BEH Supply SIG – Desalination Summary Report

Neptune Energy

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Acronyms and Abbreviations

Acronym / Abbreviation	Description
ATR	Autothermal Reforming
BBL	Balgzand Bacton Line
BCA	Bacton Catchment Area
BEH	Bacton Energy Hub
BGT	Bacton Gas Terminal
CAPEX	Capital Expenditure
CCS	Carbon Capture & Storage
CW	Cooling Water
EC	Electrical Conductivity
ERD	Energy Recovery Device
GOR	Gain Output Ratio
GW	Giga Watt
H_2	Hydrogen
kWh	Kilowatt-Hour
MED	Multi Effect Distillation
MED-TVC	Multi Effect Distillation coupled with Thermal Vapour Compression
MSF	Multi-Stage Flash
MW	Mega-Watt
NTS	National Transmission System
OPEX	Operational Expenditure
PEM	Proton Exchange Membrane or Polymer Electrolyte Membrane
ppm	Parts per million
PW	Product Water
PX	Pressure Exchange
RO	Reverse Osmosis
SIG	Special Interest Group
SMR	Steam Methane Reforming
SNS	Southern North Sea
SSSI	Site of Specific Scientific Interest
SWRO	Seawater Reverse Osmosis
TDS	Total Dissolved Solids
TRL	Technology Readiness Level
TVC	Thermal Vapour Compression
UK	United Kingdom

HOLDS list

HOLD	Section	Description

Executive Summary

The report documents the work of Goal7 on behalf of Neptune Energy for the Bacton Energy Hub (BEH) Hydrogen Supply Special Interest Group (SIG). Outlined is a technology review for seawater desalination to provide the water feedstock for green and blue hydrogen production, for BEH core and build out scenarios.

An initial screening (based on suitability for site, scale, technology readiness level (TRL) and water quality required for electrolysis) identified four suitable technologies:

- Seawater Reverse Osmosis (SWRO)
- Multistage Flash (MSF) Distillation
- Multi Effect Distillation (MED)
- MED with Thermal Vapour Compression (MED-TVC).

A detailed review of each technology was undertaken consisting of process description, utility requirements, consumables, maintenance requirements, energy efficiency and qualitative techno-economic assessment. This review identified SWRO as the most suitable technology due to the following:

- **Cost**: driven primarily by electricity SWRO can be of lower OPEX cost, particularly if low cost electricity is available
- **Footprint**: a compact footprint in comparison to other desalination technologies
- **Water quality**: meets the required quality for post processing feed

As a result SWRO was carried forward as the base case for BEH, site sizes and details were based off this technology.

Next steps and recommendations have been compiled for the desalination scope, primarily these are:

- The desalination technology selection should be reviewed once the blue and green hydrogen technologies have been confirmed to optimise the process and utilise any waste heat
- For the later build out cases it is recommended that the shortlisting is reperformed as currently low TRL technologies may be applicable
- The output of this report should be shared with Anglian Water to allow consideration of a larger scale desalination plant that could service the wider area

1 Introduction

1.1 Background

The UK North Sea Transition Authority (NSTA) has identified the Bacton Catchment Area (BCA) as continuing to play a significant role in the UK's energy future. This area is comprised of the gas fields in the Southern North Sea (SNS), Bacton Gas Terminal (BGT), and adjacent onshore areas where hydrogen might be used or stored. Utilising much of the current infrastructure, natural gas can be used to generate blue hydrogen with the produced carbon dioxide stored in offshore reservoirs. In addition, green hydrogen can be produced using renewable energies such as the nearby offshore wind. BGT has a few key advantages which make it an ideal location for development into a low-carbon hydrogen hub:

- Proximity to large market – five NTS feeders, two interconnectors to Europe
- Substantial storage capacity for CCS
- Available land for development of hydrogen production facilities
- Excellent onshore gas connection to London & South East region
- Access to significant natural gas feedstock
- Access to offshore wind farms for green hydrogen production
- Potential to unlock life extensions for infrastructure for up to a decade

Figure 1-1 shows how BGT could be developed into clean energy hub with a focus on low carbon hydrogen.

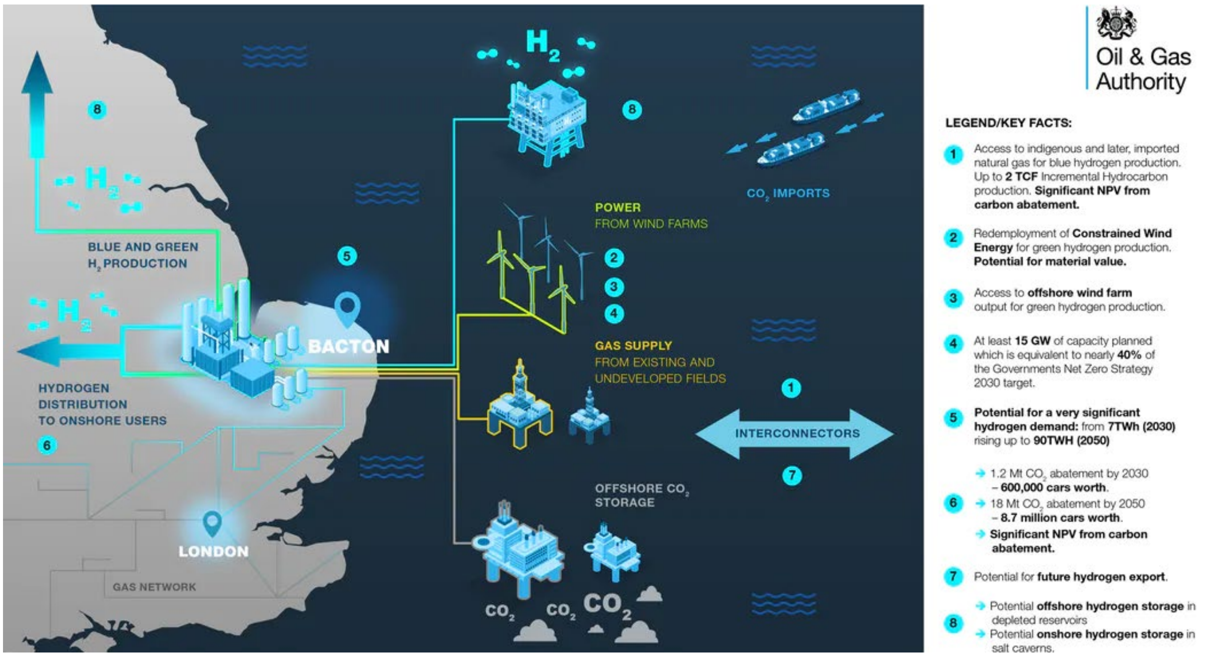

Figure 1-1: Bacton Energy Hub Development Concept [1]

Table 1-1 shows the base case and build out for the Bacton Energy Hub (BEH) development for both blue and green hydrogen production.

Table 1-1: Overview of Blue and Green Hydrogen Production Base Case and Build Out at BEH

	Core Project	Build out	Build out	Build out
Phasing	**2030-2050**	**2030**	**2040**	**2050**
Blue H_2 (SMR/ATR)	1 x 355 MW	3 x 355 MW	3 x 355 MW + 2 x 1.8 GW	2 x 1.8 GW (NB 3 x 355MW retired)
Green H_2 (Electrolyser)	-	-	1 x 2.1 GW	3 x 2.1 GW

1.2 Study Objective and Scope

Figure 1-2 shows the an overview of the proposed system at BEH, this report is focussed on the desalination unit.

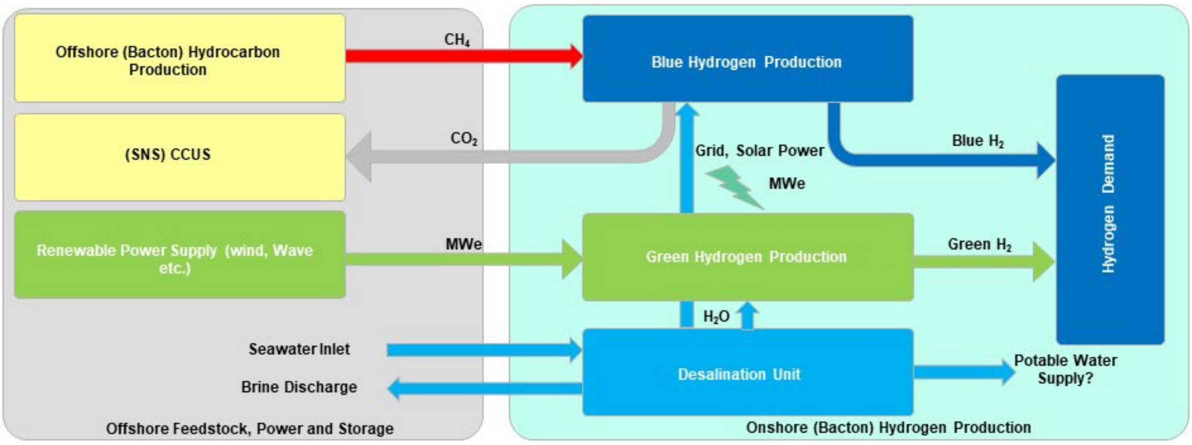

Figure 1-2: System Mapping of Hydrogen Production

The objective of this work was to review technology options and provisional sizing for a desalination plant to provide fresh water to the BEH hydrogen facilities.

This scope included the following activities:

- Reviewing technology options and provisional sizing for desalination plant to provide seawater feedstock to the blue and green hydrogen plants
- Identifying potential locations for the seawater inlet and brine discharge outfall
- Establishing key parameters for the unit – size, location, power requirements, water consumption

1.3 The Need for Desalination and Potential Combined Project

Discussions were held with Anglian Water (Anglian) to establish if a local potable water supply could be provided to negate the need for desalination. It was quickly established that this would not be possible for the following reasons:

- **Constraint:** The UK is running out of fresh water, see Figure 1-3. Considering BEH will need substantial quantities of demineralised water this would put a strain on the current water supply system
- **Licencing restrictions:** Licenses for fresh water are difficult to obtain due to habitat protection and restrictions, especially in the east of England [2]. This affects supply of water long term

In fact, Anglian Water's forecast modelling suggest a new source of water may be needed to meet future demands in this part of the region and desalination is one of the options being considered. There may be the opportunity to jointly develop infrastructure that could support BEH hydrogen production and local potable water needs.

It was agreed to share the outcome of the BEH desalination review to allow synergies to be assessed.

Other key discussion points were as follows:

- **Limitations to current wastewater plant locations:** The possibility of taking existing wastewater plants and moving to a discharge location as an indirect re-use option is limited due to the current environmental regulations
- **Potential process optimisation:** Co-location of the desalination plant and BEH provides opportunities for symbiotic relationships between parties, for example waste heat integration opportunities to maximise efficiency
- **Community value**: addition of a desalination plant to provide water to local community would be a further project benefit to the area
- **Erosion issues:** potential issue was erosional issues around BEH as it's on marine cliffs. As they are 20-30ft this may not be a concern, but still needs further investigation.
- **Discharge concerns:** Brine discharge concerns due to quantity. Potential option to dilute effluent or to use the brine waste product (note this may be limited due to impurities)

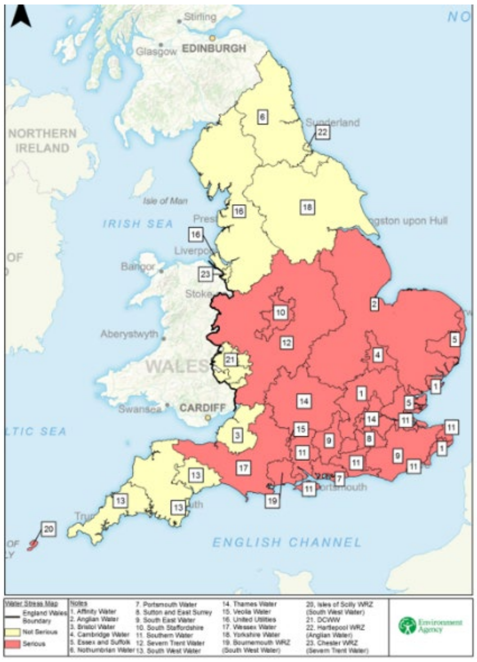

Figure 1-3: Water Stress Areas in England [3]

2 Site Selection

The following section details the site considerations, constraints and requirements in regard to the desalination plant and its intake and outfall pipelines.

