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Australian Hydrogen Council

Water for Hydrogen

Technical Paper

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CSIRO

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Executive Summary

E1 Introduction

This technical study assesses water usage for a range of hydrogen production and hydrogen carrier conversion processes.

The study considers both water quality and quantity requirements throughout the hydrogen value chain and identifies opportunities for process wastewater recycling and reuse to enable water savings.

Securing suitable and sustainable water supply is fundamental to the development of the Australian hydrogen Industry, as envisioned by the National Hydrogen Strategy[1].

The Department of Climate Change, Energy, the Environment and Water (DCCEEW) and the Australian Hydrogen Council (AHC) have commissioned Arup to undertake this technical assessment of water needs for the development of the hydrogen industry.

A review of this technical report has been undertaken by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). This assessment will provide a robust technical basis for DCCEEW and AHC to further develop communication materials aimed at engaging a wide range of stakeholders with this topic.

This study aims to better understand the water usage for:

- hydrogen production process (green and blue); and
- hydrogen carrier conversion process (liquefaction and ammonia).

The study considers both water quality and quantity requirements for usage in each stage of the process. It also identifies where water is consumed by the process and where wastewater streams are recyclable and have potential for reuse in the system to enable water savings.

This technical report details the approach and results of the assessment undertaken, including first principles calculations and numerical modelling to estimate the water requirements in a selection of hydrogen production and conversion processes. A literature review on required water quality was carried out to support the analysis of water usage in hydrogen production and carrier conversion processes.

To assist with communication of the relative water usage in making hydrogen the report also includes brief commentary on:

- Social and environmental considerations when considering a particular water source, its quantity, potential treatment and by-products
- Example transport end use comparison. A comparison of water requirement in hydrogen fuel cell electric vehicles with traditional transport fossil derived fuels (petrol and diesel) used in combustion vehicles has been provided.

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[1] Australia's National Hydrogen Strategy (industry.gov.au). COAG Energy Council, 2019

When considering water requirements as part of a hydrogen project feasibility assessment, it is important to remember that the outputs of this technical study should not be considered in isolation. Instead, a holistic approach should be taken and the overall water requirement should be evaluated together with the access to sustainable water sources, security of water supply, mitigation of environmental and social impacts associated with hydrogen use and any other co-benefits opportunities.

As the industry moves from demonstration to commercial scale, real world information of water requirement for hydrogen production will become increasingly available and should be used to refine the figures in this study.

E2 Terminology

For the purpose of this assessment, the terminology of carrier conversion, hydrogen value chain, raw water, recyclable water, treated water, water consumption, water quality requirements, water requirement and water usage have been defined.

- **Carrier conversion**: process that converts hydrogen gas to another form - such as liquefied hydrogen or liquefied ammonia - for cost effective storage and transport.
- **Hydrogen value chain**: hydrogen gas production processes including conversion of hydrogen gas to other forms (carrier conversion).
- **Raw water**: water coming directly from its source of origin without having been treated to meet the water quality requirement of a specific process. Types of raw water include river water, seawater, recycled water from a wastewater treatment plant.
- **Recyclable water**: wastewater generated from water treatment or hydrogen processes that can be recycled or reused readily in the system (e.g. cooling water blow down or water treatment plant wastewater with low salinity).
- **Treated water**: water that has undergone a water treatment process to meet the water quality requirements of a specific process.
- **Waste stream:** used water that is degraded in quality and not readily able to be recycled or reused in the process (e.g brine)
- **Water consumption**: amount of water withdrawn from a water source that is not returned to its source of origin because it is incorporated into the products, lost through evaporation, or discharged as waste stream due to its degraded quality.
- **Water quality requirements**: water quality standards for a defined use. Water quality requirements may differ depending on the process.
- **Water requirement**: amount of water usage in the defined hydrogen value chain. Water requirement is the sum of water consumption, recyclable water and waste stream. Water usage and water requirement are used interchangeably throughout the document.

E3 Water-hydrogen value chain

Water requirement for hydrogen production and carrier conversion varies substantially depending on: project location, water source quality, water treatment method, hydrogen production method, cooling method and hydrogen carrier conversion process.

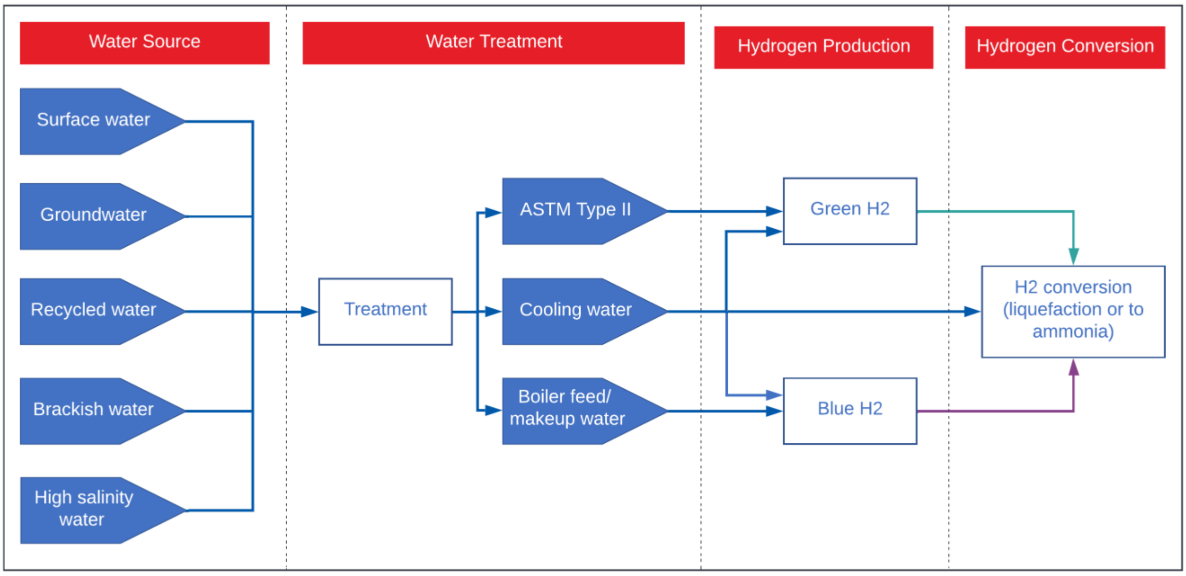
Water is essential for hydrogen production and conversion to hydrogen carriers, such as ammonia. Water can be consumed in the hydrolysis process to generate green hydrogen, as heating source in the steam methane reforming process (blue hydrogen), as well as to convert hydrogen into ammonia. Water is also required as a cooling medium in both the green and blue hydrogen production processes, and to liquefy hydrogen gas.

The water usage for hydrogen is dictated by the:

- Source water quality
- Water treatment method,
- Hydrogen production method,
- Boiler or cooling system type,
- Carrier conversion method.

Figure E-1 illustrates the relationship between the water requirement elements listed above.

Figure E-1: Flow chart of the water-hydrogen value chain considered in the scope of this study



E4 Water sources and treatment

Sources of water will vary depending on the location and the local social, environmental, regulatory, and economic factors. Water sources considered in this assessment include recycled water, surface water, groundwater, brackish water, and seawater. The water quality of raw water sources is highly variable and therefore raw water must be treated to water quality standards before being used. The water quality specifications for hydrogen production vary depending on the usage. For example, feedstock water for electrolyser (e.g for PEM electrolyser: Demineralised ASTM Type II water) would be of much higher standard than the water used for evaporative cooling system or heating.

Water sources have been categorised by their water quality and associated treatment needs to meet the input requirements for each hydrogen production type. As the quality of ASTM Type II water and cooling water is associated with conductivity or Total Dissolved solids (TDS), this has been used as an indicator of water quality. For example, low TDS values mean less treatment requirements, less energy demand and higher water recovery.

In summary the ranking of preferred raw water sources for the production of hydrogen, based on water recovery and energy efficiency considerations is as follows:

- Advanced recycled water (Class A water with RO treatment)
- Surface water & ground water with low salinity (TDS < 800 mg/L)
- Class A water (without additional treatment by RO), brackish water, and
- Seawater

Advanced recycled water is considered the most sustainable water source as it requires the least treatment level with lower water consumption compared to seawater.

Water quality requirements vary across the different hydrogen production and carrier conversion processes. The volume of water required in the water treatment process to meet the input water quality standards depends on the quality of water source. The water source quality will also determine the volume of the waste stream, with high salinity water (such as seawater) producing a brine stream that will need to be sustainably managed.

Water can be drawn from a range of sources, including:

- Surface water (e.g., lakes dams rivers and creeks)
- Groundwater (e.g., aquifers bore water springs)
- Recycled water (e.g., treated wastewater effluent)
- Brackish water sources (e.g., saline surface water and groundwater)
- High salinity water sources (e.g., seawater estuary water).

Associated and co-produced water from oil and gas extraction are a further water source. These have not been defined as a separate source as the water quality would typically match one of the categories above (depending on the salinity). For the purposes of this assessment, these water sources have been categorised by their average water quality, expressed as Total Dissolved Solids (TDS). TDS is an important parameter to determine treatment requirements to achieve the quality at point of use. Figure E-2 below shows the typical water quality and treatment steps for each water source.

Figure E-2: Water source quality, treatment requirements for hydrogen value chain applications

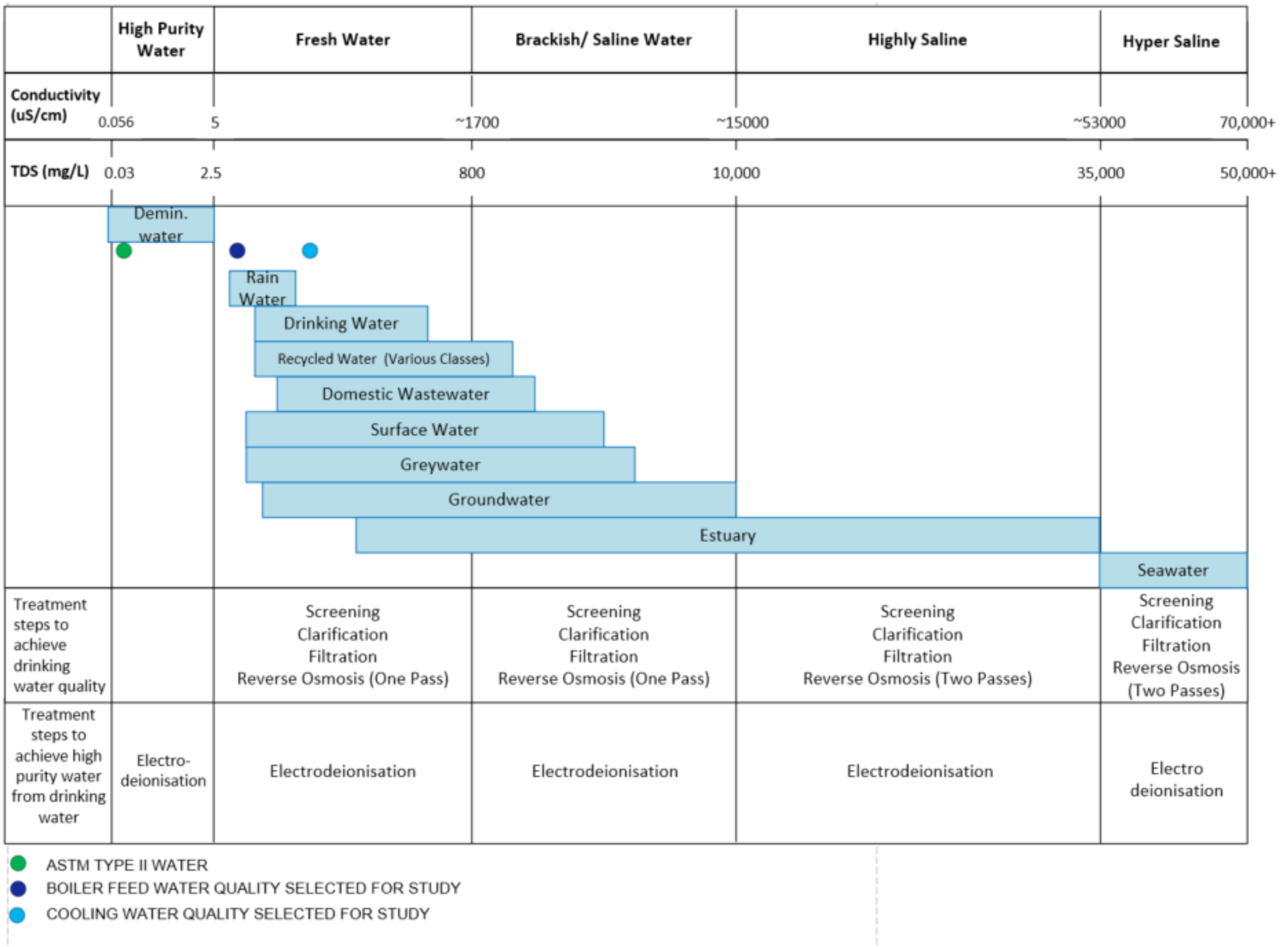


Table E-1 explains the treated water product and application in hydrogen processes that reflected in Figure E-2.

Table E-1: Treated water product required for hydrogen process application

Treated water product		Application
●	ASTM Type II water	PEM (Proton exchange membrane) electrolyser
●	Cooling water	Hydrogen processes that involve cooling water
●	Boiler feed makeup water	Blue hydrogen – Steam Methane Reformation

E5 Water Use in Hydrogen Production

Water is used and consumed for hydrogen production and carrier conversion as both feedstock and cooling agent. Water is consumed in the electrolyser and reacting with methane as steam to produce green and blue hydrogen respectively. Feedstock water consumption is relatively known by the industry, as reported in numerous publications such as the Australia's National Hydrogen Strategy[2].

This study reports that **9 – 11 litres of demineralised water are consumed to produce 1 kg of green hydrogen,** using PEM electrolysis technology. This range accounts for various mode of electrolyser operations, and under different type of climate zone and age of the electrolyser. **5 litres of boiler feed water in the form of steam are required to produce 1 kg of blue hydrogen**.

Cooling water has the potential to be the largest contributor to water usage in the hydrogen value chain. Cooling water requirements range substantially based on cooling process type and climatic conditions. Evaporative, air cooled and once-through cooling processes were assessed in this study. Overall, water usage is the highest for once-through cooling systems and lowest for evaporative cooling systems. Once -through systems do not present water losses while evaporative cooling systems require makeup water to account for some losses.

For evaporative cooling system, makeup water can range from 3 litres in the coolest or high humidity area to 60 litres in the hottest or low humidity area per kg of green hydrogen. Cooling water for blue hydrogen production is less than for green hydrogen, ranging between 20 to 24 litres per kg of hydrogen.

The wide range of water consumption for cooling highlights the need to carefully consider water-efficient cooling system design in water-scarce and high evaporation regions.

E5.1 Cooling system alternatives

The type of cooling system used for hydrogen production and carrier conversion has a significant effect on the amount of water usage in a system. For this reason, our review has included the three main cooling system options: evaporative closed loop cooling, once-through cooling and air cooling, indicating where water is consumed by the process.

While water requirements for once-through cooling are significantly higher than for evaporative cooling, this water is not consumed in the process. Assumed with adequate material of construction for the cooling system, all water sources assessed in the report can be used with simple filtration process and it can return to the environment, provided impacts are appropriately managed (refer to Section 7.9 for management of environmental impacts).

An overview of the differences between these cooling systems is presented in Table E-2 below and Section 2 of this report.

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[2] Australia's National Hydrogen Strategy. COAG, 2019. Pp12. Australia's National Hydrogen Strategy (industry.gov.au)

Table E-2: Cooling Technologies Advantages and Disadvantages

ONCE THROUGH COOLING		EVAPORATIVE COOLING		AIR COOLING	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**	**Advantages**	**Disadvantages**
Little or no water consumption No treatment of cooling water needed Low energy use	Large & continuously replenished total water requirement Siting must be adjacent to water body Potential environmental impact due to high temperature of return water High maintenance	Less total water required than once through Lower energy use Higher efficiency in removing heat	Higher water consumption due to evaporation, higher in dry zone Treatment of cooling water required High maintenance	Zero water required Lower maintenance No waste stream discharge	High capital cost High energy use Large footprint Less effective in dry zone, high temperature Fan noise

E5.2 Green hydrogen production

There are several key variables that affect the water requirements for green hydrogen production. The variables assessed in this study include electrolyser efficiency, electrolyser types (PEM versus Alkaline), electrolyser design (Low end vs High end), climatic conditions (Dry zone versus Wet zone), age of equipment (Beginning of life versus End of life) and operating profile (Variable versus Constant).

Alkaline electrolysers are currently more commonly used for electrolytic hydrogen production, however, due to operational and performance enhancements, PEM electrolysers are becoming more common and seen to be appropriate for utilization in renewable energy systems (RES) because of their ability to operate dynamically with rapid response times. In general PEM has lower process water requirements than Alkaline electrolysers, and new systems operated constantly are more efficient and have lower water use. There is less evaporation for hydrogen production processes in wet zones.

For example, for a new, high-end PEM electrolyser operating under a variable profile in a wet zone in Australia, the estimated total water consumption including evaporative cooling is 14 litres of treated water per kilogram of hydrogen. Alternatively, a low-end PEM electrolyser at the end of life, operating under constant conditions in a dry zone in Australia has an estimated water consumption including evaporative cooling of 60 treated litres of water per kilogram of hydrogen.

A summary of green hydrogen water requirements is provided in Table E-3.

