Working days per year		330			
FTE cost per hour	€	15,00			
Cost of kWh	€	0,08			
Electrical consumption (RO)		3,30 kW/m3			
Electrical consumption (MEP)		2,53 kW/m3			
Electrical consumption Cooling towe		1,20 kW/m3			
Electrical consumtion UF		0,20 kW/m3			
Cost of hot water (m^3)	€	-			
Coagulant (20%)		0,24 €/Kg	4,999		
Flocculant (37%)		0,00 €/Kg	0		
Sodium Metabisulphite (97%)		1,30 €/Kg	0		
Antiscalant / Scale Inhibitor (68%)		0,60 €/Kg	2	2	2
Biocide (99%)		4,50 €/Kg			1

Capital Investment		MEP		assRO + Cooling To		RO + Sea Cooling
Desalination Equipment				Redacted		
Air Coolers						
Sea Cooling						
Installation						
Comissioning						
Testing						
Training						
EDI						
EDI Installation						
UF						
Filtrex CB-999-350-C						
Total investment Cost	€	2 053 794,00	€	1 779 000,00	€	1 307 800,00
Plant depreciation		10		10		10
Interest rate		5%		5%		5%
Capital recovery factor		0,1003		0,1003		0,1003
Annual Capital Cost	**€**	**205 944,62**	**€**	**178 389,59**	**€**	**131 139,91**
Desalinatedcwater productioncosts per m based on Capital Investmenat	**€**	**1,04**	**€**	**0,90**	**€**	**0,66**

Variable Annual Cost			
	MEP	RO + Cooling Tower	RO + Sea Cooling
Thermal energy(per year)			
Electric energy(per year)			
Antiscalant (per year)			
Floculant (per year)			
Coagulant (per year)		Redacted	
Sodium Metabisulphite (per year)			
Biocide			
Cleaning agents(per year)			
Annual Variable Costs	**€ 76 788,00**	**€ 169 188,22**	**€ 172 158,22**
Desalinated water production costs per m' based on Variable annual	**€ 0,39**	**€ 0,85**	**€ 0,87**

Annual Capital Cost	**€ 205 944,62**	**€ 178 389,59**	**€ 131 139,91**
Annual Fixed Costs	**€ 32 920,00**	**€ 149 800,00**	**€ 149 800,00**
Annual Variable Costs	**€ 76 788,00**	**€ 169 188,22**	**€ 172 158,22**
Total Anual Cost	€ 315 652,62	€ 497 377,82	€ 453 098,14
Cost of one m3 of desalinated water	€ 1,59	€ 2,51	€ 2,29