The desalination plant will be located at the selected site for the BEH development. This is located on and around the existing BGT and wider BCA (Figure 2-1). There is brownfield land adjacent to the BGT which has the potential to be developed for hydrogen production facilities, as well as the land west of BGT which could hold potential for scale up. The total area of BGT is ~705,500 m^2. The exact location and layout of BEH is covered within the Infrastructure SIG work scope.

2.1 BEH Location Considerations

Along the coastline at Bacton, there are a few constraints to note that could impact the potential location of the desalination plant:

- Highlighted by the turquoise cross-hatch in Figure 2-1 is Site of Specific Scientific Interest (SSSI), which may affect the laying of new pipelines
- The dark blue along the coastline in Figure 2-1 shows 20-30 ft maritime cliffs. Figure 2-2 shows the use of horizontal directional drilling using a vertical shaft and tunnel onshore crossing for the existing Balgzand Bacton Line (BBL) pipeline. This will have to be considered for the intake and outfall systems
- There is a coastal path along the beachfront
- Structural constraints such as listed buildings should be considered, inclusive of the Great Barn – Scheduled monument, UID: 1002884, Paston Great Barn – Grade II, List UID: 1306240 , Church of St Margaret, Grade I Listing, UID: 1373419

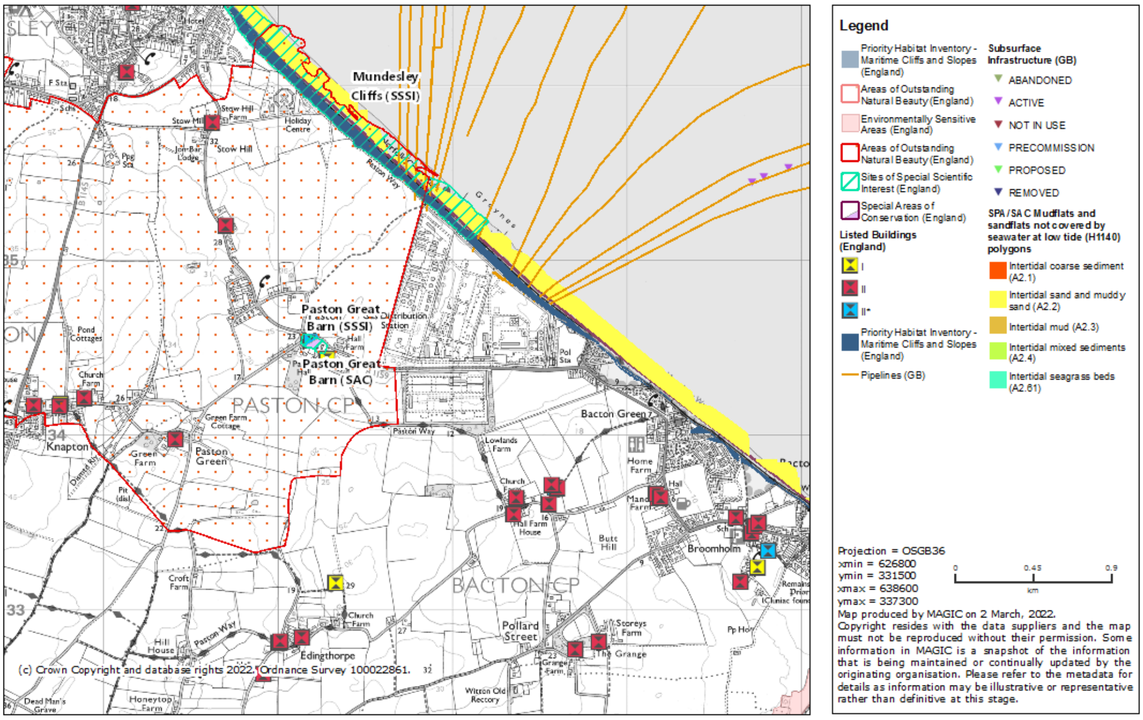

Figure 2-1: BCA wider area overview [4]

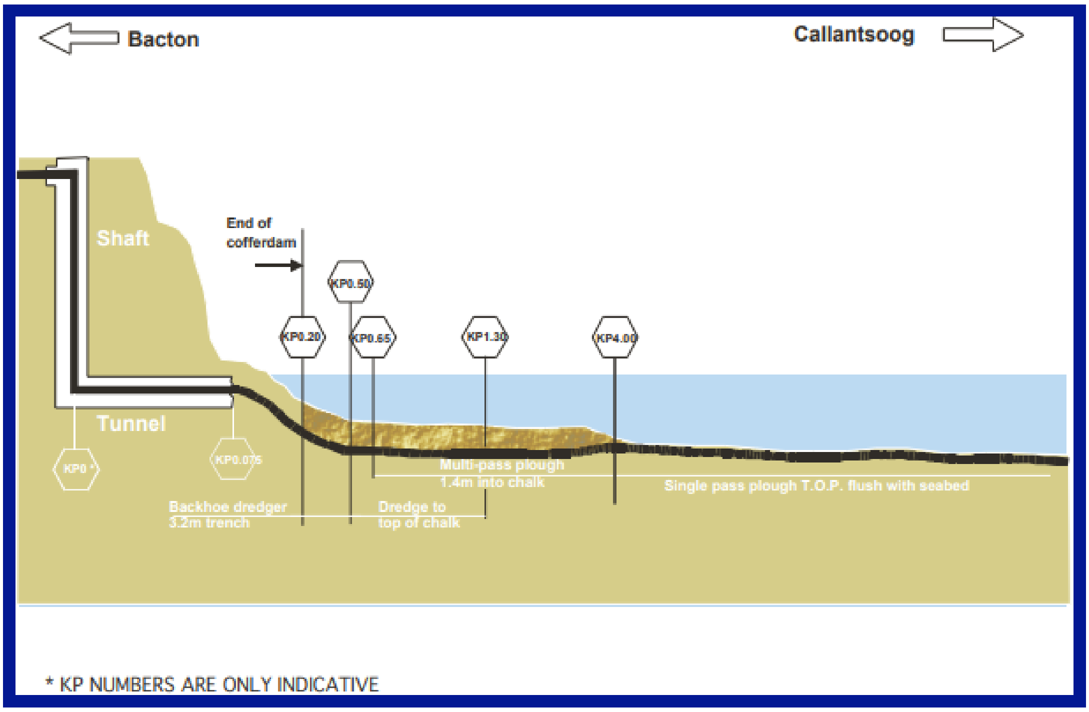

Figure 2-2: Vertical Shaft Bringing the Pipeline Close to the Onshore Gas Plant [5]

2.2 Pipeline Routing

2.2.1 Intake and Outfall

A key component of the desalination plant is the pipeline inlet and outlet for the feedstock and brine disposal. The following sections outline the key considerations for the routing and construction of these pipelines.

2.2.1.1 Key Considerations

The following elements are key considerations for the seawater intake and brine outfall systems:

- **Availability of decommissioned pipelines:** re-use of existing pipelines at BGT could be investigated, alternatively the build of new pipelines would be required for the desalination process. Note if the facility is for public water supply, water supply regulations would prohibit reuse of pipelines
- **Depth of intake structure:** the depth of the intake structure has an impact on the desalination feedwater quality. An intake structure sufficiently from shore with extraction point raised a few metres from seafloor provides a feedwater with less sediment and suspension. This location would also reduce the impact of waves on the structure. It should be noted that Anglian water use a limit of +6m sea depth for the location screening process
- **Location of seawater abstraction and brine outfall points:** should be located a minimum of 500 m apart and 250-500 m from the shore [6]. This varies by site, depending on local coastal conditions such as waves, currents and bathymetry
- **Avoidance of recirculation:** consideration of the abstraction and outfall location as per the above point should mitigate against recirculating the brine from the outfall back through the process via the abstraction point
- **Discharge plume suitability:** salinity concentration of the brine stream from RO plant is typically double that of ambient seawater conditions, the allowable salinity of the diluted effluent plume is 33,000-36,000 ppm [7]

- **Impact of brine density:** the density of the brine discharge in relation to ambient seawater conditions should be taken into consideration in dispersion modelling, Figure 2-3 illustrates the impact of density

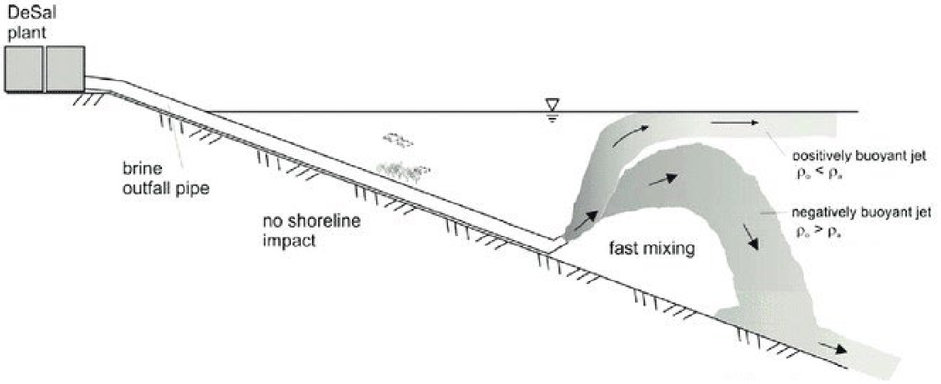

Figure 2-3: Impact of Brine Density on Dispersion of Submerged Discharge [8].

- **Appropriate authorisations:** permits and consents for abstraction and discharge of water must be acquired
- **Relative legislative and water quality guidelines:** the Water Act 2003, Coastal Protection Act 1949 and Water Framework Directive (amended 2014)
- **Interaction with other area users:**
    - **Fishing** – fishing nets block intake screens and discharges can affect aquatic life
    - **Shipping** – consideration of shipping routes, particularly awareness of anchorage locations is important as ship anchors can damage sub-surface structures

- **Existing outfalls:** identification of the location of any existing outfalls is important to be able to determine impact
- **Consideration of areas of significance:** Locate plant intake and outfall away from areas of high biological significance and sensitivity such as coral reefs, kelp/seagrass beds, aquatic animal sanctuaries, water habitat restoration zones and highly productive coastal wetlands

2.2.1.2 Bathymetry

Figure 2-4 shows bathymetry in the marine area adjacent to BEH as well as the existing pipelines. The water depth close to the site ranges from an initial ~ 4.3 m before shelving off to 9.3 m. This change in water depth should be taken into consideration when identifying the route of the pipelines.

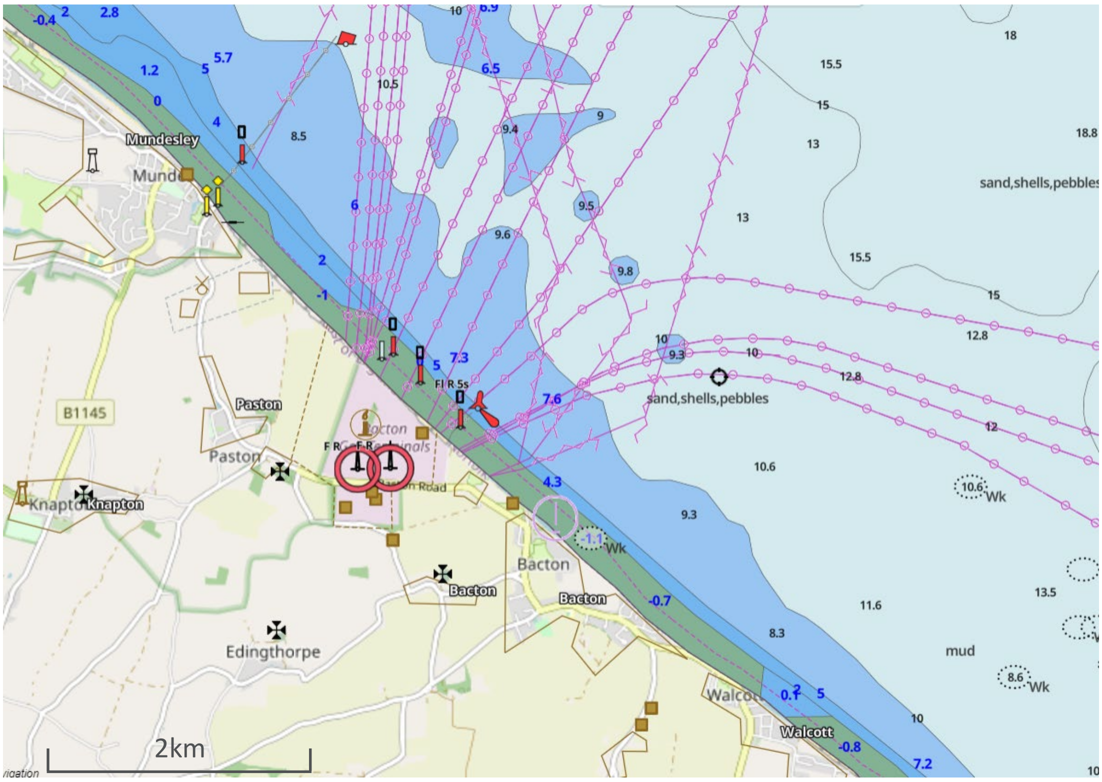

Figure 2-4: Bathymetry at BEH [9]