Table E-3: Green Hydrogen Water Requirements

Water application	PEM electrolyser operating conditions			Treated water consumed @ point of use		Raw water requirement from source (L/kg of H_2)				
	Asset condition	**Asset performance**	**Climate zone**	**(L/kg H_2)**	**Ref. in report**	**Surface water**	**Ground water**	**Recycled water**	**Brackish water**	**Seawater**
Process water	Beginning of Life	High end	Dry zone	9.1	Table 3-4	15.0	17.4	25.1	23.8	25.1
	Beginning of Life	Low end	Dry zone	9.2	Table 3-4	15.1	17.6	25.3	24.1	25.4
	End of Life	Low end	Dry zone	9.3	Table 3-5	15.3	17.8	25.6	24.4	25.6
	Beginning of Life	High end	Wet zone	9.1	Table 3-8	15.0	17.4	25.1	23.8	25.1
Evaporative cooling water	Beginning of Life	High end	Dry zone	23.0	Table 3-4	27.1	39.6	53.8	51.1	57.0
	Beginning of Life	Low end	Dry zone	43.0	Table 3-4	50.7	74	100.6	95.6	106.7
	End of Life	Low end	Dry zone	61.2	Table 3-5	72.2	105.3	143.2	136	151.9
	Beginning of Life	High end	Wet zone	14.0	Table 3-8	16.5	24.1	33.9	31.1	34.7
Total water requirement with evaporative cooling system	Beginning of Life	High end	Dry zone	32.1		42.1	57	78.9	74.9	82.1
	Beginning of Life	Low end	Dry zone	52.2		65.8	91.6	125.9	119.7	132.1
	End of Life	Low end	Dry zone	70.5		87.5	123.1	168.8	160.4	177.5
	Beginning of Life	High end	Wet zone	23.1		31.5	41.5	59	54.9	59.8
Total water requirement with air cooling system	Beginning of Life	High end	Dry zone	9.1		15.0	17.4	25.1	23.8	25.1
	Beginning of Life	Low end	Dry zone	9.2		15.1	17.6	25.3	24.1	25.4
	End of Life	Low end	Dry zone	9.3		15.3	17.8	25.6	24.4	25.6
	Beginning of Life	High end	Wet zone	9.1		15.0	17.4	25.1	23.8	25.1

E5.3 Blue hydrogen production

For blue hydrogen, this study indicates that there is less variability in water requirements, with 5.2 litres of treated water per kilogram of hydrogen and a range of 13-19 litres of treated water per kilogram of hydrogen if evaporative cooling is used, depending on the climatic zone (wet zone versus dry zone).

The variability in cooling requirement for blue hydrogen production plants is limited. This means that the variability in water requirements is also limited if a water-cooling system is used. The two main parameters that impact the system's cooling requirement are process efficiency and carbon capture rate. These parameters are not expected to vary significantly between plants. Steam methane reforming (SMR) is an established technology that has been optimised over many years and no significant improvements are expected in the future. The International Energy Agency, in their "The Future of Hydrogen" report[3], assume the efficiency of steam methane reforming with carbon capture to remain constant in the future. Similarly, the carbon capture rate for future plants is assumed to remain around the 90% mark, as lower rates would lead to increased emissions that could impact the "low-emissions" definition of the hydrogen produced, while higher rates could significantly increase the capital and operational costs of the plant.

A summary of blue hydrogen water requirements is provided in Table E-4.

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[3] “The Future of Hydrogen”, International Energy Agency, 2020 https://iea.blob.core.windows.net/assets/29b027e5-fefc-47df-aed0-456b1bb38844/IEA-The-Future-of-Hydrogen-Assumptions-Annex_CORR.pdf

Table E-4: Blue Hydrogen water requirements

Water application	Site operating conditions	Treated water consumed @ point of use		Raw water requirement from source (L/kg of H_2)				
	Site climate zone	(L/kg of H_2)	Ref. in report	Surface water	Ground water	Recycled water	Brackish water	Seawater
SMR - Process water	Dry zone	5.2	Table 4-4	8.6	9.9	14.3	13.6	14.3
	Wet zone	5.2	Table 4-4	8.6	9.9	14.3	13.6	14.3
SMR - Evaporative cooling tower - Makeup water	Dry zone	19.0	Table 4-4	22.4	32.7	44.4	42.2	47.1
	Wet zone	15.0	Table 4-4	17.7	25.8	35.1	33.3	37.2
Total water requirement with evaporative cooling system	Dry zone	24.0		31	42.6	58.7	55.8	61.4
	Wet zone	20		26.3	35.7	49.4	46.9	51.5
Total water requirement with air cooling system	Dry zone	5.2		8.6	9.9	14.3	13.6	14.3
	Wet zone	5.2		8.6	9.9	14.3	13.6	14.3

E5.4 Water use for boiler feed water

Steam is used as a heat source and feedstock in the SMR process for blue hydrogen production, as well as heat source in the conversion of hydrogen to ammonia gas as alternative hydrogen carrier. Steam is produced in a steam generator or boiler where water is boiled, and the vapour is discharged at a controlled temperature and pressure. As vapour leaves the boiling water, the dissolved solids originally in the water are left behind and becomes increasingly concentrated and eventually reaches a level where further concentration could cause scale or deposits, resulting in problems with steam quality and purity. Steam can be consumed in the process such as SMR or lost within the process via pressure relief valve, but the majority is recirculated within the boiler system. Water makeup is only used to compensate steam losses and to top up the boiler feed to keep the dissolved solids under the threshold.

E6 Water use in hydrogen carrier conversion

Both liquefaction of hydrogen and conversion to ammonia (Haber Bosch process) require water for process cooling. Cooling water demand per kg of hydrogen is ranging from **13 – 31** litres for hydrogen liquefaction and is approximately 28 litres for conversion to ammonia.

E6.1 Hydrogen liquefaction

While the hydrogen liquefaction process does not consume any process water, it does require considerable water for cooling. The water cooling load varies significantly depending on the design efficiency of the liquefaction process and its specific energy consumption (SEC [MJ/kg H_2]). To facilitate the development of a large-scale hydrogen economy, new hydrogen liquefiers must be designed with strong efficiency in mind to minimise water consumption and costs. Increasing efficiency for the liquefaction process is not out of reach because to date liquefaction plants have been designed with the main goal of minimising initial capital expenses rather than achieving high efficiencies. Consequently, there is great potential to improve the hydrogen liquefaction process and thus reduce the SEC for large-scale hydrogen liquefiers.

For a current low efficiency design (SEC = 54 MJ/kg H_2) using evaporative cooling, the estimated water consumption is 31 litres of treated water per kilogram of hydrogen.

A high number of conceptual design studies on highly efficient large-scale hydrogen liquefaction plants have been published in the literature. The U.S. Department of Energy selected 6.0 kWh/kg (SEC = 21.6 MJ/kg) as their target for hydrogen liquefaction SEC[4]. For this future design efficiency (SEC = 21.6 MJ/kg H_2) using evaporative cooling, the estimated treated water consumption is 13 litres of water per kilogram of hydrogen.

The expected transition towards more energy efficient liquefaction processes, together with the likely increase in the number and size of hydrogen liquefaction plants, will lead to the achievement of considerably higher liquefaction efficiencies. Therefore, it is safe to assume that in the near future the efficiency of hydrogen liquefaction plants will be between the current high-efficiency plants and the U.S. Department of Energy efficiency target.

A summary of hydrogen liquefaction water requirements is provided in Table E-5.

Table E-5: Hydrogen liquefaction water requirements

Water application	**System Efficiency**	**Treated water consumed @ point of use**		**Raw water requirement from source (L/kg of H_2)**				
		(L/kg of H_2)	**Ref. in report**	**Surface water**	**Ground water**	**Recycled water**	**Brackish water**	**Seawater**
Hydrogen liquefaction – Process water	Not applicable as no process water involved							
Hydrogen liquefaction - Evaporative cooling tower - Makeup water = Total water requirement	Low	31	Table 5-4	36.6	53.3	72.5	68.9	76.9
	High	25	Table 5-4	29.5	43.0	58.5	55.6	62.0
	Future target	13	Table 5-4	15.3	22.4	30.4	28.9	32.3
Hydrogen liquefaction with air cooling system – Total water requirement				0	0	0	0	0

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[4] DOE Technical Targets for Hydrogen Delivery, Office of Energy Efficiency & Renewable Energy https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-delivery

E6.2 Ammonia water requirements

For the process of converting green hydrogen to ammonia, there are no process water requirements, however there is a cooling load in the Air Separation Unit (used to produce the nitrogen) and in the ammonia synthesis. A summary of water requirements for ammonia conversion is provided in the table below. Note that this excludes the water that is used in the hydrogen production process, which is captured separately in Section E5.

A summary of ammonia conversion water requirements is provided in Table E-6.

Table E-6: Ammonia conversion water requirements

Water application	**Treated water req'd @ point of use**		**Raw water requirement from source (L/kg of H_2)**				
	(L/kg of H_2)	**Ref. in report**	**Surface water**	**Ground water**	**Recycled water**	**Brackish water**	**Seawater**
Ammonia conversion – process water	Not applicable as no process water involved						
Conversion to liquid ammonia via Haber Bosch process - Evaporative cooling tower - Makeup water	28.0	Table 6-3	33.0	48.2	65.5	62.2	69.5

E8 Hydrogen value chain summary

E8.1 Water requirement

The water requirements for each hydrogen value chain as provided in Table E-3 to Table E-6 have been plotted and shown in Figure E-3 to Figure E-5.

The study found that the water requirement for the production of green hydrogen is generally higher than blue hydrogen due to both water feedstock consumption and cooling water consumption/losses.

When carrier conversion to liquid ammonia or liquefied hydrogen is required there is additional water requirement. It is expected that future advancements in the liquefaction process technology may reduce the water usage for liquefaction, and have the potential to have water usage well below that for ammonia in the future.

With regard to cooling options, air cooling does not use water and should be adopted where conditions are suitable to reduce the overall water requirement. Once-through cooling has high water requirement however almost all of the water is recyclable back to the raw water source. Evaporative cooling has high water requirement and high water consumption / losses due to evaporation. Evaporative cooling is suited to a wide range of conditions, and there are less evaporative water losses in wet climate conditions.

Figure E-3: Total water requirement for hydrogen production, evaporative cooling (dry zone)

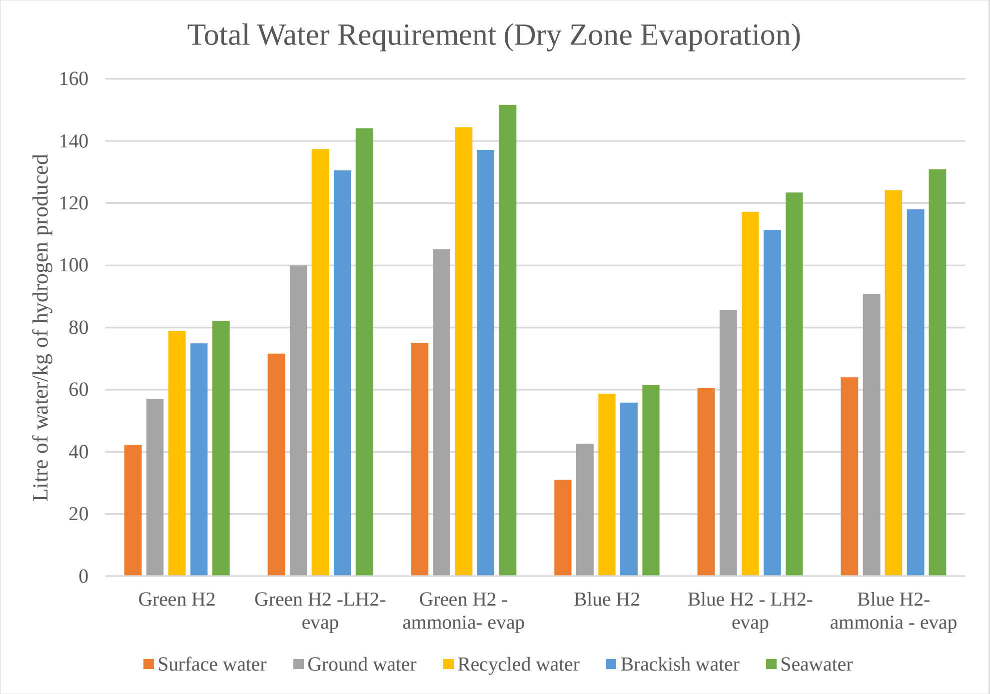


Figure E-4: Total water requirement for hydrogen production (wet zone)

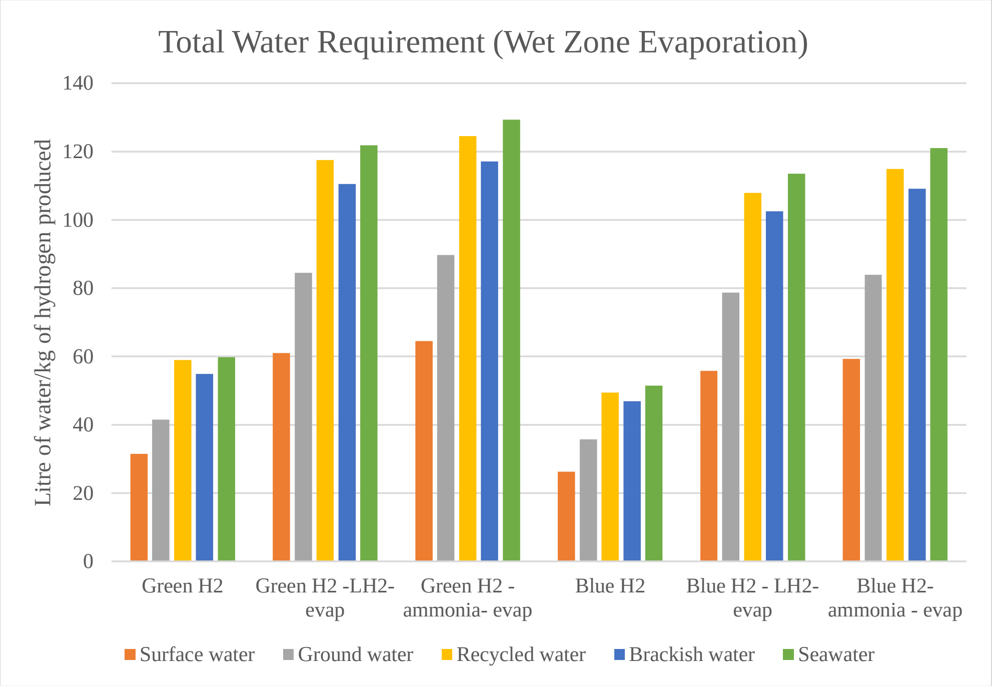
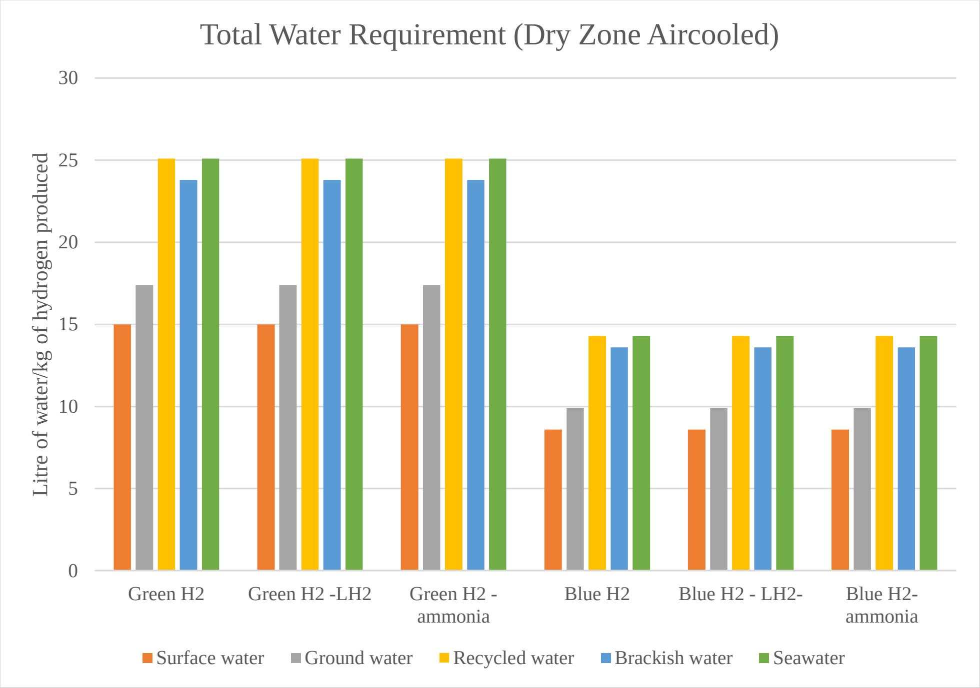


Figure E-5: Total water requirement for hydrogen production (air cooled)



E8.2 Water consumption and recyclable water

Figure E-6 provides a summary of water consumed for each of hydrogen production and carrier conversion process for each raw water source. Evaporative cooling and air cooling is assumed for the hydrogen value chains and a comparison between wet and dry climatic conditions assessed.

How much water is consumed and what can be recycled or reused needs to be considered during assessment of water requirement and its source. This will determine the net amount of water requires from the source, and how much can be safely returned to help the environment if reuse is not required.

Figure E-6: Range of total water consumption for production method assessed

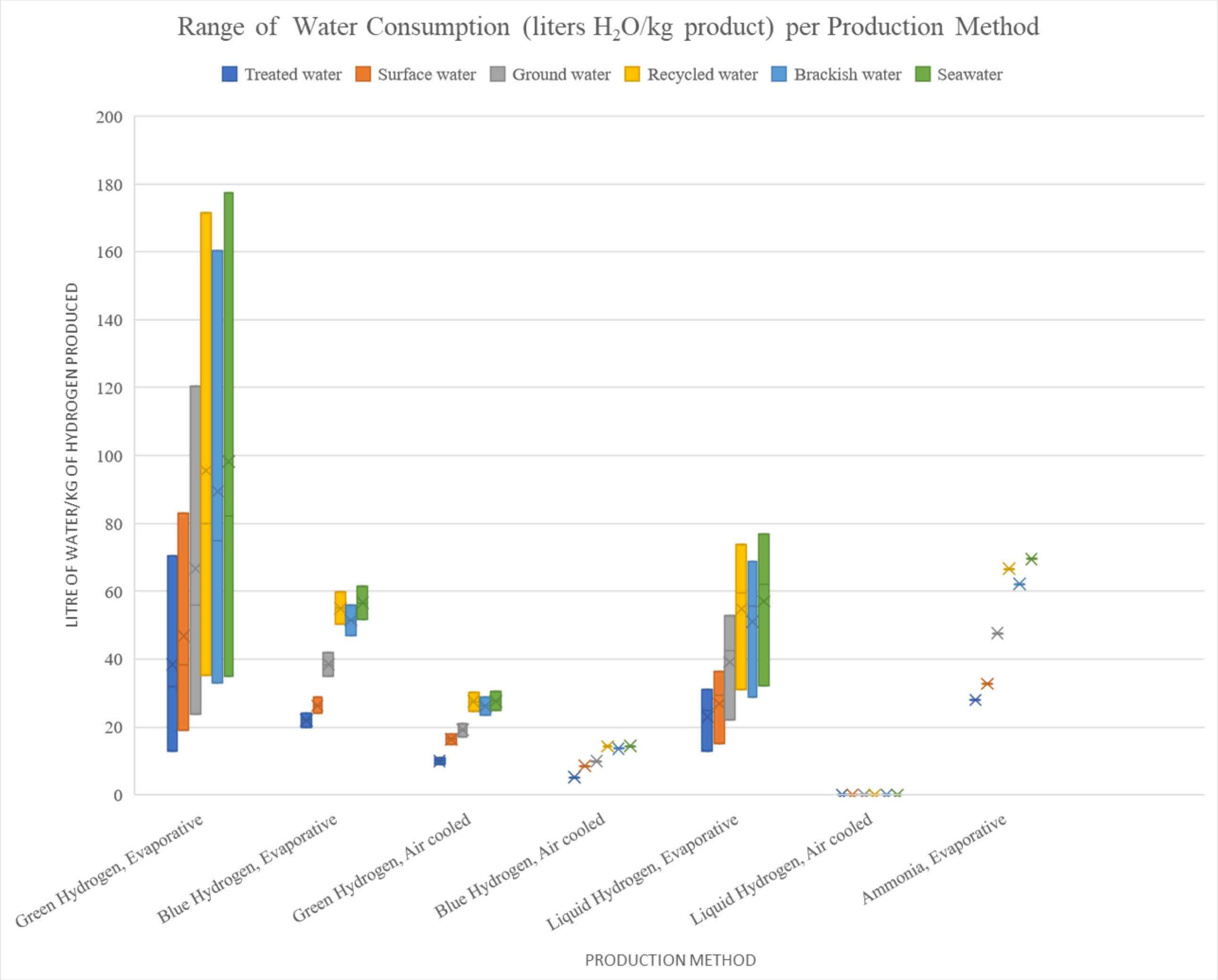


Figure E-6 Note:

- Figure E-6 summarises water consumption used in hydrogen production and carrier conversion processes for the source water categories assessed
- Water consumption volumes provided in the graph cover various climate zones, electrolyser design efficiency and electrolyser operating condition for each production method.
- For the total water consumption of a hydrogen carrier supply chain (liquified hydrogen or ammonia), the water consumed for hydrogen production needs to be added to the water consumed for hydrogen carrier conversion.
- Water returned to a source system such as in once through water cooling is not included in the Figure E-6 water consumption graph. Water requirement including for once through cooling is provided in the water requirement calculation tables for each value chain in this report.

Figure E-7 to Figure E-9 provide a breakdown of water requirements for green hydrogen production only (without carrier conversion) and use evaporative and air-cooling systems under wet and dry climate zones. Below is the summary of the assessment:

- Air-cooling system has lower water usage than evaporative cooling system, however advantages and disadvantages of various cooling technologies should be considered in the overall assessment,

- Cooling water makeup contribute a large portion on water usage, and site within wet climate zone tends to have lower water usage than dry zone,
- To produce 1kg of H_2, the order from lowest to highest water usage is:
  - Surface water
  - Ground water
  - Brackish water
  - Recycled water
  - Seawater
- Manufactured water sources such as from wastewater treatment plants (recycled water) and desalinated seawater provide sustainable supply and are less likely to compete with existing water use and thus gain community acceptance.
- Seawater has the highest water usage with the least recyclable water availability as waste streams from the treatment processes are too saline for reuse. This is similar to brackish water.

Figure E-7: Total Water Requirement Breakdown (Dry Zone)

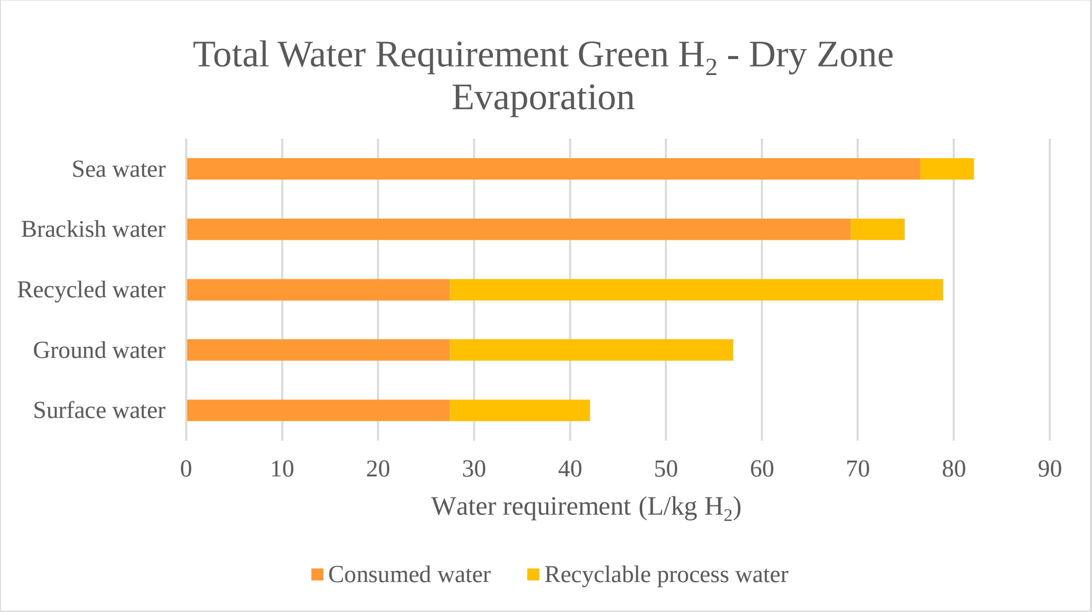


Figure E-8: Total Water Requirement Breakdown (Wet Zone)

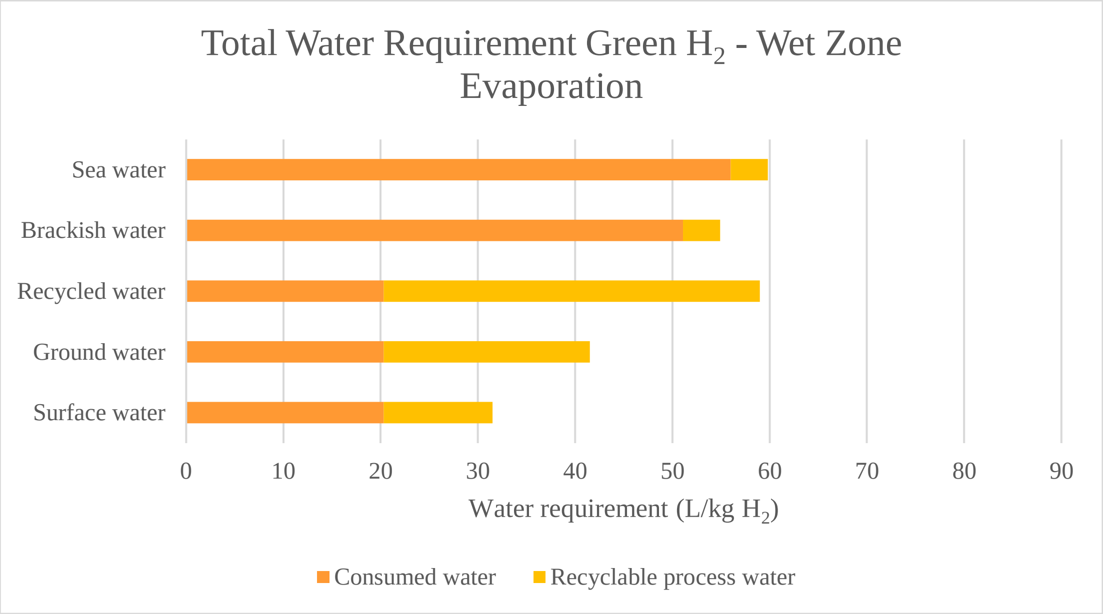
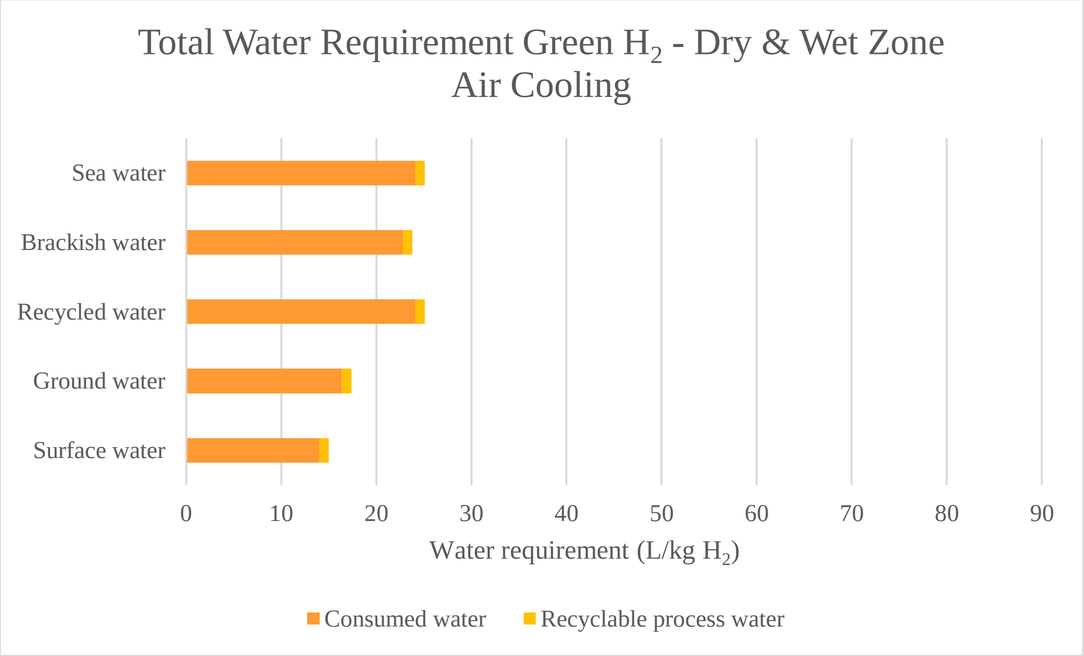


Figure E-9: Total Water Requirement Breakdown (Air Cooling)



E8 Example end use comparison – alternative transport fuels

A comparison of water usage for select transport end-use cases was undertaken. Hydrogen fuel cell electric vehicles (FCEV) and fossil fuel combustion engines - diesel & petrol, for both passenger car and bus applications - were considered.

The assessment has provided ranges of water consumed per 100km travelled. The water use ranges are predominantly reflective of the variance in water usage in fuel production including process cooling (Section 8.6 for petrol and diesel). The assumptions on fuel consumption for vehicles are provided in Section 0. It is noted that FCEV also produce water in the tailpipe however this was not assessed.

This study found that the water consumption for hydrogen used in FCEV passenger cars and buses is generally within comparable ranges of fossil fuels used in traditional combustion engines.

For passenger vehicles, it is notable that the water consumption is similar to an evaporative water-cooled system hydrogen production and traditional fuels; however if air cooling is used, then the water consumption for hydrogen is significantly lower.

Water consumption of diesel fuelled combustion engine buses is also generally considered within comparable range to FCEV for blue and green hydrogen using air cooling and also the lower range of evaporative cooling of blue hydrogen i.e. low evaporation (wet, cooler) conditions. Water requirement for evaporative cooling processes for green hydrogen is considerably higher particularly when operating in the upper limits of high evaporation (hot and dry) environments of Australia.

E8.1 Water consumption of petrol and diesel production

Water is used in the drilling and recovery operations of crude oil. It is also used in the refining process, when converting to products such as diesel or petrol. Water is also naturally present in the rocks and may be extracted along with oil. This co-produced water needs to be treated and disposed or reused according to regulations and with consideration of environmental impact. The quantity and quality of water used, produced and disposed of varies depending on local geology, recovery technologies and regulations[5].

Water consumption in crude oil production depends on the type of oil field, oil recovery technology, age of the oil well and degree of produced water recycling. The results of this desktop literature review indicate that the water consumption of petrol and diesel is dominated by the water consumed during crude oil production, with 1.3 - 5.1 litres of water consumed per litre of petroleum product[6]. During refining, petrol refining consumes the largest amount of water, 0.60–0.71 L water/L petrol, due to the energy-intensive (and thus water-intensive) processing of petrol components.[7]

The water consumption of diesel is most sensitive to refinery configuration with 0.20, 0.30, and 0.40 L water/L diesel for cracking, light coking and heavy coking configurations, respectively.[8]

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[5] American Geosciences: Water in the Oil and Gas Industry, 2018 https://www.americangeosciences.org/geoscience-currents/water-oil-and-gas-industry

[6] Consumptive water use in the production of ethanol and petroleum gasoline, Argonne National Laboratory, 2009 https://www.researchgate.net/publication/236532942_Consumptive_water_use_in_the_production_of_ethanol_and_petroleum_gasoline

[7] Estimation of U.S. refinery water consumption and allocation to refinery products https://www.sciencedirect.com/science/article/pii/S0016236117309511

[8] Estimation of U.S. refinery water consumption and allocation to refinery products https://www.sciencedirect.com/science/article/pii/S0016236117309511

A summary of water consumption associated with petrol and diesel production supplied from literature is provided in Table E-7.

Table E-7: Summary of water consumption for petrol and diesel production

	Petrol	**Diesel**
Water consumption during crude oil production (L/L petroleum product)[9]	1.3 - 5.1	1.3 - 5.1
Water consumption during refining (L/L petroleum product)[10]	0.6 - 0.71	0.2 - 0.4
Total water consumption (L/L petroleum product)	1.9 - 5.8	1.5 – 5.5

E8.2 Comparison of water consumption of hydrogen to petrol and diesel in vehicles

This summary provides a comparison of the water consumption associated with hydrogen used in a fuel cell electric vehicle and petrol and diesel used in passenger vehicle combustion engines.

Fuel consumption per 100 km travelled have been assumed as follows:

- Hydrogen Electric Fuel Cell Passenger Vehicle: 1 kg hydrogen per 100 km[11]
- Petrol Combustion Engine Passenger Vehicle: 11.1 L petrol per 100 km in 2020[12]
- Diesel Combustion Engine Passenger Vehicle: 11.4 L petrol per 100 km in 2020[13]
- Fuel Cell Electric Bus (FCEB): 9.5 kg hydrogen per 100 km in 2021[14]
- Diesel bus: 42.5 L diesel per 100km in 2021[15]

It is noted that fuel/energy consumption of all vehicles is dependent on a number of factors including engine efficiency and maintenance, and driving conditions for metro or regional settings. For the purposes of this study fuel consumption for each vehicle option has been selected from literature to reflect comparable Australian conditions where possible.

Table E-8 shows the water consumption of travelling 100 km using green or blue hydrogen in an electric fuel cell vehicle compared to a petrol or diesel combustion engine.

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[9] Consumptive water use in the production of ethanol and petroleum gasoline, Argonne National Laboratory, 2009 https://www.researchgate.net/publication/236532942_Consumptive_water_use_in_the_production_of_ethanol_and_petroleum_gasoline

[10] Estimation of U.S. refinery water consumption and allocation to refinery products https://www.sciencedirect.com/science/article/pii/S0016236117309511

[11] Research on Hydrogen Consumption and Driving Range of Hydrogen Fuel Cell Vehicle, 2021 https://www.mdpi.com/2032-6653/13/1/9/pdf#:~:text=According%20to%20the%20data%20in,is%200.983%20kg%2F100%20km.