2.2.1.3 Subsite Components

The pipelines for the desalination plant can be split into several subsite components, Figure 2-5 below provides an overview on these components [10]:

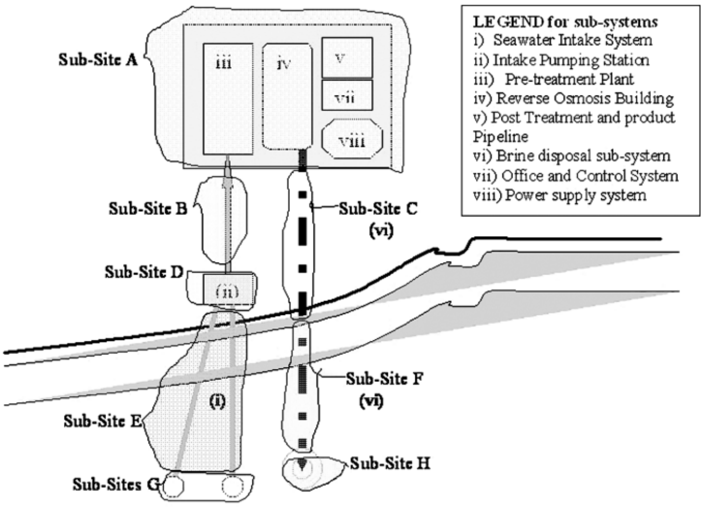

Figure 2-5: Subsite Components on Desalination Pipelines [10]

Detail on sub-site requirements (see Appendix A: Subsite Components):

- Sub-site A: key land components of main desalination facility as detailed in section 2.2.1.1
- Sub-site B & C: land for seawater and brine pipeline installation – suitable for excavation and not in an environmental conservation area

- Sub-site D: land on which the intake pit and pumping station shall be constructed – suitable for excavation and typically close to shoreline
- Sub-site E/F: strip of seabed on which the marine intake/ brine-out pipelines(s) shall be installed – suitable of facilitating installation of pipelines
- Sub-site G: one or more plots at the bottom of the sea, at end of the marine intake pipelines – location is critical to ensure quality of seawater abstracted for desalination.
- Sub-site H: offshore at outer end of submarine brine-out pipeline - location critical to ensure conditions favour mixing to avoid creation of highly saline areas

2.3 Desalination Site Location Requirements

The following criteria should be used to assist during the identification and consideration of an efficient and suitable location for the desalination plant [10], [11]**:**

- **Proximity to saline source:** preferably 1 km to saline water source and location of the brine discharge
- **Distance from other locations:** At least 30 m away from residential dwellings, hotels, hospitals, places of worship and other developments sensitive to increased levels of noise and traffic
- **Electrical supply:** ability to connect to an electrical supply such as grid, site generated or renewable source
- **Heat supply** (technology dependent)**:** access to a heat source such as steam or outlet of cooling system
- **Topography of area:** both land and inshore marine environment must be suitable for the construction of the desalination plant including intake and outfall structures
- **Water supply network** (dependent on Anglian involvement): suitable connection point in the water supply network to export potable water

3 Review

Desalination technologies have been identified and reviewed for the supply of water for green and blue hydrogen production at BEH. This section reviews current and emerging technologies for BEH inclusive of considerations for core and build out cases (2030-2050).

3.1 Introduction

Industrial-scale desalination was first used in the 1930s, spreading around the world by the 1960s [12]. As per Section 1.3 seawater has been chosen as the feedstock to provide the blue and green hydrogen units with desalinated water. Seawater desalination plants make up the majority (61%) of the existing desalination capacity worldwide [13]. The North Sea has an average salinity of 34,000 ppm of total dissolved solids (TDS) [14]. Removing salt from seawater can be achieved by various methods with different resultant properties. Most technologies can be categorised into membrane or thermal processes.

Thermal desalination: evaporates water from the saline solution and condenses it to produce fresh water.

Membrane assisted desalination: relies on the semipermeable character of a membrane and a pressure gradient for salt removal to produce fresh water.

Typical trends in desalination are detailed in Figure 3-1, where a significant increase in Reverse Osmosis (RO) over the past 20 years can be seen.

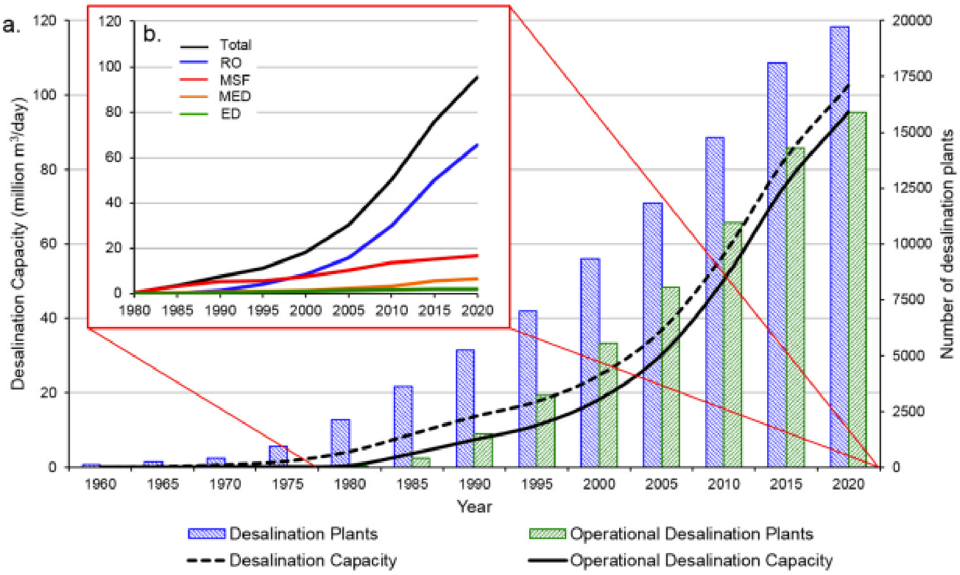

*Figure 3-1: Trends in Global Desalination** [15]

*Line graph shows operational capacity by desalination technology and bar graph shows number of total and operational desalination

A desalination plant typically includes:

- **Seawater intake**: pumps and pipelines to take water from the sea
- **Pre-treatment**: filtration of seawater to remove solid components and the addition of chemicals to reduce scaling, corrosion and foaming
- **Desalination**: fresh water is extracted from salt water
- **Post-treatment** (depending on end use): pH correction, re-mineralisation or further purification such as demineralisation for electrolysis

3.2 Key Criteria for BEH

The following criteria has been identified as important to take into consideration during the technology reviews to ensure that those taken forward are suitable for the needs of BEH.

Water quality: Electrolysers require a high quality of water, the exact specification is dependent on the type of electrolyser chosen, namely Alkaline or PEM. The design of a suitable water treatment plant is necessary for ensuring the supply of demineralised water to the electrolyser system.

Table 3-1: Electrical Conductivity for Feedwater of Electrolyser Technologies [16]

Criteria	Range (μS/cm)	For Design (μS/cm)
Alkaline Electrolyser	1-2	1
PEM Electrolyser	0.1	0.1

As shown in Table 3-1, the required water electrical conductivity for the PEM electrolyser is much stricter than the Alkaline electrolyser. Poor water quality is one of the main reasons for stack failure for PEM electrolysers [17]. Section 4.4 details the post treatment necessary to achieve the required water quality.

Heat recovery and usage: For the design of the green hydrogen facility at BEH, around 500 MW of waste heat will be produced from the 2.1 GW electrolyser. Within the Genesis green hydrogen report it has been assumed for the base case that air cooling will be used [18]. This reduces the water demand on the desalination unit. If cooling water were to be used, it is estimated that it would require around 560 m^3/hr for a 2.1 GW electrolyser [16], [19]. It would have to be designed at a later stage as to how much of this cooling water could be recycled. If cooling water is utilised in the green hydrogen production, it could be used as a heat source to the desalination process if a thermal process is selected.

From the work carried out on the blue hydrogen plant, it is unclear what the cooling water requirement is. An estimated 45 tonnes/hr of water is required for the 350 MW blue hydrogen plant, inclusive of both feedstock and utilities usage. It is therefore unclear what heat could be recovered in a cost effective way for use in the desalination process.

3.3 Initial Screening

Due to specific project requirements of BEH, detailed in Section 1.1 and 3.2, a preliminary screening of technologies was performed to filter out any that do not meet an initial set of criteria.

The initial screening criteria is:

1. **TRL**: the technology needs to be ready for implementation in 2027 (current TRL level 6-9)
2. **Capacity**: the technology needs to be capable of meeting at least the 2030 build out water requirements for BEH
3. **Water quality**: output needs to be higher than that of potable water
4. **Feedstock**: the technology needs to be able to cope with seawater as an input

The technologies in Table 3-2 have been assigned with a Y (yes) or N (no) against the BEH cases to identify if the desalination technologies meet the criteria prescribed above based on publicly available data.

From Table 3-2 any technology currently below TRL level 6 has been assessed as not suitable to be taken forward. This is due to it being unlikely to be ready for deployment in 2027 at the scale required. Technologies that do not take seawater as an input have been screened out due to the currently assumed lack of brackish water in area. This initial screening has left technologies 1-3 and 5 as the potential technologies to take forward in the shortlisting process.

Table 3-2: Initial Screening of Technologies [20]–[23] * Assessment of Technology to Meet Criteria

	Technology	Type of technology	Water Input	TRL Level (current for SW)	Output Water Quality [ppm]	Typical Unit Capacity [m^3/day]	Base Case (1,080 m^3/day) *	2030 (3,240 m^3/day)*	2040 (36,650 m^3/day)*	2050 (78,340 m^3/day)*
1	Multi-Effect Distillation	Evaporation and Condensation	SW	9	10	5,000-15,000/unit Plant: <900,000	Y	Y	Y	Y
2	Multi-Stage Flash	Evaporation and Condensation	SW	9	10	50,000-70,000/unit Plant: <900,000	Y	Y	Y	Y
3	Thermal Vapour Compression	Evaporation and Condensation	SW	9	10	10,000-35,000/unit Plant: <800,000	Y	Y	Y	Y
4	Mechanical Vapour Compression *	Evaporation and Condensation	SW	9	10	<4,000/unit	Y	Y	N	N
5	Salt water Reverse Osmosis	Filtration	SW	9	5-500	~24,000/unit Plant: < 600,000	Y	Y	Y	Y
6	Brackish Water Reverse Osmosis	Filtration	BW	-	5-500	Similar to SWRO	Y	Y	Y	Y
7	Forward Osmosis	Filtration	SW, BW	5		<10,000	N	N	N	N
8	Nanofiltration	Filtration	BW, SW	6			N	N	N	N
9	Electrodialysis	Filtration	BW	4	150-500		N	N	N	N
10	Capacitive Deionization	Filtration	BW	4-5			N	N	N	N
11	Hydration	Crystallisation		4			N	N	N	N
12	Secondary Refrigerant Freezing	Crystallisation		4			N	N	N	N
13	Membrane Distillation	Filtration	SW	5			N	N	N	N
14	Ion Exchange Resin	Filtration					N	N	N	N
15	Solar Still Distillation	Evaporation and Condensation		5			N	N	N	N
16	Solar Chimney	Evaporation and Condensation		4			N	N	N	N
17	Humidification Dehumidification	Evaporation and Condensation		4			N	N	N	N

*The shortlist was be narrowed down to four key technologies to allow a detailed review, whilst Mechanical Vapour Compression met the initial criteria it was not further considered as its scale would not be suitable for the later build out phases.