[12] Australian Bureau of Statistics - Survey of Motor Vehicle Use in Australia, 2020 https://www.abs.gov.au/statistics/industry/tourism-and-transport/survey-motor-vehicle-use-australia/latest-release

[13] Australian Bureau of Statistics - Survey of Motor Vehicle Use in Australia, 2020 https://www.abs.gov.au/statistics/industry/tourism-and-transport/survey-motor-vehicle-use-australia/latest-release

[14] Institute of Transport and Logistics Studies: Comparative assessment of zero emissions electric and hydrogen buses in Australia, 2021 pp7 https://www.sydney.edu.au/content/dam/corporate/documents/business-school/research/itls/zero-emission-electric-and-hydrogen-buses.pdf

[15] Institute of Transport and Logistics Studies: Comparative assessment of zero emissions electric and hydrogen buses in Australia, 2021 pp6 https://www.sydney.edu.au/content/dam/corporate/documents/business-school/research/itls/zero-emission-electric-and-hydrogen-buses.pdf

Table E-8: Comparison of water consumption of alternative fuels in select transport applications

	Fuel type					
Vehicle type	**Green hydrogen (air cooling)** [16]	**Green hydrogen (evaporative cooling)** [17]	**Blue hydrogen (air cooling)**	**Blue hydrogen (evaporative cooling)**	**Petrol**	**Diesel**
Passenger vehicle - Water consumption (L / 100 km)	Process water: 9 – 11	Process water and cooling water: 21 - 71	Process water: 5.2	Process water and cooling water: 18 - 24	From crude oil production: 14 - 57 From refining: 7 - 8	From crude oil production: 15 - 58 From refining: 2 - 5
Passenger vehicle – Total water consumption (L / 100 km)	**9-11**	**21 - 71**	**5.2**	**18 - 24**	**21 - 64**	**17 - 63**
Buses - Water consumption (L / 100 km)	Process water: 86 - 105	Process water and cooling water: 200 - 675	Process water: 49	Process water and cooling water: 171 - 228	-	From crude oil production: 55- 217 From refining: 9 - 17
Buses - Total Water consumption (L / 100 km)	**86 - 105**	**200 - 675**	**49**	**171 - 228**	**-**	**64 - 234**

For passenger vehicles, water consumption is within comparable ranges between hydrogen FCEV and fossil fuels in traditional combustion engines. Green hydrogen production using evaporative water-cooled system is most similar to fossil fuels, whilst green hydrogen and blue hydrogen using air cooled processes are significantly lower water usage.

For heavier vehicles such as buses, the heavier the load that the vehicle is required to carry, the higher the fuel consumption. Water consumption of diesel fuelled combustion engine buses is also generally considered within comparable range to blue and green hydrogen using air cooling and also the lower range of evaporative cooling of blue hydrogen ie low evaporation (wet, cooler) conditions. Water usage for evaporative cooling processes for green hydrogen is considerably higher particularly in the upper limits of high evaporation (hot and dry) environments of Australia.

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[16] Refer to section 3.3 for details on the range

[17] Refer to section 3.3 for details on the range

1. Introduction

1.1 Study Purpose & Use of Information

Securing suitable and sustainable water supply is fundamental to the development of the Australian hydrogen Industry as envisioned by the National Hydrogen Strategy[18].

The Department of Climate Change, Energy, the Environment and Water (DCCEEW) and the Australian Hydrogen Council (AHC) have commissioned Arup to undertake this study, to provide a technical assessment of water needs for the development of the hydrogen industry. Review has been provided by the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

The Department of Climate Change, Energy, the Environment and Water (DCCEEW) is responsible for consolidating the Government's efforts to drive economic growth, productivity and competitiveness by bringing together industry, energy, resources and science. DCCEEW supports the Hydrogen Project Team with activities to advance Australia's hydrogen industry and in implementing the National Hydrogen Strategy.

The Australian Hydrogen Council (AHC) is the peak body for the hydrogen industry in Australia representing its membership across the hydrogen value chain.

Water supply is one of the key components in the production of hydrogen. The ability to supply and manage this scarce resource in a sustainable way has been identified by DCCEEW and AHC as a critical area in which to provide support and engage industry stakeholders.

DCCEEW and AHC have engaged Arup to undertake this 'Water Usage in Hydrogen' study to better understand the considerations and potential design requirements regarding the supply and treatment of water for the production of hydrogen and conversion of hydrogen carriers in Australia.

This study aims to provide DCCEEW and AHC with a robust technical basis upon which to further develop communications materials, progress communications with stakeholders and support the wider industry to better engage with the topic. This study has been undertaken within the parameters agreed with DCCEEW and AHC for this intended purpose. It is not intended to be used as a standalone publication.

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[18] Australia's National Hydrogen Strategy (industry.gov.au). COAG Energy Council, 2019

1.2 Terminology

The following terminology is defined for use in this study:

Table 1-1: Terminology

Terminology	Definition for this report
Basis of design	Assumptions on equipment configuration and battery limits of the assessment for the water usage in hydrogen study.
Carrier conversion	Process that converts hydrogen gas to another form - such as liquefied hydrogen or liquefied ammonia - for cost effective storage and transport.
Hydrogen process	A process that involves either production or conversion of hydrogen. In this report, hydrogen process refers to green hydrogen production, blue hydrogen production, hydrogen liquefaction or ammonia conversion.
Hydrogen value chain	Hydrogen gas production processes including conversion of hydrogen gas to other forms (carrier conversion).
Raw water	Water coming directly from its source of origin without having been treated to meet the water quality requirement of a specific process. Types of raw water include river water, seawater, recycled water from a wastewater treatment plan
Recyclable water	Wastewater generated from water treatment or hydrogen processes that can be recycled or reused readily in the system (e.g. cooling water blow down or water treatment plant wastewater with low salinity).
Treated water	Water that has undergone a water treatment process to meet the water quality requirements of a specific process.
Water requirement	Amount of water usage in the defined hydrogen value chain. Water requirement is the sum of water consumption, recyclable water and waste stream. Water usage and water requirement are used interchangeably throughout the document.
Water consumption	Amount of water withdrawn from a water source that is not returned to its source of origin because it is incorporated into the products, lost through evaporation, or discharged as waste stream due to its degraded quality.
Water quality requirement	Water quality standards for a defined use. Water quality requirements may differ depending on the process. Water quality requirements are summarised in Section 7.4.
Waste stream	Used water that is degraded in quality and not readily able to be recycled or reused in the process (e.g brine)

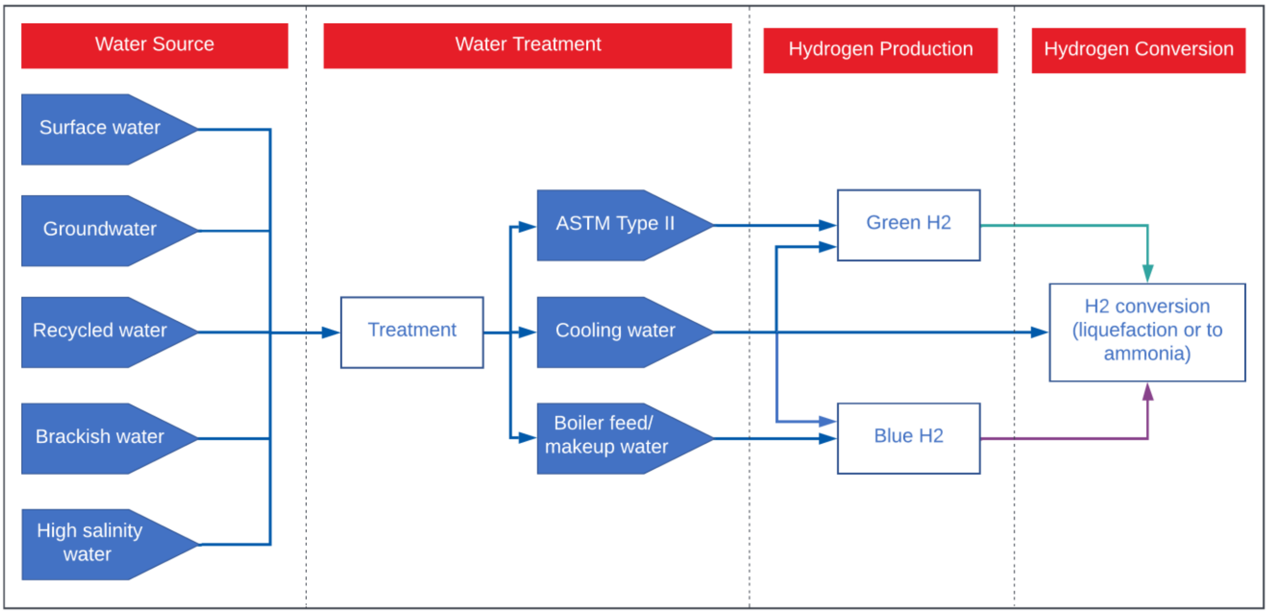
1.3 Scope of Study

The Water Use in Hydrogen study focusses on water usage and consumption of defined hydrogen value chains as depicted in Figure 1-1. These water-hydrogen value chains include:

- Water source treatment
- Hydrogen production (green and blue)
- Hydrogen carrier conversion (liquified hydrogen and ammonia)

To support the technical study, some commentary on key considerations for stakeholders and industry when considering a particular water source, its quantity, potential treatment and by-products is included. For context a comparison of water usage requirements for hydrogen value chains with alternative fuels is also provided.

Figure 1-1 Flow chart of the water-hydrogen value chain considered in the scope of this study



The scope was broken into discrete work packages (Table 1-2) to support the delivery of this technical paper addressing the water usage requirements of the hydrogen value chain as depicted in Figure 1-1.

Table 1-2: Discrete Work Packages

Work package	Purpose
1	Understanding water requirements for green hydrogen production
2	Understanding water requirements for blue hydrogen production
3	Understanding water requirements for hydrogen conversion (liquefaction)
4	Understanding water requirements for hydrogen conversion (ammonia)
5	Independent review of Work Packages 1.1-1.4
6	Exploring raw water sources and water treatment options
7	Evaluating environmental considerations & integrating circular economy concepts to hydrogen production
8	Comparison of water requirements for hydrogen with water requirements for alternative fuels

1.3.1 Assumptions

The work packages above have been undertaken based on the following assumptions:

- For the study, all mass flow balances and water requirements were developed using system water recovery calculations from first principals and informed by industry knowledge. This exercise is a high-level estimate and should not be used as the basis of any future design and/or planning of specific projects.
- The water usage associated with electricity generation, embedded water in construction and water associated with transportation of end products has been excluded from the scope.

2. Cooling system alternatives

Water is used and consumed for hydrogen production and carrier conversion as both feedstock and cooling agent. Water is consumed in the electrolyser and reacting with methane as steam to produce green and blue hydrogen respectively. Feedstock water consumption is relatively known by the industry, as reported in numerous publications such as in page 12 of the Australia's National Hydrogen Strategy[19].

This study reports that **9 – 11 litres of demineralised water are consumed to produce 1 kg of green hydrogen,** using PEM electrolysis technology. This range accounts for various mode of electrolyser operations, and under different type of climate zone and age of the electrolyser. **5 litres of boiler feed water in the form of steam are required to produce 1 kg of blue hydrogen**.

Cooling water has the potential to be the largest contributor to water usage in the hydrogen production and carrier conversion processes. Cooling water requirements range substantially based on cooling process type and climatic conditions. Evaporative, air cooled and once-through cooling processes were assessed in this study. Overall, water usage is the highest for once-through cooling systems and lowest for evaporative cooling systems. Once -through systems do not present water losses while evaporative cooling systems require makeup water to account for some losses.

For evaporative cooling system, makeup water can range from 3 litres in the coolest or high humidity area to 60 litres in the hottest or low humidity area per kg of green hydrogen. Cooling water for blue hydrogen production is less than for green hydrogen, ranging between 20 to 24 litres per kg of hydrogen.

The wide range of water consumption for cooling highlights the need to carefully consider water-efficient cooling system design in water-scarce and high evaporation regions.

2.1 Overview of cooling system alternatives

Cooling water can be a significant water demand during hydrogen production. There are three basic types of cooling water systems: once-through, closed recirculating (non-evaporative), and open recirculating (evaporative) systems. Each system has different cooling efficiency, water quality requirements and water consumption. A summary of relative advantages and disadvantages of each cooling system is provided below.

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[19] Australia's National Hydrogen Strategy. COAG, 2019. Pp12. Australia's National Hydrogen Strategy (industry.gov.au)

Table 2-1: Cooling Technologies Advantages and Disadvantages

ONCE THROUGH COOLING		EVAPORATIVE COOLING		AIR COOLING	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**	**Advantages**	**Disadvantages**
Little or no water consumption No treatment of cooling water needed Low energy use	Large & continuously replenished total water requirement Siting must be adjacent to water body Potential environmental impact due to high temperature of return water High maintenance	Less total water required than once through Lower energy use Higher efficiency in removing heat	Higher water consumption due to evaporation, higher in dry zone Treatment of cooling water required High maintenance	Zero water required Lower maintenance No waste stream discharge	High capital cost High energy use Large footprint Less effective in dry zone, high temperature Fan noise

2.2 Once-through cooling system

Once-through cooling water systems use large volumes of water as they immediately discharge the water after it has been used for cooling. Often, raw water sources such as surface water and seawater are used. As the cooling water is discharged back into the source, once-through systems do not consume any water in the cooling process. However, the temperature and hence the evaporation rate from the body of water does increase. Once-through cooling systems are limited in their application as they have large footprints and must be adjacent to an abundant water source. Environmental restrictions, for example in the case of using lake or river water, may also prevent set-up of such a system in certain areas due to potential aquatic environmental impacts.

If freshwater is abundant, once-through cooling systems typically have the lowest construction and maintenance costs. The cooling water requires limited treatment before use. Generally, only mechanical screening is applied to protect equipment from serious damage from foreign materials. Once-through cooling also has greater thermal efficiency, especially for large thermal power stations and plants that require significant heat dissipation. Nevertheless, the complications that affect all water-cooling systems, viz. corrosion, scaling, fouling and biological control, need to be controlled.

Due to the environmental impacts of once-through cooling, existing systems are being retrofitted with closed-loop cooling towers and new cooling water structures are required to reflect the best technology available for minimising adverse environmental impact, which often precludes construction of new once-through cooling towers[20].

For the purpose of this investigation, an increase in temperature of 10°C from the source has been assumed. Higher delta in temperature can reduce the flowrate of cooling water, for example a delta Temperature of 15ºC, there could be 33% reduction in cooling water demand. However, further

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[20] Massoudi, M., & Cerha, M. (2013, October 22). *Converting Once-Through Cooling to Closed-Loop*. Power Engineering. https://www.power-eng.com/coal/converting-once-through-cooling-to-closed-loop/

cooling of the heated water may be required before disposal to the environment as well as larger heat exchanger system will be required.

2.2.1 Seawater cooling

Seawater cooling systems are a proven technology and are widely used in coal-fired and nuclear power plants[21] at sites near the sea. Seawater is abundant, stable and low in temperature, so often cooling is more efficient. Operation of seawater cooling systems, almost all of which utilise the once-through approach, is simple compared to other cooling technologies.

However, seawater as the cooling medium brings special challenges because the high concentration of dissolved salts and microorganisms in seawater make fouling, scaling and corrosion common operational problems[22]. Thus, a seawater cooling system must be treated at scheduled intervals, generally through the use of chemicals such as chlorine for shock chlorination and other anti-fouling or anti-scaling chemicals which are toxic to marine organisms and potentially environmentally harmful. Sound management of seawater cooling systems is necessary to minimise its environmental impact and effluents need to be regularly monitored to ensure compliance with discharge standards.

As freshwater scarcity and environmental protection is becoming increasingly pertinent, seawater is also being adopted in open- or closed-circuit cooling systems. The composition of seawater changes the physical and chemical properties of the water, dictating careful cooling tower material evaluation. Provided the impacts of the seawater are properly accounted for, circulating cooling water towers can perform adequately with seawater.

2.3 Open-circuit cooling system

Open-circuit cooling systems are the most widely used in industry and reuse water to cool process equipment after heat is dissipated through evaporation. The most common method used to dissipate heat is with cooling towers.

Wet cooling towers reject heat through the natural process of evaporation. Warm recirculating water is sent to the cooling tower where it comes into direct contact with ambient air that is drawn through the tower. As this occurs, a small volume of water is evaporated, lowering the temperature of the remaining water which is circulated back into the system. Water is lost from the system primarily through evaporation. Typically, 1% is lost as water vapour for each 5 °C of cooling[23]. A portion of the cooling water is also discharged as waste, known as “blowdown”, to maintain a suitable water quality within the cooling circuit. Another source of water loss is drift. Drift loss occurs from droplets of water that are carried along with the air leaving the tower. Very little water is lost from drift – usually about 0.1-0.3% of the circulation water rate[24]. All lost water is replaced with makeup water.