4 Technology Shortlist

4.1 Seawater Reverse Osmosis

4.1.1 Detailed Process Description

SWRO uses pressure to overcome the naturally occurring osmotic pressure over the membrane to push the water from the saline side to the fresh water side (Figure 4-3). It can be split into the following steps:

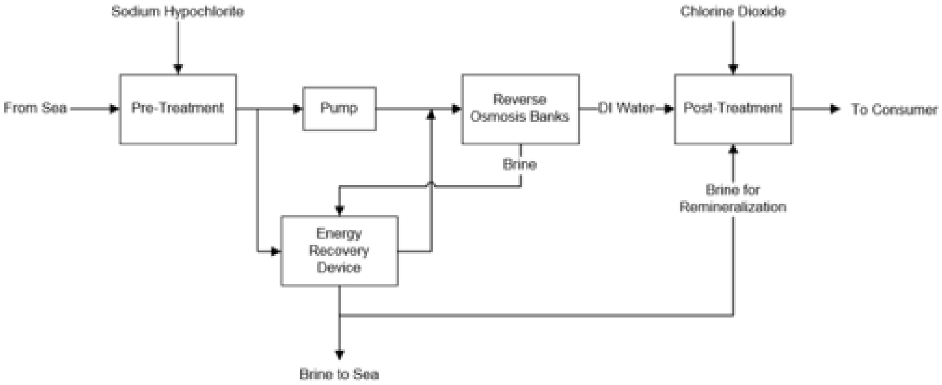

Figure 4-1: Block diagram of SWRO process [24]

Pre-Treatment: seawater is taken from the ocean and pumped to a pretreatment facility. Many chemical species and ions are dissolved in seawater. Units are employed to remove large particles and solids before the SWRO to reduce fouling and/or scaling on the surface of the RO membrane. Typical pre-treatment processes are; macro-filtration, flocculation, microfiltration, activated carbon, ultrafiltration and nano-filtration. Sodium hypochlorite is added to remove the particulates and biological matter.

Pump: There are two types of high-pressure pumps used in RO systems – centrifugal and positive displacement plunger. Plunger pumps typically operate at much higher efficiency (88% vs. 55-75%) and are used where high energy costs exist and for flowrates less than 570 m^3/day [25]. Centrifugal pumps are generally used in larger plants due to higher efficiency and reduced cost and maintenance requirements.

Reverse Osmosis: The external pressure gradient for SWRO is between 54-80 bar. The most common RO membrane used is spiral wound thin film composite (Figure 4-2). Manufacturers include Dow Chemicals, Hydronautics, Osmonics and Toray [26].

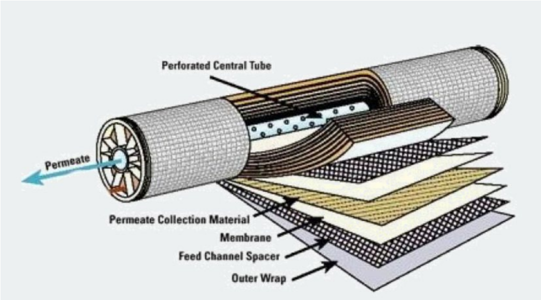

Figure 4-2: RO Spiral wound membrane [27]

After the RO system, the desalinated fresh water is obtained while concentrate is discharged from the RO train. In the concentrate, a considerable amount of pressure remains. Pressure drop across the membranes is typically 1.5-2 bar [27].

To improve energy efficiency, the pressure in the concentrate should be recovered by Energy Recovery Devices (ERD) [28]. The need for a booster pump to get to feed pressure is sometimes necessary.

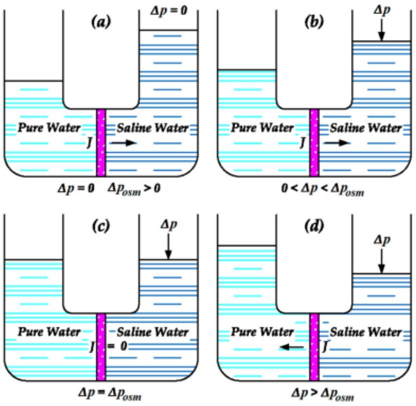

Figure 4-3: Reverse Osmosis Concept [29].

Post Treatment: (varies upon final application) For BEH green hydrogen electrolysis, strict water feedstock quality requirements (Table 3-1) indicate the need for a second pass RO to reduce TDS content. This will influence CAPEX and OPEX of the plant. Typical post treatment processes include chemical dosing system, neutralisation and chlorination.

4.1.2 Utility Requirements

Table 4-1: Utility Requirements for SWRO Process [30], [31]

Parameter	Value	Unit
Typical Unit Size	24,000	m^3/day
Electrical Energy Consumption	3-7	kWh/m^3
Thermal Energy Consumption	0	kJ/kg
Electrical Equivalent for Thermal Energy	0	kWh/m^3
Total Equivalent Energy Consumption	3-7	kWh/m^3

Table 4-1 shows the electrical energy consumption for the SWRO process. Most of the energy needed is for the RO membrane and high-pressure pumping system (8-12%). The variety of consumption of energy will also be dependent on the need for a second pass due to water quality requirements for BEH.

Seawater requirement per cubic metre product water is ~3 m^3 [32].

4.1.3 Effluents and Consumables

Membranes: the largest single consumable for the SWRO process due to colloidal and/or biological fouling. Fouling is a direct result of either inadequate feed source quality or pretreatment equipment. An increase in membrane life will significantly lower the OPEX.

Brine Discharge: 2 m^3 brine produced per 1 m^3 product water. Outlet streams of desalination plants include hyper-saline solutions at densities higher than circulating ocean water. Concentration varies from 50-70 g/L.

This difference in density will cause the brine to settle to the ocean floor, resulting in negative effects on the fauna and flora. Mixing, diffusion and dilution is recommended to aid mixing the brine with seawater. Strong currents can also assist [15].

Water treatment chemicals: algaecides, antifoams, biocides, boiler water chemicals, coagulants, corrosion inhibitors, disinfectants, defoamers, flocculants, neutralising agents, oxidants, oxygen scavengers, pH conditioners, resin cleaners and scale inhibitors.

4.1.4 Maintenance and Operations

Membrane fouling is inevitable for the RO system, and if not managed correctly can lead to higher operation pressures, costs and reduced water quality. Cleaning is required every 3-12 months depending on asset and should extend membrane life and increase efficiency.

Standard practice in operations such as appropriate pre and post treatment, ozone and ClO_2 dosing systems can aid in limiting the frequency of maintenance [33].

4.1.5 Suitability for Site

Depending on the electrical generation as well as blue and green technologies selected for BEH, RO may have an advantage over the other desalination technologies. As RO is driven by electricity and not thermal energy the OPEX would benefit from the availability of cheap electricity. This process would not be able to utilise any waste heat directly in the process. The overall footprint of RO is compact, this could have a benefit to the overall BEH space requirement.

4.1.6 Energy Efficiency and Recovery

As mentioned in Section 4.1.1 ERDs are used to recover the hydraulic energy from the brine and reuse it to pressurise the seawater feed. This helps to minimise energy costs within the system. Table 4-2 shows the common ERD technologies in commercial use.

Table 4-2: Comparison of Commercially Available ERD [34].

Technology/Process	Advantages	Disadvantages	SEC kWh/m^3	Energy Reduction (%)[1]
Francis Turbine	Common/Proven	Double Energy Conversion	6.2-6.7	0
Pelton Wheel	Common/Proven	Double Energy Conversion	3.5-5.9	27
Piston-ERD	Single Energy Conversion	Additional Capital/Maintenance Cost Potential Increase in Feed Salinity	3.5-4.6	37
Pressure Exchange (PX)	Single Energy Conversion Compact Durable Modular	Potential Increase in Feed Salinity	3-5.3	36

[1] The energy reduction is compared with SWRO with the Francis Turbine as the minimum requirement for a SWRO plant.

PX, and other similar rotary driven ERDs, are generally the preferred ERD due to efficiencies of around 97% and as per the advantages in Table 4-2.

As noted in Section 4.1.1 a second pass (with consideration of a third) is necessary for RO to achieve the water quality required. This improves the permeate quality, however increases the energy and chemical usage in the process. The specific energy consumption for a two stage process is 4-4.8 kWh/m^3 [34]. Variations on this can be incorporated, such as partial two pass and split partial second pass, depending on design conditions.

Utilising renewable electricity such as wind or solar could provide cost and emission reductions.

4.1.7 Advantages and Disadvantages

Table 4-3: RO Advantages and Disadvantages

Advantages	Disadvantages
• Proven Technology (commercial scale) • Lower footprint area required • High water quality output (<500ppm) • Suitable for most temperature locations	• Pre-treatment needed • Energy Intensive (still with ERD) • Costs high to build and operate • Maintenance costs • Chemical Consumables (disposal) • Brine discharge environmental impact

4.2 Multistage Flash Distillation

4.2.1 Detailed Process Description

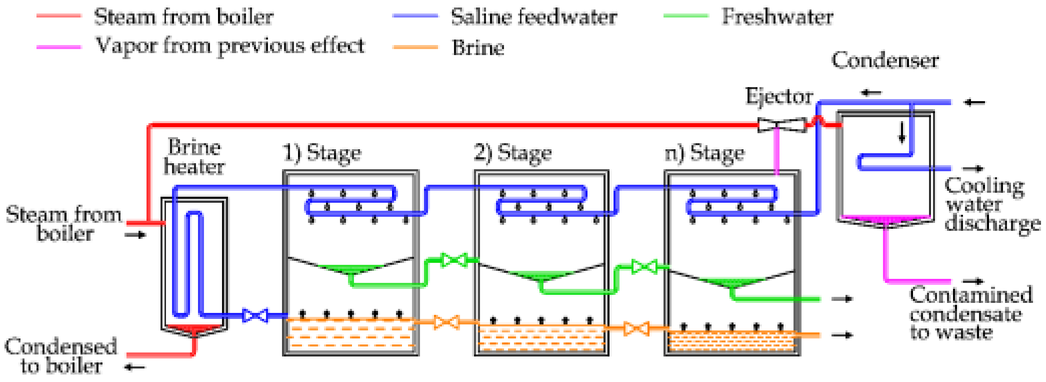

Figure 4-4: Multi-Stage Flash Distillation [29]

MSF distillation utilises thermal energy to separate seawater into fresh water and a high salinity fluid (brine). Seawater is pumped from an intake in the sea, filtered for solids and dosed with chemicals to reduce scaling, foaming and corrosion, depending on feedwater conditions. The process contains multiple stages which evaporate and collect fresh water from brine. The process is usually made up of between 10 and 30 stages [35].

Post pre-treatment the incoming seawater is utilised as cooling water for the process, entering the final stage first. In this stage it condenses the fresh water vapour which is collected as the final product. The seawater flows through all stages, gaining heat from the condensing fresh water until it reaches the brine heater. Steam is injected to heat the seawater to the required temperature before it proceeds to the first stage. Fresh water vapour evaporates from the brine in each stage, condensing on the incoming seawater pipes. The brine continues through each stage, increasing in salinity concentration as fresh water evaporates. Operating conditions decrease in temperature and pressure in each successive stage. This occurs due to the temperature of the brine decreasing through the process, requiring a pressure reduction to allow evaporation to occur. The steam utilised in the heating of the seawater is returned to the boiler as condensate. The steam utilised as a motive fluid in the ejector to generate a vacuum in the stages is cooled by a portion of incoming seawater which is discharged back to sea, with the condensate and brine also being discharged.

Due to the low recovery rate of fresh water in this process, in certain situations a portion of the final discharge brine can be mixed with the incoming feedwater. This increases recovery, reduces the water treatment chemical required and can lower operating costs. The increase in dissolved solids have an impact on boiling point temperature, as well as increasing corrosion and scaling so it is a process that must be carefully designed and managed.

4.2.2 Utility Requirements

Table 4-4: Utility Requirement for MSF [30], [31], [36]

Parameter	Value	Unit
Typical Unit Size	50,000 – 70,000	m^3/day
Electrical Energy Consumption	4 – 6	kWh/m^3
Thermal Energy Consumption	190 – 390	kJ/kg
Electrical Equivalent for Thermal Energy	9.5 – 19.5	kWh/m^3
Total Equivalent Energy Consumption	13.5 – 25.5	kWh/m^3
Gain Output Ratio (GOR)	8 – 12	$kg_{distillate}/kg_{steam}$

Table 4-4 shows the typical capacity of MSF units, along with the electrical and heating requirements. The electrical equivalent for thermal energy is an assumption of the electrical energy the steam would have otherwise generated in a turbine – assuming the condenser in the turbine is kept at 0.1 bara at seawater temperature of 35 °C and steam extraction pressure is 3.5 bara (loss of 475 kJ/kg steam) [30].