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[21] World Nuclear Association. (2020, September). *Cooling Power Plants*. https://world-nuclear.org/information-library/current-and-future-generation/cooling-power-plants.aspx

[22] Emregul, C. Y. (2021, August 2). *Seawater Cooling Systems Treatment*. Process Cooling. https://www.process-cooling.com/articles/90411-seawater-cooling-systems-treatment

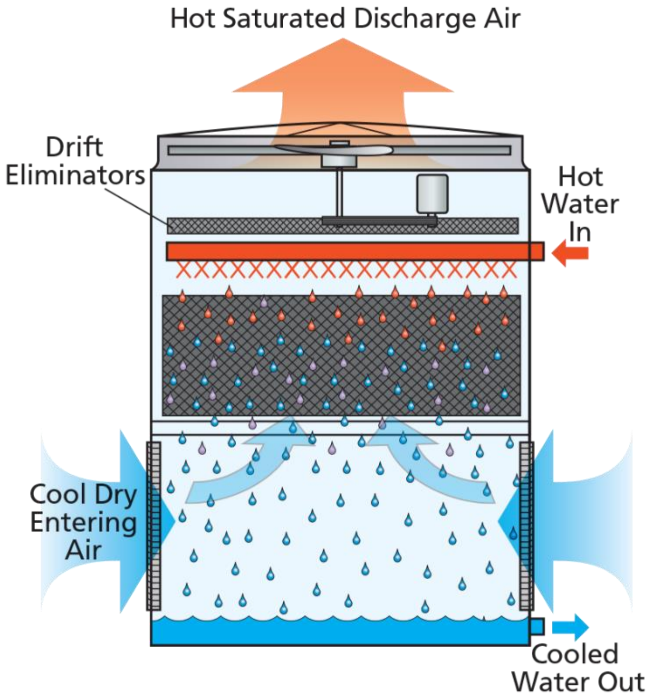
[23] Pugh, S., Hewitt, G. F., & Müller-Steinhagen, H. (2003). Fouling During the Use of Seawater as Coolant—The Development of a ‘User Guide.’ *Heat Exchanger Fouling and Cleaning: Fundamentals and Applications*. Engineering Conferences International. https://dc.engconfintl.org/heatexchanger/3

[24] Vengateson, U. (2017, April 1). *Cooling Towers: Estimate Evaporation Loss and Makeup Water Requirements*. Chemical Engineering. https://www.chemengonline.com/cooling-towers-estimate-evaporation-loss-and-makeup-water-requirements/

Since water is continually reused, open recirculating cooling systems greatly reduce the amount of water consumed compared to once-through cooling. They also often have low set-up costs. However, open-circuit cooling systems are subject to more water treatment-related problems which increases operating costs. In all cooling systems there will be impurities present in the cooling water, but especially so when using open cooling systems because the cooling towers are exposed to the atmosphere. Dissolved impurities and particulates in the cooling water accumulate through evaporation and deposit on equipment, causing fouling, scaling and corrosion that lead to a loss of efficiency. Blowdown alone is insufficient to protect recirculating cooling systems against these problems, so cooling water may need to be chemically treated depending on the quality of the water source. Moreover, blowdown water may also have to be treated or incur wastewater costs[25].

As water efficiency has become more important, "zero-discharge" open-circuit cooling systems have also been designed. In such a system, blowdown water is typically treated with RO with pre-treatment by filtration and sometimes with ion exchange resins to reduce scaling potential to the RO unit. However, recirculating blowdown water may not be possible in all situations. Consideration should be made regarding the quality of the water and how it will impact the efficient operation of the cooling system, as well as the ability to meet the required cooling demand[26].

Figure 2-1: Diagram of a counterflow open-circuit evaporative cooling tower[27].



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[25] Process Cooling. (2001, September 12). *How to Protect Open, Recirculating Cooling Systems*. https://www.process-cooling.com/articles/84005-how-to-protect-open-recirculating-cooling-systems

[26] Chopra, D. (2013). *Zero Discharge Treatment Method for Cooling Towers and Heat Exchangers with SP3, I-SOFT-OB, OXYDES & KATALOX LIGHT*. Watch Water. https://www.watchwater.de/wp-content/uploads/2019/01/Zero-Discharge-Cooling-Towers.pdf

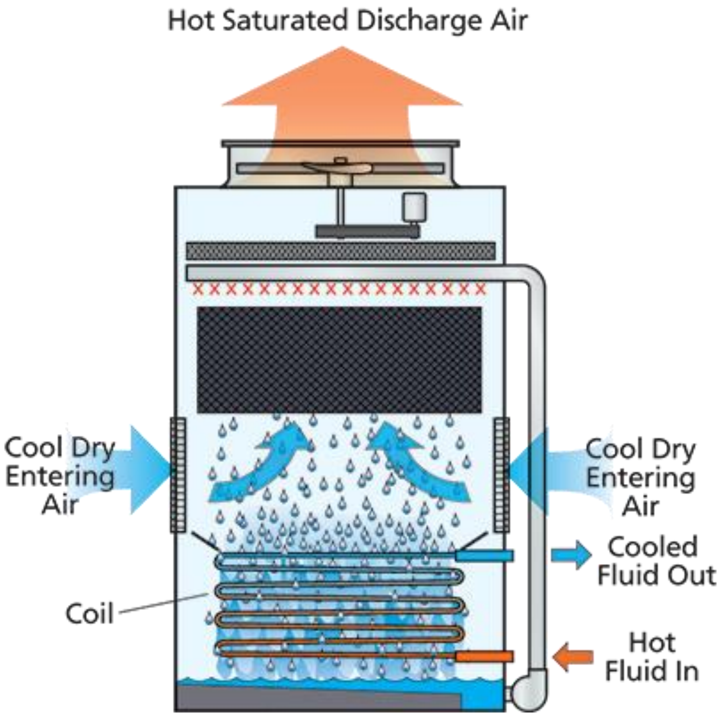
[27] EVAPCO. (2017b, March 31). *Evaporative Cooling 101*. http://www.evapco.com.au/technologies/evaporative-cooling-101

2.4 Closed-circuit cooling system

Closed-circuit systems can be evaporative or non-evaporative. They differ from open-circuit cooling systems in that the cooling water circulates through a heat exchanger coil to remove heat via two process streams. It is an indirect system because the water to be cooled (i.e., the "working fluid") is not directly exposed to the coolants, which could be both water recirculating through a cooling tower or air via a fin-fan cooler. For system that used water as coolant, water from the cooling tower is sprayed onto the coil (heat exchanger) containing the warm water; simultaneously air is blown through the tower opposite to the water flow. A small amount of the cooling tower water evaporates and dissipates heat while warm moist air is discharged to the atmosphere. The remaining cooling tower water is reused continuously and replenished with minimal makeup water. Closed-circuit cooling towers reduce water loss through evaporation and minimise blowdown losses, compared to open-circuit cooling systems[28].

Closed-circuit systems offer other advantages compared to open-circuit systems. Though installation costs are often greater, lifetime operational costs are generally reduced simply because evaporation of the circulating cooling water is virtually eliminated, and the quality of the water is maintained. This in turn not only lowers makeup water and blowdown costs, but also reduces the degree to which water treatment is required and decreases maintenance demands of equipment that is exposed to fewer contaminants. Moreover, the components of closed cooling systems often do not require the filtration equipment and plate-and-frame heat exchangers in open-circuit cooling towers that are highly susceptible to fouling[29].

Figure 2-2: Diagram of a closed-circuit cooling tower[30]



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[28] IQS Directory. (n.d.). *Open Loop and Closed Loop Cooling Towers: Operation, Types, Applications and Benefits*. Retrieved May 16, 2022, from https://www.iqsdirectory.com/articles/cooling-tower/open-loop-and-closed-loop-cooling-towers.html

[29] Edmondson, C. (n.d.). How to Pick a Cooling Tower: Comparing Open and Closed Loop Towers. *James M. Pleasants Company*. Retrieved May 18, 2022, from https://jmpcoblog.com/hvac-blog/how-to-pick-a-cooling-tower-comparing-open-and-closed-loop-towers

[30] EVAPCO. (2017b, March 31). *Evaporative Cooling 101*. http://www.evapco.com.au/technologies/evaporative-cooling-101

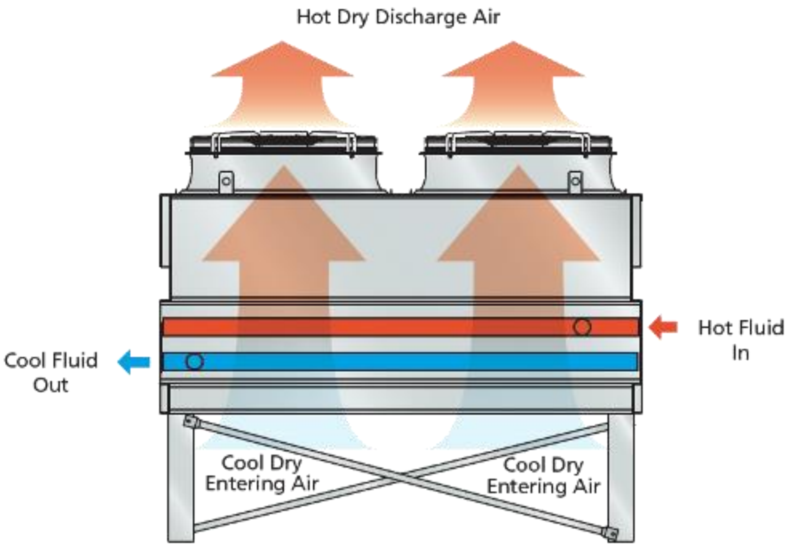
2.5 Air cooling system

Air cooling systems, also known as dry cooling systems, are similar to the typical closed-circuit system except that the evaporative cooling tower is replaced with dry cooling towers where ambient air is used to cool the working fluid instead of water. Heat is directly transferred to air flowing past an array of tubes containing the cooling water. There is no water loss due to evaporation because the working fluid and cooling air do not come into contact, and the cooling water is kept in a closed system. In practise, dry cooling systems use about 95% less water than wet systems[31].

Although dry cooling has great advantages for water conservation and environmental protection, it suffers from lower efficiency, especially in hot, arid climates because cooling water temperatures are limited by the ambient dry-bulb temperature[32]. Capital costs as well as operation and maintenance costs will likely be higher for dry cooling systems than for wet cooling systems. Thus, dry cooling towers are usually only cost effective where water supplies are very limited.

Despite the drawbacks, one major advantage of dry cooling systems is that it offers considerable flexibility of location to new plants, since they will not be dependent on a major body of water or water source if cooling water requirements do not exist.

Figure 2-3: Diagram of a flat configuration dry cooling tower[33].



Hybrid cooling systems combine both wet and dry cooling and offer a compromise between efficiency and water consumption constraints. Water use is reduced relative to wet systems while performance is improved during hot weather. Wet/dry hybrid systems are typically designed to utilize either evaporative or dry cooling, rather than both at once. For example, they can be operated as dry

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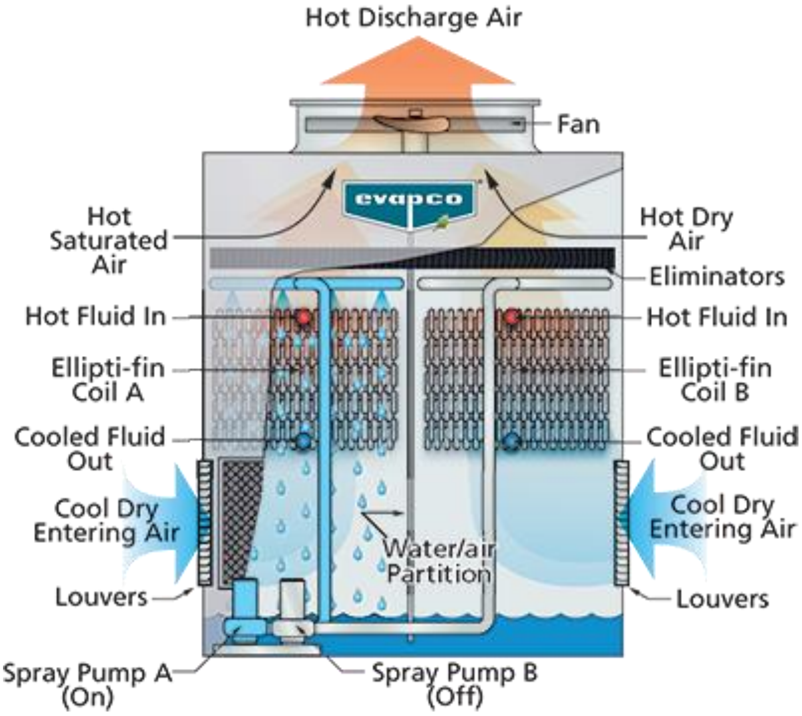
[31] U.S. Energy Information Administration. (2018, August 29). *Some U.S. electricity generating plants use dry cooling*. https://www.eia.gov/todayinenergy/detail.php?id=36773

[32] Hooman, K., Guan, Z., & Gurgenci, H. (2017). 9—Advances in dry cooling for concentrating solar thermal (CST) power plants. In M. J. Blanco & L. R. Santigosa (Eds.), *Advances in Concentrating Solar Thermal Research and Technology* (pp. 179–212). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100516-3.00009-5

[33] EVAPCO. (2017c, August 28). *Dry Cooling 101*. http://www.evapco.com/dry-cooling-101

systems during the cooler seasons and as wet cooling systems during the hotter seasons, when dry cooling towers have lower efficiency. However, some hybrid systems can operate in both wet and dry modes simultaneously[34].

Figure 2-4: Diagram of a hybrid cooling tower.



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[34] EVAPCO. (2017a, January 9). *Hybrid Cooling 101*. http://www.evapco.com.au/technologies/hybrid-cooling-101

3. Water requirements for green hydrogen production

Water is used and consumed in hydrogen production and carrier conversion for both feedstock and cooling uses. Water is consumed as feedstock for green hydrogen production for electrolyser and boiler feed water respectively. Feedstock water consumption is relatively known by the industry and reflective of reported numbers in publications such as Australia's National Hydrogen Strategy.

Based on this assessment, **9 – 11 litres of demineralised water is consumed to produce 1 kg of green hydrogen** using PEM electrolysis technology. This range accounts for the relatively small impact of the mode of electrolyser operation, climate zone and age of the electrolyser on water consumption.

Cooling water has the potential to contribute the largest proportion of water usage in the hydrogen production and carrier conversion processes. Cooling water usage requirements range substantially based on cooling process type and climatic conditions. Evaporative, air cooled and once- through cooling were assessed. Water usage is highest for once-through cooling systems with no water losses. However, for evaporative cooling system, there are water losses and required makeup.

For evaporative cooling system, makeup water per kg of green hydrogen can range from 3 litres in coolest or high humidity area to 60 litres in the hottest or low humidity area.

This highlights the need to consider water-efficient cooling system design in water-scarce and high evaporation regions.

3.1 Process overview

Green hydrogen is produced through electrolysis, a process that separates water into hydrogen and oxygen using electricity from renewable sources. There are different methods of producing hydrogen in an electrolyser, but the following overall reaction is common to all water electrolysis:

$$H_2O(1) \rightarrow H_2(g) + \frac{1}{2}\,O_2(g).$$

There are two types of electrolysers that will be discussed in this report given their commercial availability and differences in cooling requirements and water consumption:

- proton exchange membrane (PEM) electrolysers; and
- alkaline electrolysers.

Alkaline electrolysers are currently more commonly used for electrolytic hydrogen production, however, due to operational and performance enhancements, PEM electrolysers are becoming more common and seen to be appropriate for use in renewable energy systems (RES) because of their ability to operate dynamically with rapid response times.

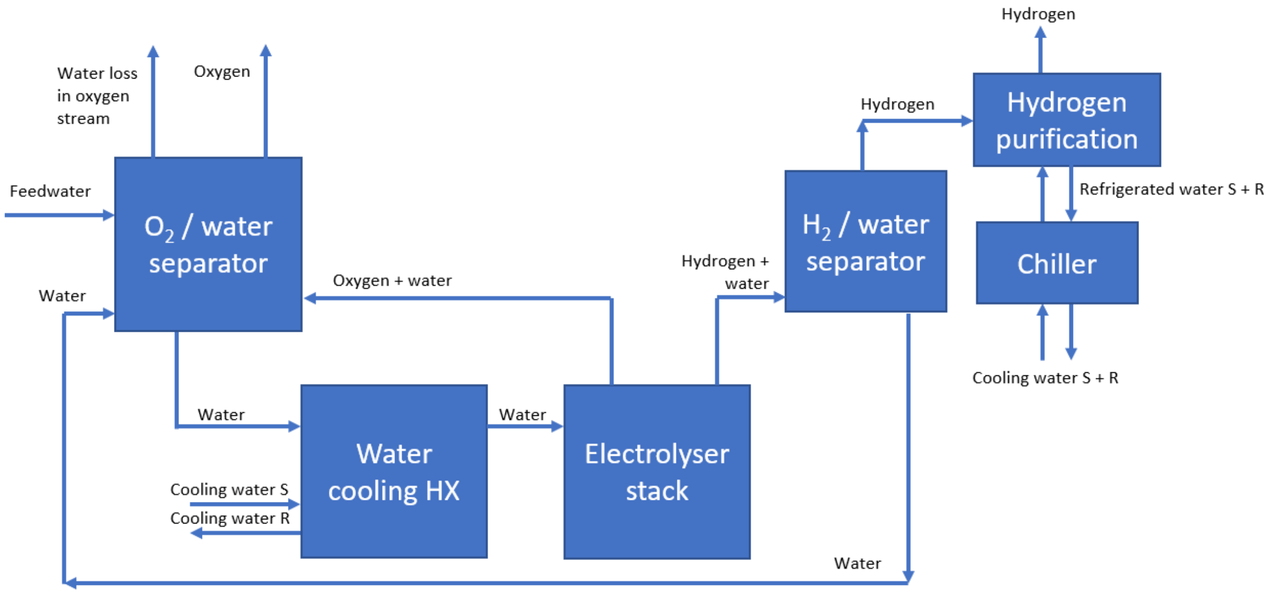
The process of an electrolyser plant (Figure 3-1) can be broken into three main sections:

1. **The pre-processing section**, consisting of sub-units that prepare and deliver water to the electrolyser at the required flow rate and conditions.
2. **The electrolyser section**, which consists of the electrolyser and is the site of the electrochemical reaction where the inlet (water and electricity) is used to produce oxygen, hydrogen and heat.