MSF requires roughly 10 m^3 of seawater to produce 1 m^3 of fresh water (Figure 4-5). This is the result of 7 m^3 required for cooling, and a recovery ratio of around 0.22. Roughly 9 m^3 of discharge will be generated requiring disposal at elevated temperatures, salinity and with entrained chemicals.

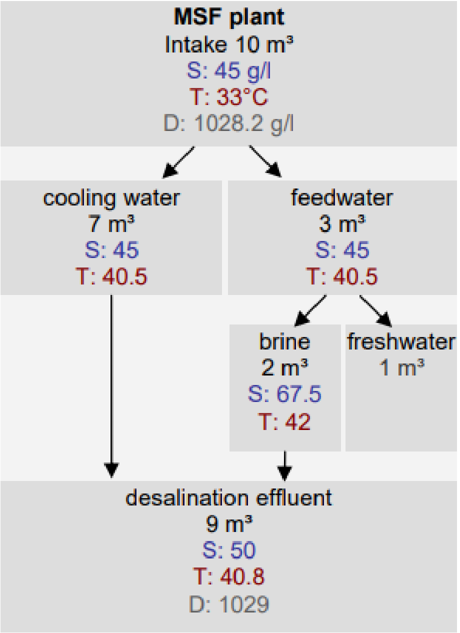

Figure 4-5: MSF Water Flow with Indicative Properties[32]

Note: S is salinity, T is temperature, D is density

This process produces fresh water with a TDS value of around 10 ppm, and a conductivity of around 10 µS/cm [37], [38].

4.2.3 Effluents and Consumables

Table 4-5 shows the indicative quantity and type of chemicals required per cubic metre of fresh water produced.

Table 4-5: Indicative Chemical Usage per 1m^3 of Fresh Water Produced [32], [39]

Parameter	Chemical	Value	Unit
Seawater	-	10	m^3
Disinfectant	Chlorine	20.5	g
Antiscalent	Polycarbonic Acid/ Phosphonates	6-12	g
Chlorine removal/ Oxygen Scavenging	Sodium bisulfite	Dependent on conditions	g
Antifoam	Propylene glycol	1	g

The chemicals involved in MSF can be harmful when released back to the marine environment in the brine. It should be ensured they are optimised to minimise the impact on the environment around discharge.

Chlorine is highly toxic resulting in negative effects on the aquatic life. There will be elevated levels of chlorine due to dosing the cooling water, resulting in a discharge of 1.8-4.5 g/m^3 of product water [32]. Sodium Bisulfite is an oxygen scavenger so overdosing is cause for concern due to depleting dissolved oxygen levels of the marine environment.

Table 4-6 shows the brine discharge from the MSF process per cubic metre of fresh water produced. This brine will be mixed with the cooling water before discharge, diluting the salinity to around 5 g/l above ambient seawater conditions. The discharge system must allow for the brine to be well distributed on discharge to avoid high temperature and salinity concentrations. It should also be noted that heavy metals may be present in the brine discharge due to corrosion of the MSF unit, depending on construction materials.

Table 4-6: Indicative MSF Brine Discharge [32], [39]

Parameter	Value	Unit
Chlorine	0.7	g
Polycarbonic Acid/ Phosphonates	6	g
Heavy metals (e.g. copper)	Dependent on corrosion and construction materials	
Propylene glycol	0.09	g
Salinity	+20	g/l above seawater
Temperature	+8 – 10	°C above seawater

4.2.4 Maintenance and Operations

MSF distillation is easy to operate and has a low maintenance requirement. There are minimal major moving parts which positively contributes to maintenance and reliability, and no requirement for replacement items such as membranes like in other desalination techniques. Cleaning is required every one to two years, depending on scaling. Corrosion is one of the main maintenance issues to monitor. Both scaling and corrosion can be limited through correct chemical treatment.

There are no complicated pretreatment steps with MSF as there are with membrane technologies, further simplifying the operation.

4.2.5 Suitability for Site

Depending on the technology selected for blue hydrogen production, steam may be available on site which could be used in the MSF process. If no steam is available, a dedicated steam plant would be required.

Waste heat, notably from the green hydrogen electrolysers if cooling water is utilised, could provide a heat source to reduce the requirement for steam and hence lower the OPEX.

4.2.6 Advantages and Disadvantages

Table 4-7: MSF Advantages and Disadvantages

Advantages	Disadvantages
• Large capacity per unit • Minimal pre-treatment required • Reliable with proven long operating life • High water quality output • Can treat highly saline water (70,000 mg/l) • Easy to operate • Can utilise waste steam and/or waste heat to reduce OPEX	• Large CAPEX • Energy intensive process • Scaling and corrosion issues • Temperature of brine produced is higher than that of ambient seawater - harmful for marine life • Large footprint • Cannot operate below 60% capacity • Not suitable to combine with intermittent energy supplies – slow start-up

Advantages	Disadvantages
	- Susceptible to corrosion – high quality materials required - Low recovery ratio

4.3 Multi Effect Distillation

4.3.1 Detailed Process Description

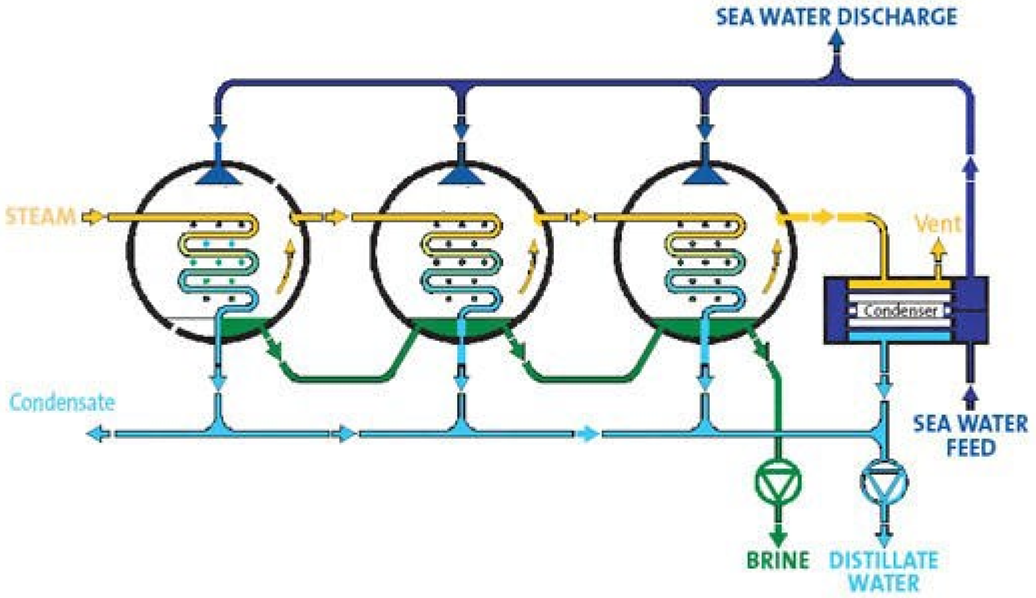

Figure 4-6:Multi-Effect Distillation Process Showing Three Effects [40]

MED utilises thermal energy to separate seawater into fresh water and a high salinity fluid (brine). Seawater is pumped from an intake in the sea, filtered for solids and dosed with chemicals to reduce scaling, foaming and corrosion, depending on feedwater conditions. The seawater can be preheated using the outgoing streams (brine and fresh water) and gains heat by being utilised as a cooling fluid to condense the vapour from the final effect. The seawater is then split across the effects.

In each effect, the seawater is sprayed from the top to create a thin film on the tubes of the heat exchanger. A heating fluid, usually steam, flows through the inside of the tubes in the first stage. In subsequent stages, the fresh water vapour from the previous effect is used as the heating fluid. This evaporates some of the water from the saline solution, leaving the brine to be collected in the base of the unit. This brine is transferred to subsequent effects to improve fresh water recovery due to the next effect being at a lower pressure, flashing off additional water. The steam is only required for the first stage, so returns as condensate to the boiler. The fresh water vapour is used as the heating medium in the following effect, therefore is cooled and collected as product.

This process can be repeated multiple times depending on design considerations – up to around 14 effects [40]. In each successive phase, the temperature of the heating vapour decreases and so the pressure of operation decreases to ensure evaporation occurs. This is achieved by vacuum pumps on each effect. The final stage vapour is cooled by incoming seawater, a portion of which is rejected back to the sea.

4.3.2 Utility Requirements

Table 4-8: Utility Requirements for MED [30], [31], [36]

Parameter	Value	Unit
Typical Unit Size	5,000 – 15,000	m^3/day
Electrical Energy Consumption	1.5 – 2.5	kWh/m^3
Thermal Energy Consumption	230 – 390	kJ/kg
Electrical Equivalent for Thermal Energy	5 – 8.5	kWh/m^3
Total Equivalent Energy Consumption	6.5 – 11	kWh/m^3
Gain Output Ratio (GOR)	10 – 16	kg$_{distillate}$/kg$_{steam}$

Table 4-8 shows the typical capacity of MED units, along with the electrical and heating requirements. The electrical equivalent for thermal energy is an assumption of the electrical energy the steam would have otherwise generated in a turbine – assuming the condenser in the turbine is kept at 0.1 bara at seawater temperature of 35 °C and steam extraction pressure is 0.5 bara (loss of 258 kJ/kg steam)[30].

As can be seen in Figure 4-7, MED requires roughly 9 m^3 of seawater to produce 1 m^3 of fresh water. This is due to 6 m^3 being required for cooling, and a recovery ratio of around 0.25. Roughly 8 m^3 of discharge will be generated requiring disposal at an elevated temperature and salinity, with entrained chemicals.

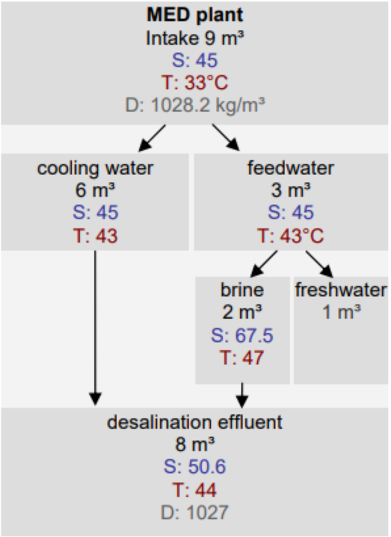

Figure 4-7: MED Water Flow with Indicative Properties [32]

Note: S is salinity, T is temperature, D is density.

4.3.3 Effluents and Consumables

Table 4-9: Indicative Chemical Usage per 1m^3 of Fresh Water Produced [32], [39]

Parameter	Chemical	Value	Unit
Seawater	-	9	m^3
Disinfectant	Chlorine	18.5	g

Parameter	Chemical	Value	Unit
Antiscalent	Polycarbonic Acid/ Phosphonates	6-12	g
Chlorine removal/ Oxygen Scavenging	Sodium bisulfite	18	g
Antifoam	Propylene glycol	0.9	g

The chemicals used in the MED process can be harmful when released back to the marine environment in the brine. This is an important consideration and it should be ensured they are used in the correct quantities to minimise the impact on the environment upon discharge.

Chlorine is highly toxic resulting in negative effects on the aquatic life. There will be elevated levels of chlorine due to dosing the cooling water, resulting in it containing and discharging 1.6-4.0 g/m^3 of product water [32]. Sodium Bisulfite is an oxygen scavenger, so overdosing is cause for concern due to depleting dissolved oxygen levels of the marine environment.

Table 4-10: MED Brine Discharge [32], [39]

Parameter	Value	Unit
Chlorine	0.7	g
Polycarbonic Acid/ Phosphonates	6	g
Heavy metals (e.g. copper)	Dependent on corrosion and materials	
Propylene glycol	0.09	g
Salinity	+20	g/l above seawater
Temperature	+12 – 30	°C above seawater

shows the brine discharge from the MED process per cubic metre of fresh water produced. This brine will be mixed with the cooling water before discharge, diluting the salinity to around 5.5 g/l above ambient seawater conditions. The discharge system must allow for the brine to be well distributed on discharge to avoid high temperature and salinity concentrations. It should also be noted that heavy metals may be present in the brine discharge due to corrosion of the MED unit, depending on construction materials.