3. **The post-processing section**, functions to control the composition, temperature and pressure of the hydrogen leaving the plant. This section includes a gas liquid separator for the hydrogen product stream and a condenser for adequate water removal. Additional post processing is often required depending on end use. In high purity applications associated with transportation fuel, dryers, compressors and deoxidizers are included in the system boundaries.

Cooling water streams In Figure 3-1 below include Supply (S) and Return (R).

Figure 3-1: Block flow diagram for PEM electrolyser plant



Arup performed a literature review and collected information on efficiency for several types of electrolysers, which were rated for a range of operating conditions. This is reported in Table 3-1 and Table 3-2, below. Selection of an operation point is highly dependent on electrolyser type/catalyst, operation profile and desired outcomes. Factors including membrane thickness and material, operating temperature, pressure, voltage and current density impact water consumption of hydrogen production from both a process and utility perspective.

Table 3-1: Efficiency of PEM electrolysers documented across literature

Supplier / Reference		USDOE	Cummins	Siemens	EU	Hydrogenics
Source		[35]	[36]	[37]	[38]	[39]
Electrolyser Type		PEM	PEM	PEM	PEM	PEM
Stack Efficiency Max	kWh/kg		40			
Stack Efficiency Min	kWh/kg		50			
System Efficiency Min	kWh/kg	56	51	52	52	
System Efficiency Max	kWh/kg	55			48	52

Table 3-2: Efficiency of alkaline electrolysers documented across literature

Supplier / Reference		NREL	USDOE	NEL	McPhy	Cummins
Source		[40]	[41]	[42]	[43]	[44]
Electrolyser Type		AE	AE	AE	AE	AE
Electrolyte				25% KOH (aq) Solution		30% KOH (aq) Solution
Stack Efficiency Max	kWh/kg			45	56	
Stack Efficiency Min	kWh/kg			52		
System Efficiency Min	kWh/kg	62	60			60
System Efficiency Max	kWh/kg	54	48			55

Many of the reported values specify air cooling as the method of temperature control in the system. Reported efficiency values consider beginning of life performance, and operating conditions and process components may vary across sources.

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[35] Peterson, D., Vickers, J., & DeSantis, D. (2019). *Hydrogen Production Cost From PEM Electrolysis—2019*. DOE Hydrogen Program. https://www.hydrogen.energy.gov/pdfs/19009_H_2_production_cost_pem_electrolysis_2019.pdf

[36] Cummins. (2021). *HyLYZER® WATER ELECTROLYZERS*. https://mart.cummins.com/imagelibrary/data/assetfiles/0070328.pdf

[37] Siemens Energy. (2021). *PEM electrolyser technology—Flexible, efficient and scalable*. https://www.energyforum.in/fileadmin/user_upload/india/media_elements/Presentations/20210714_H_2_large/Siemens_Energy.pdf

[38] Aricò, A. S., Siracusano, S., Briguglio, N., Baglio, V., Van Dijk, N., Yildirim, H., Greenhalgh, D., Merlo, L., Tonella, S., Grahl-Madsen, L., Kielmann, G., & Steinigeweg, S. (2016). *High Performance PEM Electrolyser for Cost-effective Grid Balancing Applications*. HPEM2GAS Consortium. https://hpem2gas.eu/download/public_reports/public_deliverables/HPEM2GAS-D2-1-Protocols.pdf

[39] Thomas, D. (2019). *Large scale PEM electrolysis: Technology status and upscaling strategies*. HyBalance. https://hybalance.eu/wp-content/uploads/2019/10/Large-scale-PEM-electrolysis.pdf

[40] Ruth, M., Mayyas, A., & Mann, M. (2017). *Manufacturing Competitiveness Analysis for PEM and Alkaline Water Electrolysis Systems*. Clean Energy Manufacturing Analysis Center. https://www.nrel.gov/docs/fy19osti/70380.pdf

[41] Genovese, J., Harg, K., Paster, M., & Turner, J. (2009). *Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis*. National Renewable Energy Laboratory. https://www.hydrogen.energy.gov/pdfs/46676.pdf

[42] Nel. (2018, May 31). *Atmospheric Alkaline Electrolyser*. https://nelhydrogen.com/product/atmospheric-alkaline-electrolyser-a-series/

[43] McPhy. (n.d.). *New generation of pressurized alkaline electrolysis for large-scale platforms (multi-MW/GW)*. https://mcphy.com/en/equipment-services/electrolyzers/augmented/

[44] Cummins. (2020). *HySTAT® ALKALINE ELECTROLYZERS*. https://www.power.cummins.com/sites/default/files/2021-08/Cummins-hystat-70-specsheet.pdf

3.2 Assumptions and design basis

Green hydrogen has recently been an increasing focus of governments, investors and industry yet the practical requirements and technical challenges around production are not yet widely understood or proven. The methodology of this work package was developed to assess aspects of water consumption in green hydrogen that, despite having significant impact, are not always considered.

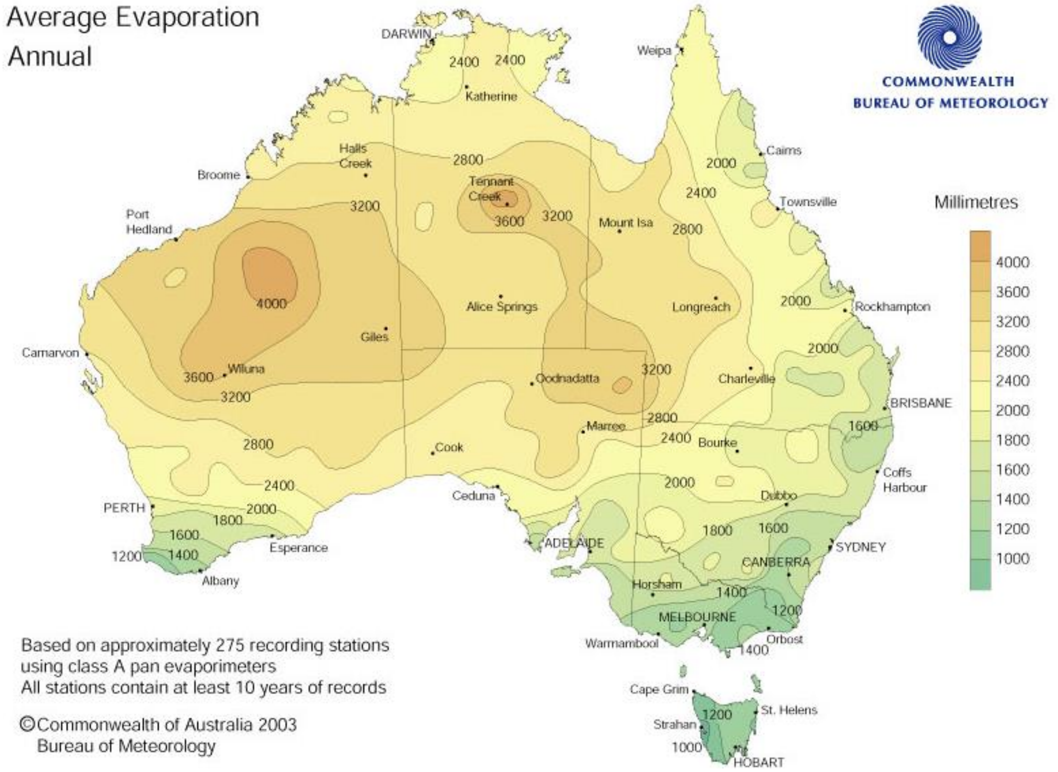
This analysis breaks down the variables that affect system efficiency, as this impacts the water requirements of green hydrogen production. Rather than basing this analysis on reported efficiency or water usage numbers, plant performance was defined and calculated based on first principles and derived empirical relationships for physical, material properties of equipment. See Table 3-3 for assumptions.

The variables assessed included different operating profiles, process conditions, climatic conditions and equipment types in Australia. For each variable used to calculate water usage in the green hydrogen production process, a range of values was obtained for commercially available technologies from multiple sources. The following variables were assessed in this analysis:

- Comparison of the water usage of high vs low performance PEM electrolysers producing the same amount of hydrogen
- Comparison of PEM electrolyser cell stack water usage at beginning of life (BOL) and end of life (EOL)
- Comparison of alkaline and PEM electrolyser water usage producing the same amount of hydrogen
- Comparison of water consumption in dynamic and constant load operation of PEM electrolysers producing a similar daily quantity of hydrogen
- Comparison of electrolyser performance under variable load profiles derived for potential renewable production assets produced in Australia’s most extreme evaporative zones
- Comparison of makeup water consumption of the same electrolyser operating at a constant rate across climatic zones in Australia

To develop a range for water usage in different climatic zones, the Bureau of Meteorology (BOM)’s average annual evaporation map, Figure 3-2 was used. The extreme zones on the map were used to select a “wet zone” (lowest evaporation) and “dry zone” (highest evaporation).

Figure 3-2: Average annual evaporation map for Australia



Based on approximately 275 recording stations using class A pan evaporimeters
All stations contain at least 10 years of records

©Commonwealth of Australia 2003
Bureau of Meteorology

This analysis used three main approaches for water usage calculations, as outlined below. All calculations are supported by reputable literature reviews and Arup’s global in-house domain awareness. These components were derived using the methodology described below:

- Hydrogen production cost optimisation model built in Calliope[45] for determination of renewable electricity profile that would characterize the lowest cost of hydrogen production in the wet and dry zones.
  - Annual hourly wind (onshore and offshore, if relevant) and solar profile data was generated for each location point determined in site selection exercise using Renewables Ninja and used to characterize wet and dry zone renewable energy generation potential https://www.renewables.ninja/
  - Technology cost and performance metrics used in modelling were determined based on Arup’s past projects and in house market knowledge
- Bespoke steady state and time varied models of electrolyser plant were developed to characterise both process water consumption and all cooling loads that were practical for the water-cooling system; assumed stack cooling and product cooling of hydrogen stream would be picked up by cooling water system.

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[45] Pfenninger, S., & Pickering, B. (2018). Calliope: A multi-scale energy systems modelling framework. *Journal of Open Source Software*, *3*(29), 825. https://doi.org/10.21105/joss.00825

- Empirical data was used with derived physical characteristics based on commercially available electrolysers to size and calculate a representative electrolyser performance and water usage[35,46,47,48]
- Electrical loads from optimisation model were used to appropriately size PEM electrolysers operating under variable conditions to ensure comparable hydrogen output given the loading profile and assumed stack characteristics.
- An annual production capacity of around 1,500 tonnes H_2 (meeting purity of 99.99% and above) was used as a benchmark for system sizing and performance in all scenarios, the process flow for each plant is detailed in the following section. This is nominally equivalent to an 8 to 10 MW PEM electrolyser. It was assumed compression and cooling to 40 bar and standard temperature, respectively, in order to draw a comparison across scenarios for green hydrogen.
- Post processing loads and losses were calculated based on appropriate first principles and/or design equations or derived from literature. See Table 3-3 for assumptions.
- Each scenario was shaped around comparisons listed earlier in this section.

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[46] IRENA. (2020). *Green Hydrogen Cost Reduction*. https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

[47] Lettenmeier, P. (2021). *Efficiency—Electrolysis*. Siemens Energy. https://assets.siemens-energy.com/siemens/assets/api/uuid:a33a8c39-b694-4d91-a0b5-4d8c9464e96c/efficiency-white-paper.pdf

[48] James, B., Colella, W., Moton, J., Saur, G., & Ramsden, T. (2013). *PEM Electrolysis H_2A Production Case Study Documentation*. Strategic Analysis Inc. https://www.nrel.gov/hydrogen/assets/pdfs/h2a-pem-electrolysis-case-study-documentation.pdf

Table 3-3: Assumptions used to develop performance model for each case

Variable	Case							Reference		
Zone	Dry					Wet		Unit	Assumption	
Type	AE	PEM								
Load Flow? (Y/N)	N	N			Y	N	Y			
Grade	Mid	Low		High						
Age	BOL		EOL	BOL						
V_{ref}	1.68	2	2	1.619	1.619	1.619	1.619	V	Cell voltage	[35]
j_{max}	0.2	3	3	1.8	1.8	1.8	1.8	A/cm^2	Maximum current density	[49]
j_{min}	40	10	10	10	10	10	10	%	Minimum turndown	[40]
A	29,850	1,675	1,843	2,742	6,854	2,742	6,854	m^2	Total active area	[35]
dT	5	5	5	5	8	5	8	K	Rated temperature change across stack	[50]
k	10	1.5	2	1	1	1	1	%	Permeation loss	[46]
t	1	1	80,000	1	1	1	1	h	Operating time	[51]
V_{loss}	2	2	2	2	2	2	2	μV/h	Cell degradation rate	[35]
η_{dryer}	1%	0%	0%	0%	0%	0%	0%	%	Purification loss	[52]
T_{outlet}	20							C	H_2 product temperature	[37]
T_{inlet}	60	80	80	60	60	60	60	C	Stack temperature	[40]
P_{in}	10	40	40	40	40	40	40	bar	Stack pressure (H_2 side)	[39]
P_{out}	40							bar	H_2 product pressure	[50]

Energy simulations of assumed cooling plant for variable and constant load for both the wet and dry zones built in IES[53] to estimate cooling water makeup; plant consisting of a closed water and condenser water loops, water cooled system with two variable flow 50% part load chillers, a heat exchanger and cooling tower.

- Assumed cooling loads profiles developed in bespoke electrolyser model were used to size and simulate cooling loop requirements of process side for constant load and variable load operation in both wet and dry zones
- Psychrometric calculations included to estimate the cooling tower loss that would be experienced in projects located in the wet and dry zones
- Annual hourly climatic conditions for wet and dry zones derived from ASHRAE[54] and weather data from the BOM[55]

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[49] Hamdan, M., & Norman, T. (2009). *II.E.3 PEM Electrolyzer Incorporating an Advanced Low-Cost Membrane*. DOE Hydrogen Program. https://www.hydrogen.energy.gov/pdfs/progress09/ii_e_3_hamdan.pdf

[50] Arup, past projects

[51] Plug Power. (2020). *GenFuel® The 5MW Electrolyzer*. https://www.plugpower.com/wp-content/uploads/2020/10/2020_5MWELX_Spec_100620_F.pdf

[52] Colella, W. G., James, B. D., Moton, J. M., Saur, G., & Ramsden, T. (2014). *Techno-economic Analysis of PEM Electrolysis for Hydrogen Production*. Strategic Analysis Inc. https://www.energy.gov/sites/prod/files/2014/08/f18/fcto_2014_electrolytic_H_2_wkshp_colella1.pdf

[53] IES. (n.d.). *Energy Modelling*. https://www.iesve.com/services/design-analysis/energy-modelling

[54] ASHRAE. (n.d.). *ASHRAE Weather Data Center*. Retrieved May 2022, from https://www.ashrae.org/technical-resources/bookstore/weather-data-center

[55] Commonwealth of Australia Bureau of Meteorology. (2003). *Average evaporation map—Annual*. Retrieved May, 2022, from http://www.bom.gov.au/climate/map/evaporation/evap_ann.shtml

3.3 Summary of treated water requirements

This section will present the results of the analysis of treated water consumption for green hydrogen production. Generally, water consumption in all configurations of green hydrogen production is driven by four main aspects:

1. Mass losses in the system due to crossover of hydrogen in the oxygen product stream, and in post processing
2. Water losses in oxygen and hydrogen product streams that are not recovered for recirculation in the system
3. Water consumption for the production of hydrogen
4. Water requirements for cooling, if applicable.

Utilisation of water cooling can significantly increase the amount of water usage in a system. For each calculation, a breakdown will be provided of water required for evaporative closed loop cooling, once-through cooling or air cooling. While water requirements for once-through cooling are significantly higher than for evaporative cooling, this water is not consumed in the process and can be returned to the environment, provided impacts are appropriately managed. An overview of the differences between these cooling systems is presented in Section 2.

Electrolyser Design

This subsection covers a comparison of the water usage of high vs low performance PEM electrolysers producing the same amount of hydrogen.

A cell contains an anode and a cathode, which are used to move current through the electrolyser through the formation of ions in the form of hydrogen and oxygen from the splitting of water. The operating voltage which is set to achieve hydrogen production in any electrolyser is related to the cell potential. Cell potential dictates the amount of electrical and thermal energy that is needed in each cell to produce hydrogen and maintain polarity at a specific temperature, pressure and rate. The cell potential is the sum of the reversible potential, which is the electrical energy required for splitting water, and the overpotentials, which are converted to thermal energy and akin to frictional forces in the cell.

If the minimum voltage is not maintained, which increases over the lifespan of the electrolyser due to degradation, hydrogen will either be not produced at all or will be produced but not recovered in the product stream. Therefore, the cell design relates to the amount of water needed to produce a certain amount of hydrogen and maintain cell temperature.

Variation in water consumption needed to produce a certain amount of hydrogen is in part driven by the design of the electrolysers and the corresponding cell voltage, which are highly capital and operational cost driven. This is a key aspect of variation in both water usage for both hydrogen production and cooling across electrolyser manufacturers, makes and models.

Below (Table 3-4) is a comparison of the water usage of high vs low performance PEM electrolysers producing the same amount of hydrogen.

Table 3-4: High end vs. low end Electrolyser performance for Dry Zone, PEM, BOL

Plant performance	**Dry Zone, PEM, BOL**		**Unit**
	Low End	**High End**	
Rated Power	10	8	MW
Stack Usage	53	43	kWh/kg H_2 produced
Rated System Cooling Load	3,880	1,952	kW
Annualized process H_2O Consumption	14.71	14.53	Ml p.a.
Annual Cooling H_2O Makeup	68.83	34.63	Ml p.a.
Annual H_2 production (electrolyser)	1,623	1,612	tonnes H_2 p.a.
Annual H_2 production (plant)	1,598	1,596	tonnes H_2 p.a.
Process H_2O Consumption per kg H_2	9.2	9.1	litres H_2O/kgH_2
Cooling H_2O Consumption per kg H_2 (evaporative water cooling)	43	23	litres H_2O/kgH_2
Cooling H_2O Required per kg H_2 (once-through cooling)	1,813	918	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (air cooling)	9.2	9.1	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (evaporative water cooling)	52	32	litres H_2O/kgH_2
Total H_2O Required per kg H_2 (once-through cooling)	1,822	927	litres H_2O/kgH_2

The variation in water consumption per electrolyser was observed mainly in the amount of cooling required in the electrolyser system. This is due to the overvoltage loads that were calculated to be higher in the low-end electrolyser versus the high-end electrolyser. The slight amount of difference in process water consumption in the low-end electrolyser can be attributed to slightly higher permeation losses of 2% versus 1% that was assumed in the high-end electrolyser, which is in line with commercially available electrolysers with similar performance grades.

Certain electrolysers can be made more cheaply but at the expense of performance. These aspects must be weighed across different electrolyser manufacturers and may be overcome through optimised system design.

Electrolyser Cell Degradation

The minimum voltage required for the forward reaction and ion exchange increases over the lifespan of the electrolyser due to degradation. Frequent start-up and shutdown, impurity build up and extreme operating conditions can hasten typical cell degradation, which is reported to vary from 1-6mV/1000hours[52] of operation. It was found that most normal cell degradation was reported to be around 2mV/kh, which was assumed for this comparison at 80,000 hours of operation of a PEM electrolyser[56].

This subsection is a comparison of PEM electrolyser cell stack water usage at beginning of life (BOL) and end of life (EOL). Results are reported in Table 3-5 below:

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[56] Spendelow, J., Alia, S., Pivovar, B., Mauger, S., & Myers, D. (2022). *Overview of Proton Exchange Membrane Electrolyzer Electrocatalysis*. H_2NEW U.S. Department of Energy. https://www.energy.gov/sites/default/files/2022-04/5-H2-AMP%20Workshop-ANL.pdf

Table 3-5: System Treated Water Usage at Beginning of Life vs End of Life for Dry Zone, Low End PEM

Plant performance	**Dry Zone, Low End PEM**		**Unit**
	BOL	**EOL**	
Rated Power	10	11	MW
Stack Usage	53	57	kWh/kg H_2 produced
Rated System Cooling Load	3,880	4,767	kW
Annualized process H_2O Consumption	14.71	14.98	Ml p.a.
Annual Cooling H_2O Makeup	68.83	84.56	Ml p.a.
Annual H_2 production (electrolyser)	1,623	1,644	tonnes H_2 p.a.
Annual H_2 production (plant)	1,598	1,611	tonnes H_2 p.a.
Process H_2O Consumption per kg H_2	9.2	9.3	litres H_2O/kgH_2
Cooling H_2O Consumption per kg H_2 (evaporative water cooling)	43	61.16	litres H_2O/kgH_2
Cooling H_2O Required per kg H_2 (once-through cooling)	1,813	2,199	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (air cooling)	9.2	9.3	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (evaporative water cooling)	52	71	litres H_2O/kgH_2
Total H_2O Required per kg H_2 (once-through cooling)	1,822	2,208	litres H_2O/kgH_2

As shown in the comparison, cell degradation is directly related to an increase in total overpotential that is observed in a cell, which is apparent in the increased cooling load exhibited in the water-cooled system makeup water consumption.

Oversizing of both electrolyser and cooling systems is required to overcome cell degradation attributed to normal aging of electrolysers to maintain the same hydrogen production. As stated above, the electrolyser efficiency weighed against capital cost and the auxiliary utility loads required must be weighed against each other to determine the best electrolyser size that is capable of meeting demand requirements throughout the useful lifespan.

Electrolyser Type

As stated in the process overview and block flow sections, alkaline and PEM electrolysers have some important differences that are related to water consumption from both a cooling and process water perspective. This is due to the system losses that are exhibited in alkaline electrolyser plants and lower stack efficiency.

Comparison of alkaline and PEM electrolyser water usage producing the same amount of hydrogen are examined in this subsection. A PEM and alkaline with similar production capacities were compared under constant power flow and beginning of life operation. Feed water is assumed to be ASTM Type II for both PEM and alkaline electrolyzers, although, it should be noted that alkaline electrolyzers are less sensitive to impurities than PEM electrolyzers.

Table 3-6: Electrolyser Type Treated Water Usage Comparison for Dry Zone, BOL, Low End

Plant performance	**Dry Zone, BOL, Low End**		**Unit**
	Alkaline	**PEM**	
Rated Power	10	10	MW
Stack Usage	45	53	kWh/kg H_2 produced
Rated System Cooling Load	2,869	3,880	kW
Annualized process H_2O Consumption	17.51	14.71	Ml p.a.
Annual Cooling H_2O Makeup	48.64	68.83	Ml p.a.
Annual H_2 production (electrolyser)	1,765	1,623	tonnes H_2 p.a.
Annual H_2 production (plant)	1,589	1,598	tonnes H_2 p.a.
Process H_2O Consumption per kg H_2	11	9.2	litres H_2O/kgH_2
Cooling H_2O Consumption per kg H_2 (evaporative water cooling)	31	43	litres H_2O/kgH_2
Cooling H_2O Required per kg H_2 (once-through cooling)	1,233	1,813	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (air cooling)	11	9.2	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (evaporative water cooling)	42	52	litres H_2O/kgH_2
Total H_2O Required per kg H_2 (once-through cooling)	1,244	1,822	litres H_2O/kgH_2

Due to the more significant post processing involved with alkaline electrolysers, the water usage in alkaline electrolyser systems is higher than that of PEM systems in terms of process water consumption but lower in terms of cooling water consumption. From a process water perspective, this is due to mass losses in the alkaline electrolyser system that are not observed in PEM associated with downstream purification of hydrogen exiting the electrolyser stack.

On the other hand, the overvoltage observed in the alkaline electrolyser was found to be lower than that of the low-end PEM electrolyser, the result is a lower cooling load. The higher stack efficiency in the alkaline electrolyser is thus overcome by other losses in the system. When compared to the high-end electrolyser, both the cooling and process water consumption is lower.

Operating Profile

The variable nature of operability of PEM electrolysers make them ideal for operation in renewable energy systems with a naturally variable renewable power source. Current flow and hydrogen production are directly related; however, process efficiency increases at part load conditions to a point of about 30% in PEM electrolysers. This subsection covers the comparison of water consumption in dynamic and constant load operation of PEM electrolysers producing a similar daily quantity of hydrogen.

Depending on the control system, the production efficiency within an electrolyser can increase more dramatically but depends on highly complex and difficult to manage overpotentials. For the purposes of this study, it is assumed that the current is varied with the power flow profile to deliver a constant voltage to the electrolyser. It should be noted that there are different control schemes that are being considered for variable power flow electrolyser operation that will yield different results to this comparison.

Operation of hot and cold standby modes are ignored entirely in every scenario. The variability of power supply sources across projects are critical for understanding water usage of a project. Parasitic loading and power support systems (hydrogen product consumption for backup power production) can be critical from both cost and water consumption perspectives. Though power supply and demand dynamics should be considered when determining system design and operating profile, this is not covered in this study given the degree of project specific context required to determine these types of water usage.

See Table 3-7 for comparison of a representative variable and constant operation for a characteristic dry zone in Australia:

Table 3-7: Treated Water Usage Comparison for Variable vs Constant Operation for Dry Zone, PEM, BOL, High End

Plant performance	**Dry Zone, PEM, BOL, High End**		**Unit**
	Constant	**Variable**	
Rated Power	8	20	MW
Stack Usage	43	43	kWh/kg H_2 produced
Rated System Cooling Load	1,952	4,879	kW
Annualized process H_2O Consumption	14,53	16,87	Ml p.a.
Annual Cooling H_2O Makeup	34.63	61.16	Ml p.a.
Annual H_2 production (electrolyser)	1,612	1,889	tonnes H_2 p.a.
Annual H_2 production (plant)	1,596	1,601	tonnes H_2 p.a.
Process H_2O Consumption per kg H_2	9.1	11	litres H_2O/kgH_2
Cooling H_2O Consumption per kg H_2 (evaporative water cooling)	22	38.2	litres H_2O/kgH_2
Cooling H_2O Required per kg H_2 (once-through cooling)	918	1,045	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (air cooling)	9.1	11	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (evaporative water cooling)	31	49	litres H_2O/kgH_2
Total H_2O Required per kg H_2 (once-through cooling)	927	1,056	litres H_2O/kgH_2

See Table 3-8 for comparison of a representative variable and constant operation for a characteristic wet zone in Australia.

Table 3-8: Treated Water Usage Comparison for Variable vs Constant Operation for Wet Zone, PEM, BOL, High End

Water Usage Comparison for Variable vs Constant Operation			
Plant performance	**Wet Zone, PEM, BOL, High End**		**Unit**
	Constant	**Variable**	
Rated Power	8	20	MW
Stack Usage	43	43	kWh/kg H_2 produced
Rated System Cooling Load	1,952	4,879	kW
Annualized process H_2O Consumption	14,53	16,10	Ml p.a.
Annual Cooling H_2O Makeup	22,73	5,423	Ml p.a.
Annual H_2 production (electrolyser)	1,612	1,803	tonnes H_2 p.a.
Annual H_2 production (plant)	1,596	1,579	tonnes H_2 p.a.
Process H_2O Consumption per kg H_2	9.1	10	litres H_2O/kgH_2
Cooling H_2O Consumption per kg H_2 (evaporative water cooling)	14	3	litres H_2O/kgH_2
Cooling H_2O Consumption per kg H_2 (once-through cooling)	918	1,080	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (air cooling)	9.1	10	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (evaporative water cooling)	23	13	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (once-through cooling)	927	1,090	litres H_2O/kgH_2

In both wet and dry zone cases, it was found that variable operation had higher water consumption for process water but lower consumption for cooling. Even though a much larger electrolyser is required to produce the same amount of hydrogen under variable conditions in this case, the lower electrolyser utilization factor corresponds to higher stack efficiency, this is also true of chiller efficiency, so operating at part load reduces the amount of water used from a cooling perspective.

In order to produce the same amount of hydrogen in a variable load system as a constant load system, a larger electrolyser is required based on the variability of the power source. Water consumption was found to be higher in variable load operation than constant load operation in both the wet and dry zones.

Power Flow Dynamics

This section discusses the comparison of electrolyser performance under variable load profiles derived for potential renewable generation assets that yield the lowest cost hydrogen produced in Australia's most extreme climatic locations (from an evaporative perspective). Due to the cost of certain renewable infrastructure and the local wind and solar conditions, different locations will utilize different assets to produce green hydrogen competitively.

There is a certain calculus required to understand what assets are best utilized for hydrogen production, what size these assets should be and what generation potential they have in order to correctly size green hydrogen production and storage systems and thus determine water consumption for hydrogen projects in different locations. To demonstrate this, an analysis was developed to compare water usage based on power flow profiles that a green hydrogen production system would be subjected to given certain assumptions and simplifications.

The power flow profiles were generated using site specific renewable generation potential derived from wind and solar data in a linear cost optimization model to generate 1,500 kg per day. The model yielded sized system components (cost optimized solar, wind, hydrogen system and storage systems) and their utilization. This was done to give an indicative variable flow profile and system size of the assets optimized to produce green hydrogen at lowest cost based on certain assumptions and simplifications as discussed to assess the water consumption associated with green hydrogen production based on optimal generation in the noted climactic zones.

Even PEM electrolysers, which are suitable for highly variable operation, experience certain inefficiencies depending on the relative system sizing and corresponding operating profile that the equipment experiences over its useful lifespan. These inefficiencies are specific to the operating conditions of the system and the physical properties of the electrolyser plant equipment.

Depending on the cell and stack configuration, electrolysers (both PEM and alkaline) will operate more efficiently at part load conditions up to a point. The electrochemical cell becomes more efficient until a point of low current density which are typically defined by operation of current densities that are 30% of the service envelope of a PEM electrolyser and 40% for alkaline.

To generalize yet quantify the impacts of the inefficiencies related to different operating profiles (wind driven versus solar driven), renewable generation profiles were derived based on local context and cost and applied to the high-end electrolyser cell stack configurations in the wet and dry zones. Though because the electrolyser system was limited to an operating point of 10% to avoid modelling of parasitic loads, start-up and shutdown dynamics and more severe cell degradation, both optimized generation assets comprised of both wind and solar assets to meet the constraints of the optimization. Grid electricity used to maintain the minimum electrolyzer service load are shown in Figure 3-3 and Figure 3-4 as IPP renewable generation. Therefore, this case does not necessarily indicate the best or most cost optimal means of producing hydrogen in each location.

All this said, when setting an operating point, factors such as power supply dynamics, demand requirements and storage/supply chain limitations will affect system efficiency. One solution is not applicable to all scenarios. This is especially critical when assessing the distribution of water to project sites. Depending on the operation of the electrolyser driven by the generation or curtailment profile of renewable energy assets, there will not be a nominal water requirement, and these should be understood for each project to assess feasibility of some sites for hydrogen production over others. This is highly pertinent to an Australian context as locations with known water stress have some of the highest potential to generate low-cost renewable electricity.

To look at the impact on water usage of electrolysers operating under different resource driven profiles, the derived variable operation profiles in the wet and dry zone are compared in Table 3-9 below.

Table 3-9: Treated Water Usage for Different Renewable Generation Profiles for PEM, BOL, Variable Flow

Plant performance	**PEM, BOL, Variable Flow**		**Unit**
	Dry Zone	**Wet Zone**	
Rated Power	20	20	MW
Total H_2O Consumption per kg H_2 (water cooling)	43	43	kWh/kg H_2 produced
Rated System Cooling Load	4,879	4,879	kW
Annualized process H_2O Consumption	16.87	16.10	Ml p.a.
Annual Cooling H_2O Makeup	12.21	5.423	Ml p.a.
Annual H_2 production (electrolyser)	1,889	1,803	tonnes H_2 p.a.
Annual H_2 production (plant)	1,601	1,579	tonnes H_2 p.a.
Process H_2O Consumption per kg H_2	11	10	litres H_2O/kgH_2
Cooling H_2O Consumption per kg H_2 (evaporative water cooling)	38	23	litres H_2O/kgH_2
Cooling H_2O Required per kg H_2 (once-through cooling)	1,958	1,958	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (air cooling)	11	10	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (evaporative water cooling)	49	33	litres H_2O/kgH_2
Total H_2O Required per kg H_2 (once-through cooling)	1,969	1,968	litres H_2O/kgH_2

On a whole system level, the amount of renewable energy generation needed to produce the same amount of hydrogen in two different locations is observed based on the renewable energy profile that was assumed. That said, there are some locations where, given the renewable resources available, less hydrogen production potential is possible, however, this is not necessarily the case for water consumption and must be assessed separately depending on what type of system is utilized.

Figure 3-3 and Figure 3-4 show an example of different wind and solar power profiles in different zones. A significant difference can be observed in the resulting electrolyser / system operation required to achieve 1,500 kg of hydrogen production. The different electrolyser / system operation results in (at times) reduced efficiencies as the electrolyser is required to operate under 30% load. This results in increased grid / IPP energy inputs, a moderately higher electrolyser capacity, and increased cooling water needs as the lower efficiency increases the cooling load required.

Figure 3-3: Derived renewable electricity profile in the wet zone for production of 1,500 kg H_2 per day given a nominal plant efficiency

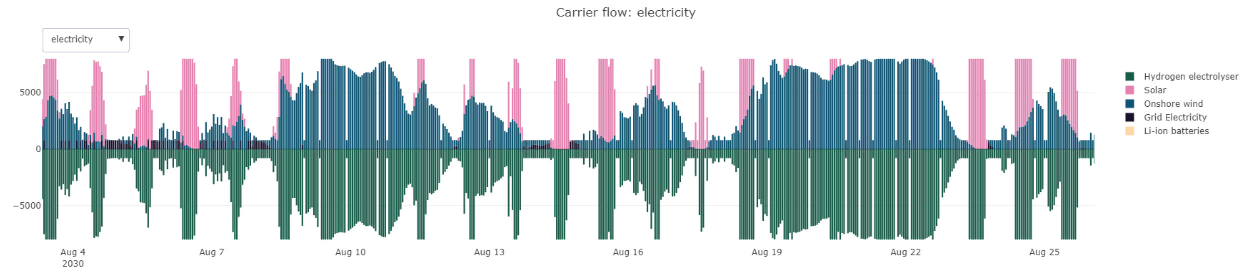
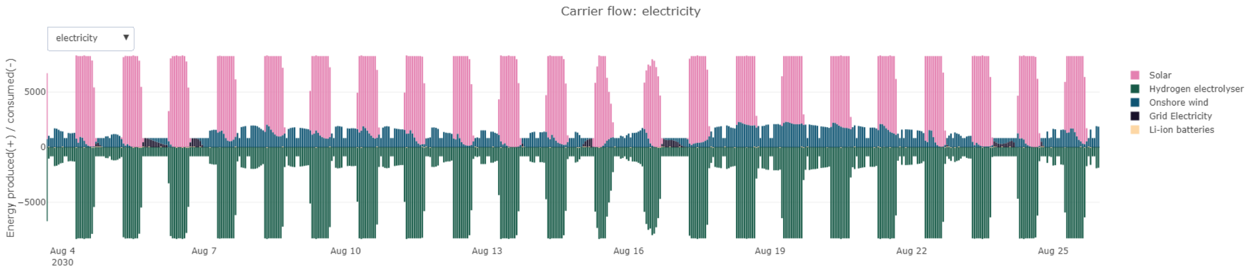


Figure 3-4: Derived renewable electricity profile in the dry zone for production of 1,500 kg H_2 per day given a nominal plant efficiency



It would be expected that electrolysers without grid connections would require some sort of backup power that could be cost effectively met by consuming some of the production yield to maintain the system. This would likely allow for the increase in renewable energy generation assets to be utilized although would decrease the plant yield and increase water consumption.