Table 4-10: MED Brine Discharge [32], [39]

Parameter	Value	Unit
Chlorine	0.7	g
Polycarbonic Acid/ Phosphonates	6	g
Heavy metals (e.g. copper)	Dependent on corrosion and materials	
Propylene glycol	0.09	g
Salinity	+20	g/l above seawater
Temperature	+12 – 30	°C above seawater

4.3.4 Maintenance and Operations

MED is easy to operate and has a low maintenance requirement. There are minimal major moving parts which positively contributes to maintenance and reliability, and no requirement for replacement items such as membranes like in other desalination techniques. Cleaning is required every year, depending on scaling. Corrosion is one of the main maintenance issues to monitor. Both scaling and corrosion can be limited through correct chemical treatment.

There are no complicated pretreatment steps with MED as there is with membrane technologies, further simplifying the operation.

4.3.5 Suitability for site

Depending on the technology selected for blue hydrogen production, steam may be available on site which could be used in the MED process. If no steam is available, a dedicated steam plant would be required.

Waste heat, notably from the green hydrogen electrolysers if cooling water is utilised, could provide a heat source to reduce or eliminate the requirement for steam and hence lower the OPEX. MED can be adapted to operate using hot water (>60 °C), according to manufacturers [41]. This could be of significant advantage by utilising the waste heat from the hydrogen production process, therefor eliminating around half of the OPEX. Conversations were held with Veolia to explore the integration of distillation units with green hydrogen production. It is at an early stage in development and has not been proven at scale, but is worth exploring further for the 2040 and 2050 build out.

4.3.6 Advantages and Disadvantages

Table 4-11: MED Advantages and Disadvantages

Advantages	Disadvantages
• MED process can operate at lower temperatures compared with other thermal desalination technologies (~70 °C vs. >100 °C), minimising corrosion and scaling • High water quality output • Feedwater quality is not as important as for membrane (RO) technologies (tolerates normal levels of biological and suspended matter) • Minimal pre-treatment required • Reliable process and easily operated • Can be operated at 0-100% capacity • Suitable with renewable energy intermittent supply • Can utilise waste steam and/or waste heat to reduce OPEX • Potential to use hot water instead of steam – significant OPEX saving	• High energy consumption • Temperature of brine produced is higher than that of ambient seawater (30-40 °C brine temperature) - harmful for marine life • High CAPEX and OPEX • Susceptible to corrosion – high quality materials required

4.3.7 MED-TVC Coupling

4.3.7.1 Detailed Process Description

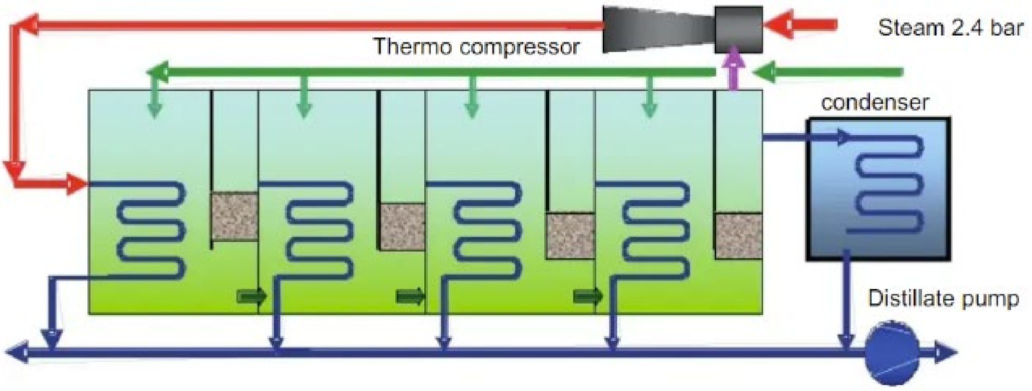

Figure 4-8: MED-TVC [42]

Thermo vapor compression (TVC) is used in combination with MED. Distillation plants using vapor compression rely on the heat generated by the compression of water vapor to evaporate salt water using TVC. TVC harnesses entrained vapour to make a vacuum to become more heat efficient compared to just MED. The feed water enters the process through a heat exchanger, and vapour is generated in the evaporator and compressed by TVC means. Compressing the vapor raises its temperature enough to serve as the heat source. The concentrated brine is removed from the evaporator vessel by the concentrate pump. This flow is then split, and a portion is mixed with the incoming feed, the remainder is pumped to discharge. In TVC a steam jet creates the lower pressure. These units are usually used in small and medium-sized applications.

4.3.7.2 Advantages and Disadvantages

Table 4-12: MED-TVC Advantages and Disadvantages

Advantages	**Disadvantages**
• Low electrical consumption • Operates at low Temp (<70 ºC) and low conc. to avoid corrosion and scaling • Low consumables • Minimal pre-treatment • Water quality (<10ppm) • Reliable and simple to operate • Low maintenance cost • Feedwater quality is not as important as for membrane (RO) technologies (tolerates normal levels of biological and suspended matter) • Can utilise waste steam and/or waste heat to reduce OPEX	• High ratio of seawater needed per m^3 product water • Lower recovery than SWRO • High energy consumption • Temperature of brine produced is higher than that of ambient seawater (30-40°C brine temperature) - harmful for marine life • High capital and operational cost • Susceptible to corrosion – high quality materials required

4.4 Shortlist Comparison

The comparison table (Table 4-13) shows an overview of the shortlisted technologies. The colour matrix highlights the most favourable (green) to least favourable (red) in each of the main parameters. This comparison has been based on key process parameters to allow the technologies to be compared. This section goes into detail around key parameters of interest.

Table 4-13: Comparison of Shortlisted Technologies. [33]–[35], [39], [42], [46]–[50]

		Unit	SWRO	MSF	MED /MED TVC
	Plant Data				
	Water Quality Output	mg/L TDS	250-500 20-100 (2-pass) <5 (3-pass)	<25	<25
	Availability	%	95-100	98	98
	Indicative Chemical Consumables		Chlorine, Sulfuric Acid, Sodium Bisulfite, Aluminium Chloride/Ferric Chloride, Polyacrylamide, Polycarbonic Acid	Chlorine, Polycarbonic Acid/ polyphosphate, Sodium Bisulfite, Propylene Glycol	Chlorine, Polycarbonic Acid/ polyphosphate, Sodium Bisulfite, Propylene Glycol
	Projected Lifetime	Years	15-20	25-40	20-25/15-25
	Recovery Ratio	%	35-43	22	24
	Seawater Required	SW/unit PW^+	2.5-3.2	10	9
	Brine Discharge	BD/unit PW^+	1.3-1.9	1.7-2 (+ 7 CW^*)	1.7-2 (+ 6 CW^*)
	Energy & Emissions				
	Thermal	kWh_{th}/m^3	0	78	69
	Electrical	kWh_{el}/m^3	3.0-7.0	4.0-6.0	1.5-2.5
	CO_2e [1]	CO_2/m^3	0.4-4.4	5.5-25	4.3-17.6
	Techno-economic				
	Capacity Range for Techno-Economics	m^3/day	1,000-320,000	23,000-528,000	1,000-90,000

	CAPEX	$US\$/m^3$	0.315	0.415	0.375
	CAPEX Breakdown	%	RO Vessel 29.8% Seawater pre-treatment 18.6% Civil electrical and I&C works 17.8% Intake Brine and Discharge 14.5% Potabalisation and water storage 8.3% Contingencies 4.8% Membranes 3.3% Auxiliary system 2.9%	Process Equipment 60.3% Contractors' overhead and profit 10.6% Owner's cost 7.1% Contingency 7.1% Feedwater supply 5.0% Auxiliary equipment 4.3% Freight and insurance 3.6% Pre-treatment 1.4% Building 0.3% Post-treatment 0.3%	MED Evaporator incl I&C 57.5% Intake Brine and Discharge 15.9% Potabalisation and water storage 6.4% Erection, commissioning, and testing 5.7% Civil electrical and I&C works ex. MED 5.3% Contingencies 4.8% Steam supply 2.3% Auxiliary system 1.6% Seawater pre-treatment 0.6%
	CAPEX Largest Contributor		Pre-treatment vessels & RO membrane	Transfer tubes/tubeplates – sensitive to market variations	Evaporator - sensitive to metal price fluctuations
	OPEX	$US\$/m^3$	0.38	0.73	0.48
	OPEX Breakdown	%	Electrical 55% Cartridge filters & RO membrane replacements 11% Maintenance 6% Chemicals 6% Labour 6% Sludge & solids waste disposal 4% Legal/Permits 2% Other 10%	Thermal 55% Electrical 22% Labour 13% Chemical <1% Parts <1%	Thermal 55% Electrical 20% Labour 18% Chemical 5% Parts 2%
	OPEX Largest Contributor		Electrical Energy	Thermal Energy	Thermal Energy
	Reduced cost if:		ERD utilised	Co-gen, waste heat use	Co-gen, waste heat use
	Biggest Consumable		Membrane/membrane pre-treatments		

[1] $CO2_e$ highly dependent on energy generation method. *CW- Cooling Water, $^+$PW- Produced Water

Water quality

Table 4-14: Water Quality Requirements [16], [39], [43], [44]

Process	Output Water Quality (mg/L)	Alkaline Electrolyser Input EC Quality (µS/cm)	Alkaline Electrolyser Additional Requirements	PEM Electrolyser Input EC quality (µS/cm)	PEM Electrolyser Additional requirements
One pass	250-500	1	Ion exchange, second pass RO, (+3rd pass potential)	0.1	Ion exchange, membrane separation, distillation
Two pass	20-100	1	Ion exchange+ third pass potential	0.1	Ion exchange, third pass RO
Three pass	<5	1	-	0.1	Ion exchange
MSF	<25	1	Ion exchange	0.1	Ion exchange
MED/MED-TVC	<25	1	Ion exchange	0.1	Ion exchange

Availability

Availability across all shortlisted technologies is high. RO ranges from 95-100% uptime (dependent on redundancy) and both thermal processes in the region of 98%. Cleaning occurs multiple times per year for RO, with MSF and MED requiring annual cleaning.

Consumables

RO requires additional chemical consumables due to the more extensive pre-treatment stage. This includes chemicals associated with the flocculation/coagulation stage required prior to RO. Membranes for the RO process are a large consumable cost, requiring a change every five to seven years.

The thermal processes also require chemical consumables – to a lesser degree – to disinfect and reduce scaling, foaming and corrosion.

Lifetime

The expected lifetime of the equipment is longer for the thermal processes, especially MSF with proven lifespans of up to forty years. RO has an expected lifespan of around twenty years (replacing the membrane every ~five years).

Recovery

The recovery ratio – quantity of product water produced per unit of feedwater (excluding cooling water) – for RO is greater than for the thermal processes. This lowers the quantity of seawater being processed through the plant per unit of product water. This is beneficial as it lowers the water abstraction requirement, reducing the impact on the marine environment surrounding the intake points.

Discharge

The discharge from all shortlisted technologies contain residual chemicals from the pre-treatment process, as well as a higher than ambient salinity. The thermal processes discharge (brine and cooling water) is also at an elevated temperature. These factors all have a negative effect on the marine environment surrounding the discharge point. The correct method and location of discharge is therefore an important consideration, as is careful management of chemical usage to minimise the effect on the marine environment. The density of brine varies between technologies, so analysis will be required to ensure accurate density measurements in relation to ambient seawater to account for plume characteristics. Across all technologies, there is the potential for pollutants, such as heavy metals, to be present in the brine due to corrosion of the process equipment.

Thermal & Electrical Energy:

It is typically accepted that RO is the less expensive process to recover fresh water however, historically these cost models do not consider imminent rises in energy prices. RO uniquely relies on electricity to operate, while the thermal processes can utilize a waste heat source or solar thermal energy more conveniently [45]. Renewable energy can be utilised in all the processes to provide the electricity and/or heat, with some being more responsive to intermittent/ variable flows than others (see Appendix C: Renewable Energy Integration). This has been noted in Sections 4.1, 4.2 and 4.3 as appropriate. The source of the thermal and electrical energy used in the process has a significant impact on the overall footprint of the desalination process. The following should be taken into consideration regarding CO_2:

- Highly dependent on electrical (and thermal, if required) energy generation. Increased energy efficiency, using cleaner fuel, renewable energy and establishing minimum targets can help reduce emissions
- Thermal processes emit more CO_2 per unit volume water treated because burning of fuel for thermal energy (assuming a fossil fuel source)
- Typical values for the carbon footprint are 5.5–25.0 kg CO_2/m^3 for MSF, 4.3–17.6 kg CO_2/m^3 for MED, and 0.4–4.0 kg CO_2/m^3 for SWRO [45]

Further detailed work was not pursued as it was out with the work scope.

4.4.1 Techno-Economics

The greatest CAPEX contributors for the four reviewed desalination technologies detailed in Table 4-13 are:

- RO: pre-treatment vessels and membranes
- MSF: transfer tubes/ tubeplates
- MED/ MED TVC: evaporator

Cost reductions in these areas are limited and linked to market variations due to cost of materials. Reduction in the membrane cost has historically been seen with the advancement in membrane design.

All desalination technologies will require intake and outfall structures and pipeline to supply the seawater and dispose of the brine. Depending on the size and scale of these (note the low recovery ratios with MSF, MED/ MED TVC) plastic piping can be selected instead of concrete for lower volumes. This would have an impact on the CAPEX. The overall distance of piping required would also have an impact and so location of the onshore elements should be considered.

The greatest OPEX contributors for the four reviewed desalination technologies detailed in Table 4-13 and have been detailed along with cost reduction opportunities in Table 4-15.

Table 4-15: OPEX Reduction

	RO	MSF/ MED/ MED TVC MED/ MED TVC
OPEX Contributors	Electrical energy	Thermal energy
OPEX Reduction Opportunities	• Due to pressures required for the membrane RO OPEX is driven primarily by the cost of electrical energy. This can be reduced by utilising low cost electricity • Advancements in the membranes have resulted in a slight pressure reduction and an extended lifespan – this has had an impact on both the energy costs and the membrane replacement costs	• Heat is the largest driver in the MSF, MED, MED TVC processes as it is used to separate desalinated water from the brine via evaporation. The cost of this can be reduced by using waste thermal energy • Low TDS compared to RO resulting in reduced post treatment requirements for electrolyser purity feed • Typically suit higher capacities (>5,000 m^3/day) as the energy consumed per unit of water is lower at higher capacities [45] • Suitable for low temperature heat, can utilise waste heat from cogeneration plants
Disadvantage		MSF does not offer advantages to MED, MED-TVC but has significantly higher electrical energy and investment costs

Water production costs for all desalination techniques as noted above is largely driven by energy costs. Larger capacity plants usually benefit in cost reductions by improving efficiencies. The quality of the water intake will also have an impact on the overall production costs as it will have an effect on the plants efficiency and energy consumption.

5 BEH Base Case

The following base case has been developed in alignment with the core and build out project scenarios for BEH as stipulated in Table 1-1. The BEH desalination base case uses SWRO as the selected technology as:

- Is suitable for the BEH capacity requirements
- Has a compact footprint
- Water quality meets post processing feed requirements
- There is sufficient publicly available data to develop high level considerations during this stage of design

5.1 Assumptions

The following assumptions have been made to allow the development of the BEH desalination base case, it should be noted that this case is not optimised and future work is required.

- Plant availability ~95 - 98% [42], [46]
- Using 2-pass SWRO as desalination technology
- 2-pass SWRO requires 4.4 kWh/m^3 H_2O produced
- SWRO recovery rate assumed 35%
- Assuming Alkaline electrolysers for green hydrogen as per Genesis report [18]
- Concentrations of influent and effluent to be defined
- 350 MW blue hydrogen requires 45 t/hr H_2O as per recommendation from Progressive Energy, this is inclusive of both feedstock and site usage. Therefore this number will be conservative as it includes an element of water that can be recycled [47]
- Electrolysis requires 10.5 kg H_2O/ kg H_2 as per Genesis report [18]
- Cooling water requirement for green hydrogen is included for conservative figures, this has been assumed as 15.5 L H_2O/kg H_2 [19]
- North Sea salinity is 34,000 mg/L [48]. See Appendix D: Seawater Salinity

5.2 Site Sizing and Details

The estimated desalination footprints and dimensions are outlined in Table 5-1. These are not inclusive of water storage which will require additional space, increasing the overall footprint. The footprint has been calculated on the assumption that cooling water for the green hydrogen facility will be required. As some of the cooling water is likely to be recirculated the current base case is a conservative estimate as it is oversized.

Table 5-1: Case Scenarios and Associated Footprints and Rough Dimensions

Case	Footprint (m^2)	Rough Dimensions (m)
Core	1,200	44 x 28
Build out (2030)	2,100	57 x 36
Build out (2040)	19,700	176 x 112
Build out (2050)	27,000	206 x 131

Table 5-2 below provides the estimated sizing of the base case RO desalination plant. Where possible this has been calculated using requirements supplied by the blue and green hydrogen work streams.

Note: water storage for one day is ~80,000 m^3 for the build out case (2050). This would require a large land space in tanks and even worth considering reservoir type storage.

Table 5-2: Base Case for BEH [11].

Parameters	Core Project 2030	Build out 2030	Build out 2040	Build out 2050
H_2 Capacity	1 x 355MW SMR/ATR	3 x 355 MW SMR/ATR	3 x 355 MW SMR/ATR + 2 x 1.8 GW upscaled SMR/ATR + 1 x 2.1 GW Electrolyser	2 x 1.8 GW upscaled SMR/ATR + 3 x 2.1 GW Electrolyser plants (NB 3 x 355MW SMR/ATR retired)
Total	355MW SMR/ATR	1GW SMR/ATR	4.7 GW SMR/ATR 2.1 GW Electrolyser	3.6GW SMR/ATR 6.3GW Electrolyser
Maximum supply from H_2 per year	Blue: 3TWh – 100% of demand	Blue: 9TWh – 100% of demand Green: 0 TWh – 0% of demand	Blue: 39TWh – 54% of demand Green: 18 TWh – 46% of demand	Blue: 30 TWh – 33% of demand Green: 54 TWh – 80% of demand
H_2O input required (m^3/hr)	45	135	1,527	3,264
Seawater intake (m^3/hr)	126	378	4,277	9,140
Electricity requirement (kW) (1)	198	594	6,720	14,363
Capacity (m^3/day)	1,080	3,240	36,656	78,344
Estimated CAPEX ($m)	2.5	7.5	84	180
Estimated OPEX ($m/yr)	0.15	0.45	5	11
Typical Plant footprint (m^2)	1,233	2,124	19,729	27,066
Water Storage (m^3) (2)	1,080	3,240	36,656	78,344
Water Storage Footprint (m^2) (2)	150	300	2,000	4,000

(1)Using 4.4 kWh/m^3 [34]. (2)Assumed 1 day storage

5.3 Build Duration

The estimated duration of design and construction for various plant sizes is detailed in Appendix B: Desalination Project Duration. This does not include project tasks such as applying for permits, planning or investment decisions. For the base case, due to the low volumes required, the project could take less than a year. At this scale, high-density polyethylene or other plastic pipes could be utilised for intake systems. Build out cases could be up to 2-3 years due to much larger intake and discharge pipes or tunnels, increased unit sizes and complexity [49].

5.4 Layout & Configuration

Figure 5-1: 3D Model Images of an Indicative 200 m3/hr Demineralisation Plant [50]Figure 5-1 shows an example layout of an RO facility producing around 200 m^3/hr. A project specific layout has not been developed during this phase. It is recommended that this is developed during future design phases once the selected technology is optimized.

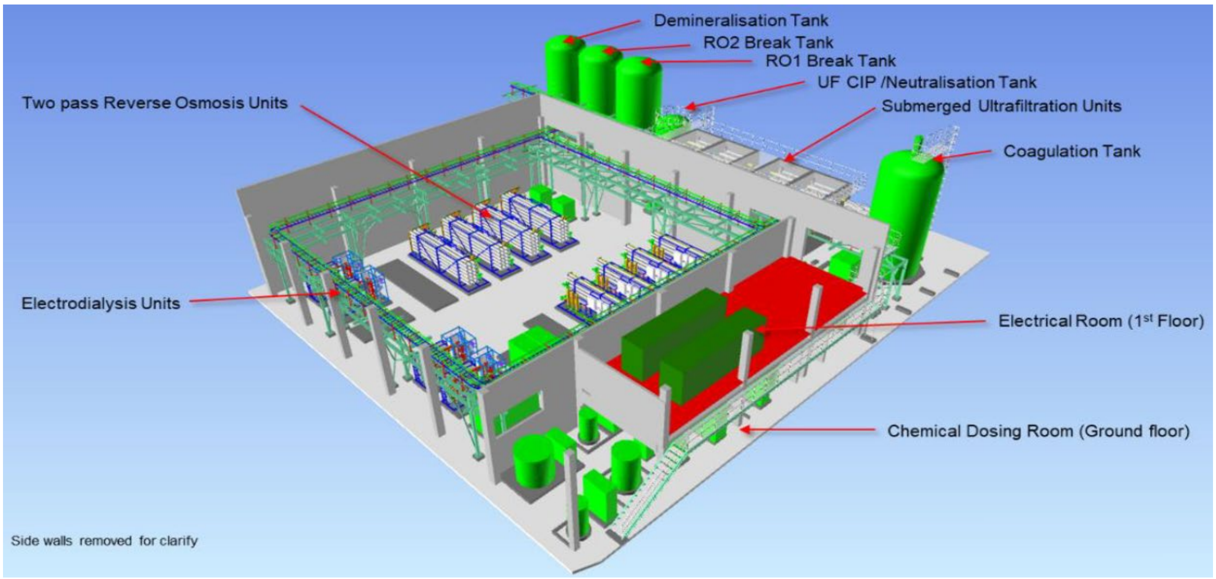

Figure 5-1: 3D Model Images of an Indicative 200 m^3/hr Demineralisation Plant [50]

6 Conclusions and Recommendations

6.1 Conclusions

The following conclusions are for the BEH desalination plant at this stage:

- Requirement for desalination at BEH:
    - Desalinated water is required due to the South-East of England being in a water stressed area, with freshwater becoming increasingly scarce [51].

- Feedstock selection:
    - Due to the proximity of BEH to the North Sea, seawater was chosen as the feed for the desalination plant
    - Brackish water was eliminated due to perceived limited availability

- Suitable desalination technologies:
    - Four technologies were shortlisted for technical review – SWRO, MED, MSF, MED-TVC
    - SWRO (two-pass) has been selected as the base case due to advantages in CAPEX/OPEX, energy usage, energy type (electrical only), capacity and discharge considerations. This however is not an optimised selection and will be dependent on other site factors

- Site synergies:
    - If a waste heat source is available, thermal desalination becomes a more attractive method due to significant OPEX reductions

- Post desalination water treatment:
    - As is common for hydrogen electrolysers using any water source, further treatment will be needed to achieve the feed water quality required. This requires technology for deionisation to produce demineralised water – detailed in Genesis green hydrogen report [18].

- Site proximity considerations for layout:
    - Connection to inlet, outlet and site distribution pipelines
    - Location to green and blue hydrogen plants to make use of waste heat (as appropriate)
    - Power connection for electrical supply

- CAPEX and OPEX drivers:
    - CAPEX across all reviewed technologies is predominantly made up of the vessel costs
    - OPEX for thermal processing is mainly thermal energy costs and for RO electricity and membrane replacement costs make up the bulk

6.2 Recommendations

The recommendations for the desalination plant at BEH are as follows:

- Continue to engage with Anglian Water to identify if it is possible to develop a centralised plant at the site that will service not only BEH but also the surrounding area

- Reassess and select technology for base case once the green and blue hydrogen technologies have been confirmed. This will allow a technology that is tailored to the availability of waste energy to be selected and developed

- For Site Selection:
    - evaluation of near- and off-shore marine resources with a focus on the type, environmental sensitivity, and location of marine species inhabiting the desalination plant intake and discharge areas
    - review of near- and off-shore bathymetry, hydrology and geology
    - preliminary analysis of the saline source water quality in terms of mineral and organic content
    - identification of alternative routes for delivery of the desalinated water to the distribution system
    - ecological and archaeological surveys

- Technology Review Selection:
    - Revise technology selection following confirmation of blue and green hydrogen technology selection to ensure that appropriate technology is selected to take advantage of waste energy
    - Revise plant sizing following confirmation of blue and green hydrogen water requirements
    - Further develop post desalination water treatment once water quality specification for BEH is known
    - For build out cases (2040 and 2050), TRL of processes may have changed so re-evaluating options will be necessary

Following the final selection of the desalination technology the next recommended steps would be to:

- Undertake a vendor and technology selection process
- Optimise process in synergy with BEH
- Redefine utility requirements
- Prepare detailed plant layouts
- Develop dispersion modelling for the brine disposal
- Prepare for an environmental impact assessment

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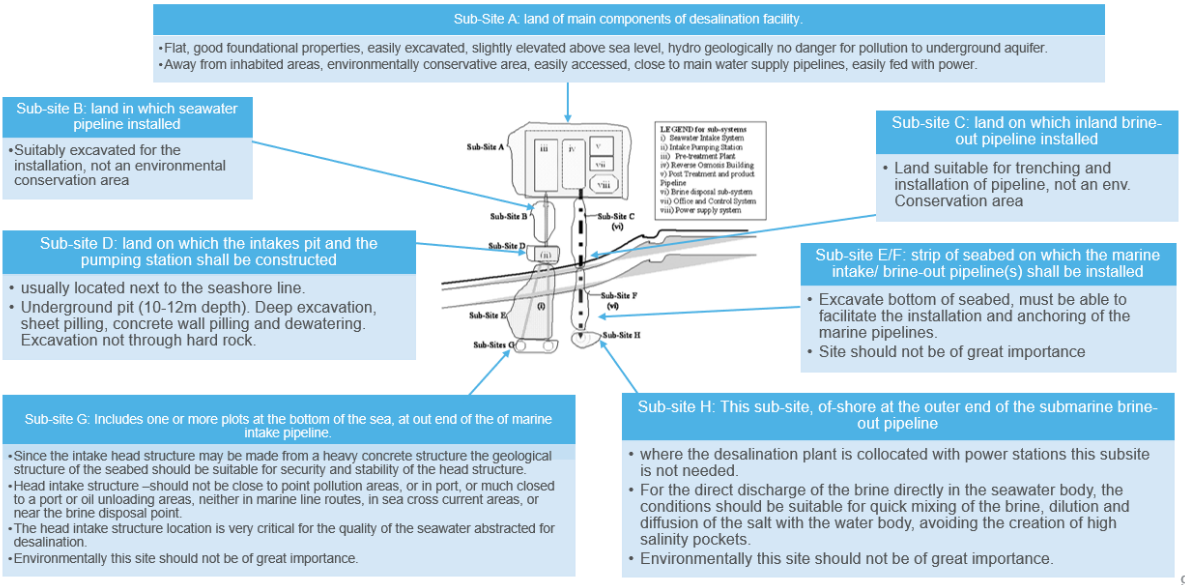
8 Appendix

8.1 Appendix A: Subsite Components



Sub-Site A: land of main components of desalination facility.

- Flat, good foundational properties, easily excavated, slightly elevated above sea level, hydro geologically no danger for pollution to underground aquifer.
- Away from inhabited areas, environmentally conservative area, easily accessed, close to main water supply pipelines, easily fed with power.

Sub-site B: land in which seawater pipeline installed

- Suitably excavated for the installation, not an environmental conservation area

Sub-site C: land on which inland brine-out pipeline installed

- Land suitable for trenching and installation of pipeline, not an env. Conservation area

Sub-site D: land on which the intakes pit and the pumping station shall be constructed

- usually located next to the seashore line.
- Underground pit (10-12m depth). Deep excavation, sheet pilling, concrete wall pilling and dewatering. Excavation not through hard rock.

Sub-site E/F: strip of seabed on which the marine intake/ brine-out pipeline(s) shall be installed

- Excavate bottom of seabed, must be able to facilitate the installation and anchoring of the marine pipelines.
- Site should not be of great importance

Sub-site G: Includes one or more plots at the bottom of the sea, at out end of the of marine intake pipeline.

- Since the intake head structure may be made from a heavy concrete structure the geological structure of the seabed should be suitable for security and stability of the head structure.
- Head intake structure –should not be close to point pollution areas, or in port, or much closed to a port or oil unloading areas, neither in marine line routes, in sea cross current areas, or near the brine disposal point.
- The head intake structure location is very critical for the quality of the seawater abstracted for desalination.
- Environmentally this site should not be of great importance.

Sub-site H: This sub-site, of-shore at the outer end of the submarine brine-out pipeline

- where the desalination plant is collocated with power stations this subsite is not needed.
- For the direct discharge of the brine directly in the seawater body, the conditions should be suitable for quick mixing of the brine, dilution and diffusion of the salt with the water body, avoiding the creation of high salinity pockets.
- Environmentally this site should not be of great importance.

Figure 8-1: Subsite Components for Desalination Pipeline [10]

8.2 Appendix B: Desalination Project Duration

Table 8-1: Estimated Project Duration [49], [52]–[54]

Plant Size (m^3/day)	Design Period (months)	Construction Period (months)	Start-up and Commissioning (months)	Total (months)
1,000 (~Base Case)	1 - 2	2 - 3	1 - 2	4 - 7
5,000 (~2030)	2 - 3	4 - 6	1 - 2	7 - 11
10,000	2 - 4	6 - 8	1 - 2	9 – 14
20,000	3 - 5	8 -10	2 - 3	13 - 18
40,000 (~2040)	3 - 6	14 - 16	2 - 3	19 - 25
100,000 (~2050)	5 - 8	18 - 20	3 - 4	26 - 32

8.3 Appendix C: Renewable Energy Integration

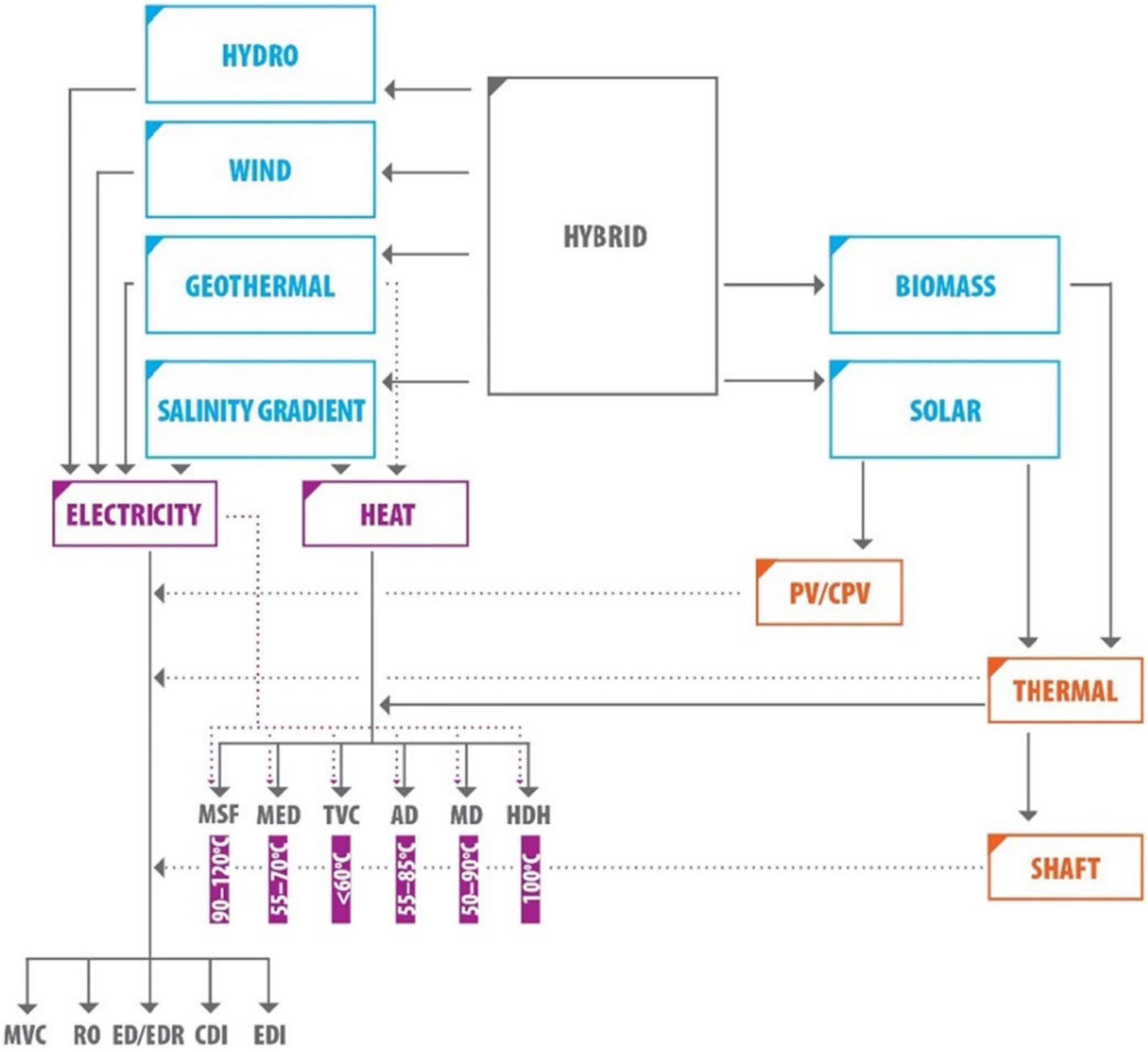


Figure 8-2: Desalination Techniques Integration with Renewable Energy [55]

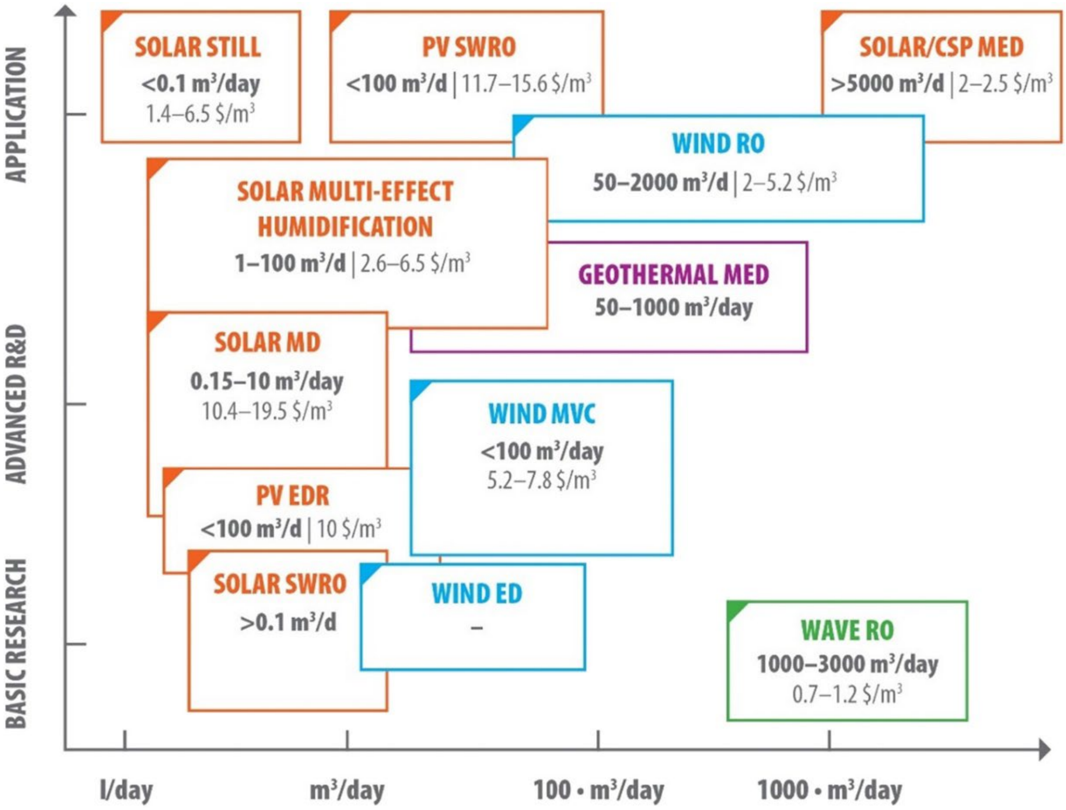


Figure 8-3: Desalination Techniques Integration with Renewables [55]

8.4 Appendix D: Seawater Salinity

Table 8-2: Ion Concentrations in Seawater [56], [57]

Chemical Ion	Concentration (g/kg)[1]	Proportion of Total Salinity (%)[2]
Chloride	19.345	55.03
Sodium	10.752	30.59
Sulfate	2.701	7.68
Magnesium	1.295	3.68
Calcium	0.416	1.18
Potassium	0.390	1.11
Bicarbonate	0.145	0.41
Bromide	0.066	0.19
Borate	0.027	0.08
Strontium	0.013	0.04
Fluoride	0.001	0.003

[1] Concentration for salinity of 35 g/kg. [2] Concentrations of ions in seawater is very consistent globally, even as overall salinity changes