If oxygen from the electrolyser plant were also treated and captured, it could be used with some of the hydrogen product in a fuel cell or turbine to produce water. If proportions are correct, this could allow for the production of high purity H_2O with condensing, which would reduce the external water consumption of a system greatly, if cooling water usage is managed.

It should also be noted that allowing production demand to be met over a longer period of time would change the resulting optimized solution and that the results of the optimization were done for demonstrative purposes only and should be considered only in the context of this comparison.

While green hydrogen production projects in certain locations may consume more water than others within the system boundaries, it is important to weigh this against a project’s access to alternative water sources like recycled water to mitigate negative impact and maximize co-benefits of green hydrogen.

Climatic Conditions

This subsection covers a comparison of makeup water consumption of an electrolyser system with the same cooling load in Australia’s most extreme climatic conditions (from an average annual evaporation perspective). These results (reported in Table 3-10) are indicative of the range of water usage across constant flow systems producing green hydrogen by utilizing water cooled systems comprised a cooling tower, chiller, closed condenser water loop and closed cooling water loop that is sized for heat rejection to maintain operating systems in the green hydrogen production process.

Cooling system design for both air- and water-cooled systems are well understood relying on psychrometric relationships that are well documented and relate to climatic conditions. It is assumed that air cooled systems do not directly consume water, although, require higher electricity consumption to achieve the same amount of cooling as a water-cooled system.

Water cooled systems utilize cooling towers, which involve direct air exchange of condenser water with ambient air. The greater degree of evaporation that is experienced in the ambient air due to the dryness of the air, the greater degree of evaporative cooling and thus loss of condenser water to the environment occurs. Blow down losses are related to the build-up of impurities in the water loop. These water losses are estimated by assuming a certain cycle of concentration, which drives the rate at which condenser water must be treated to maintain maximum impurity concentrations and is discussed in more detail in Section 3.4. Drift water losses are driven by wind and are the most minor source of water loss in the cooling tower system in this context.

Table 3-10: Treated water usage in different climatic zones for PEM, BOL, constant flow

Plant performance	**PEM, BOL, Constant Flow**		**Unit**
	Dry Zone	**Wet Zone**	
Rated Power	8	8	MW
Stack Usage	43	43	kWh/kg H_2 produced
Rated System Cooling Load	1,952	1,952	kW
Annualized process H_2O Consumption	14.54	16.87	Ml p.a.
Annual Cooling H_2O Makeup	33.33	22.73	Ml p.a.
Annual H_2 production (electrolyser)	1,612	1,612	tonnes H_2 p.a.
Annual H_2 production (plant)	1,596	1,596	tonnes H_2 p.a.
Process H_2O Consumption per kg H_2	9	9	litres H_2O/kgH_2
Cooling H_2O Consumption per kg H_2 (evaporative water cooling)	22	14	litres H_2O/kgH_2
Cooling H_2O Required per kg H_2 (once-through cooling)	918	918	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (air cooling)	9	9	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (evaporative water cooling)	31	23	litres H_2O/kgH_2
Total H_2O Required per kg H_2 (once-through cooling)	927	927	litres H_2O/kgH_2

Figure 3-5 and Figure 3-6 show the profile of evaporative loss due to the variation of daily and seasonal conditions in the dry and wet zones.

Figure 3-5: Evaporative makeup water consumption for constant load operation of a PEM electrolyser in a representative dry zone

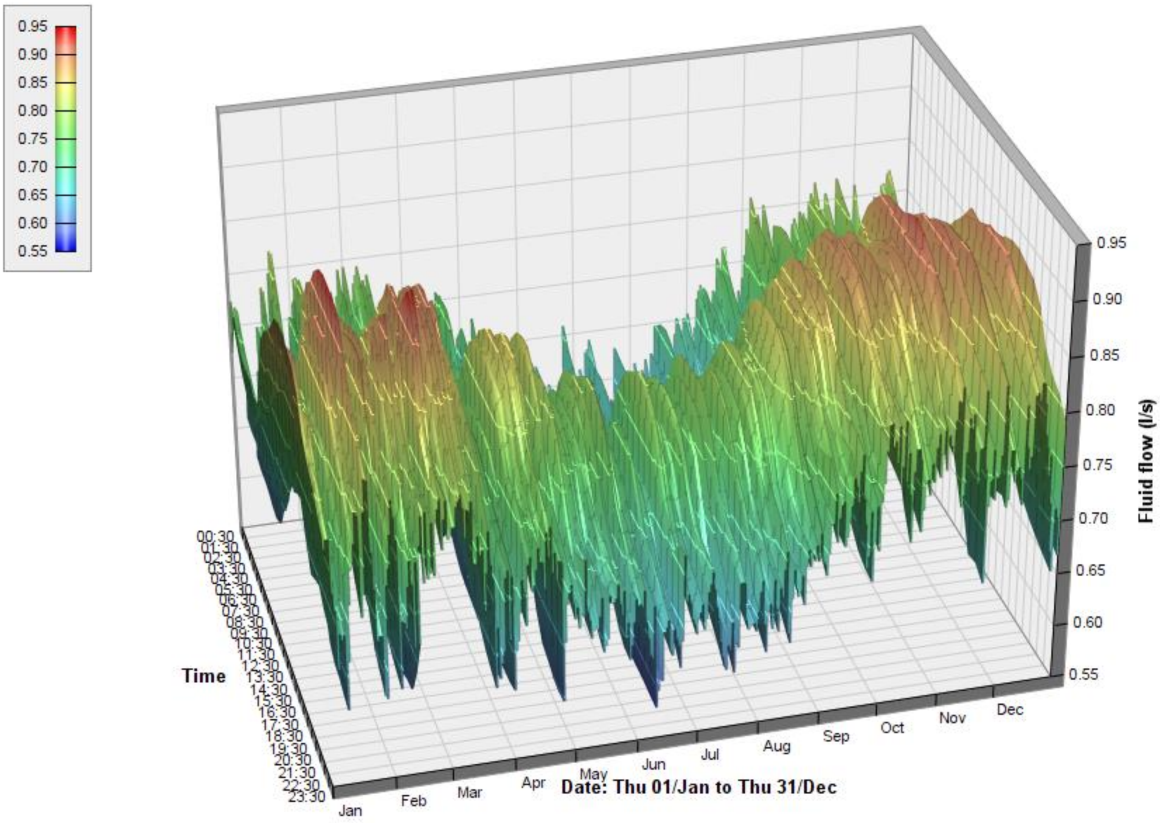
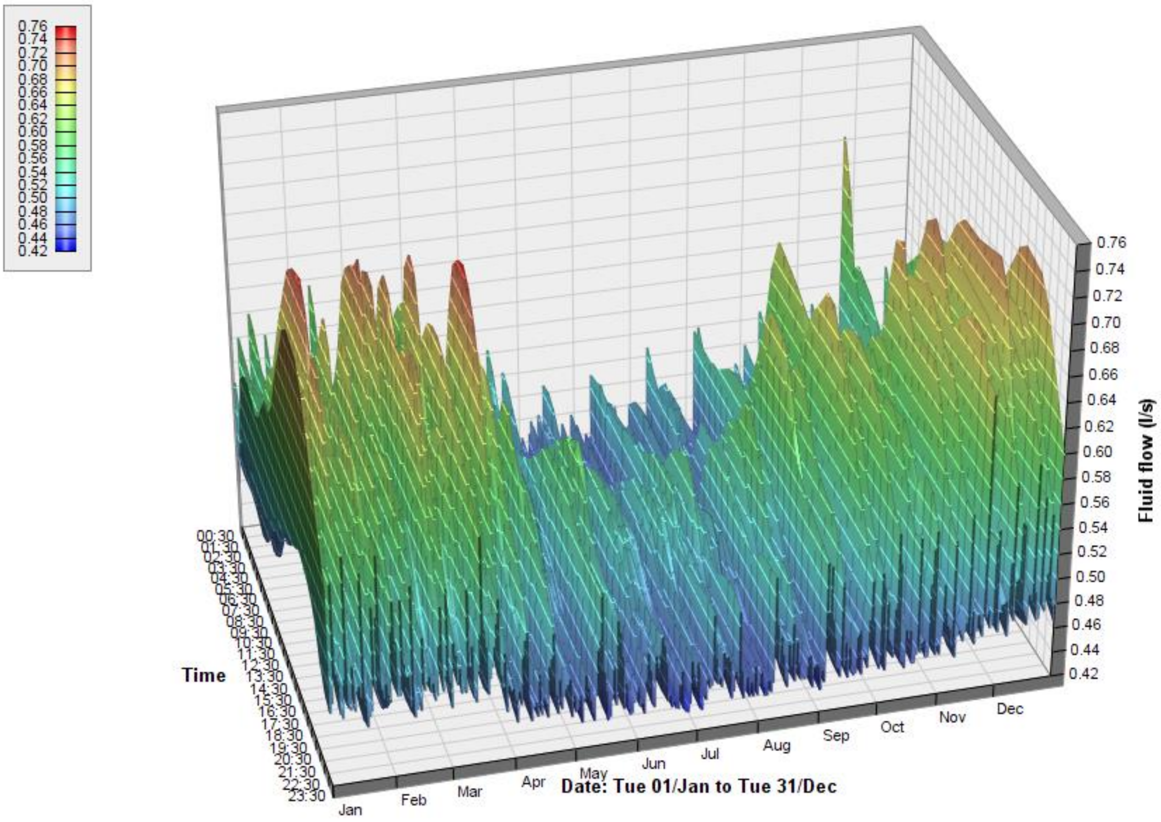


Figure 3-6: Makeup water consumption for constant load operation of a PEM electrolyser in a representative wet zone



As intuitively expected, evaporative losses in the dry zone greatly exceed that of the wet zone, which is the largest source of water consumption in the cooling system and is also directly related to blow down loss. Typically, air blast chillers are employed in electrolyser systems across Europe, which experience cooler climatic conditions. Water consumption must be weighed against cost and other parameters to determine the least negatively impactful system for each project.

3.4 Critical treated water quality parameters

3.4.1 PEM electrolyser feed water quality

The efficiency of PEM electrolyser depends on many factors, including feed water quality. If water is purer and cleaner, the chance of scaling to the electrodes will be lower and increases the efficiency of hydrogen production per kilogram of feed water. Pure water or demineralised water (demin water) contains very low level of dissolved ions (i.e., low salinity), and is the preferred feed water by most electrolyser vendors. Demin water has various quality as shown in Table 3-11 in accordance with the Standard Specification for Reagent Water by ASTM International.

Table 3-11: ATSM Standard specification for reagent water

Parameters	**Unit**	**Type I**	**Type II**	**Type III**	**Type IV**
Electrical conductivity	µS/cm at 298 K (25°C)	0.056	1.0	0.25	5
Electrical resistivity	Min.Mcm at 298 K (25°C)	18	1.0	4.0	0.2
pH	pH at 298 K	-	-	-	5.0 to 8.0
Total organic carbon (TOC) max	µg/L	50	50	200	No limit
Sodium, max.	µg/L	1	5	10	50
Chlorides, max	µg/L	1	5	10	50
Total silica, max	µg/L	3	3	500	No limit

Feed water is assumed to be ASTM Type II for both PEM and alkaline electrolysers, although, it should be noted that alkaline electrolysers are less sensitive to impurities than PEM electrolysers.

4. Water requirements for blue hydrogen production

Water is used and consumed in hydrogen production and carrier conversion for both feedstock and cooling uses. Water is consumed as feedstock for blue hydrogen production for electrolyser and boiler feed water respectively. Feedstock water consumption is relatively known by the industry and reflective of reported numbers in publications such as Australia's National Hydrogen Strategy.

Based on this assessment, 5 litres of boiler feed water (in the form of steam) is required to produce 1 kg of blue hydrogen.

Cooling water has the potential to contribute the largest proportion of water usage in the hydrogen production and carrier conversion processes. Cooling water usage requirements range substantially based on cooling process type and climatic conditions. Evaporative, air cooled and once- through cooling were assessed. Water usage is highest for once-through cooling systems with no water losses. However, for evaporative cooling system, there are water losses and required makeup.

For evaporative cooling system, makeup water per kg of blue hydrogen can range from 20 – 24 litres per kg of hydrogen.

4.1 Process overview

Today hydrogen is primarily produced from the conversion of fossil fuels. The leading technology to produce hydrogen at large scale is the Steam Methane Reforming (SMR) of natural gas. In this process, natural gas is used both as the chemical feedstock and as the fuel to provide heat to drive the conversion reaction.

The conversion of natural gas into hydrogen is performed in two main steps. Firstly, the methane contained in the natural gas reacts with water steam at high temperature (~900 °C) to yield a mixture of carbon monoxide and hydrogen, according to the following reaction equation:

$$CH_4 + H_2O + heat \rightarrow CO + 3H_2$$

The second stage is the Water-Gas Shift (WGS) reaction, which generates additional hydrogen at lower temperatures (~360 °C). The overall WGS reaction is as follows:

$$CO + H_2O \rightarrow CO_2 + H_2 + heat$$

Alongside hydrogen, carbon dioxide is also produced and typically released into the atmosphere. The production of hydrogen from SMR is responsible for 1-2% of global carbon dioxide (CO_2) equivalent emissions[57].

Carbon Capture and Storage (CCS) is a technology where the CO_2 emitted in carbon intensive processes is separated, transported and injected in underground formations. Here it can be stored for long periods of time, effectively avoiding its release to the atmosphere. When applied to the flue gases from the SMR process, CCS can reduce the CO_2 emissions to the atmosphere and allow the production of low-emission hydrogen (also called blue hydrogen).

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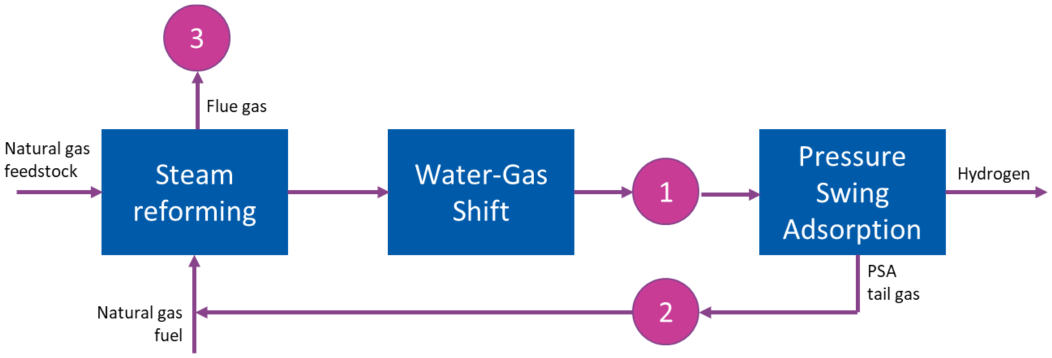
[57] Institute for Industrial Productivity. Industrial Efficiency Technology Database: Ammonia http://www.iipinetwork.org/wp-content/Ietd/content/ammonia.html (accessed 2022 -04 -14)

There are three specific locations in the SMR process where CO_2 can be captured: from the gas stream downstream of the WGS reactor (option one), after the hydrogen purification (option two) or from the flue gas exiting the steam reforming furnace (option three).

Figure 4-1: Carbon dioxide capture locations in the SMR process.



From a process perspective, the most convenient carbon capture locations are represented by option one and option two, because of the high CO_2 partial pressure and high CO_2 concentration, respectively. Carbon capture from these locations is a relatively mature technology, already implemented at several SMR plants worldwide with the purpose of producing a purified stream of CO_2 to be used in other industrial processes. However, the streams in these locations do not include the CO_2 produced from the combustion of natural gas fuel in the steam reforming furnace and can therefore only allow for the capture of up to 70% of the total CO_2 generated[58].

Compared to conventional CO_2 capture plants, CCS adds two challenges:

- the CO_2 capture rate must be considerably higher, e.g., above 90%, since the main goal of CCS is to reduce the carbon emissions to the atmosphere. This requires the application of CO_2 capture to the flue gas stream from the steam reforming furnace (option three), which presents a lower concentration and partial pressure of CO_2, and is therefore more expensive to process
- the CO_2 compression, transport and underground injection must be added to the capture process, increasing costs and technical complexity.

SMR plants are highly integrated and complex systems, with bespoke and optimised designs. This is particularly true for SMR plants that integrate carbon capture technology. Alternative technologies to produce hydrogen from natural gas are also available or under development. The most advanced is Autothermal Reforming (ATR), a process that is also based on the reaction between natural gas and water, but that differs from SMR for the way heat is supplied to the reforming reaction. While in SMR reformers the heat is provided by the combustion of a flow of natural gas and air that is kept separated from the reactants, in the ATR process the heat is generated directly within the reactor by the partial oxidation of additional natural gas feedstock. ATR is currently more expensive than SMR, however it has the potential to become competitive for hydrogen production requiring high carbon capture rates.

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[58] ETH Zürich, 2018, Project: Enabling a Zero-Carbon Economy via Hydrogen and CCS - Report on optimal plants for production of low-carbon H_2 with state-of-the-art technologies

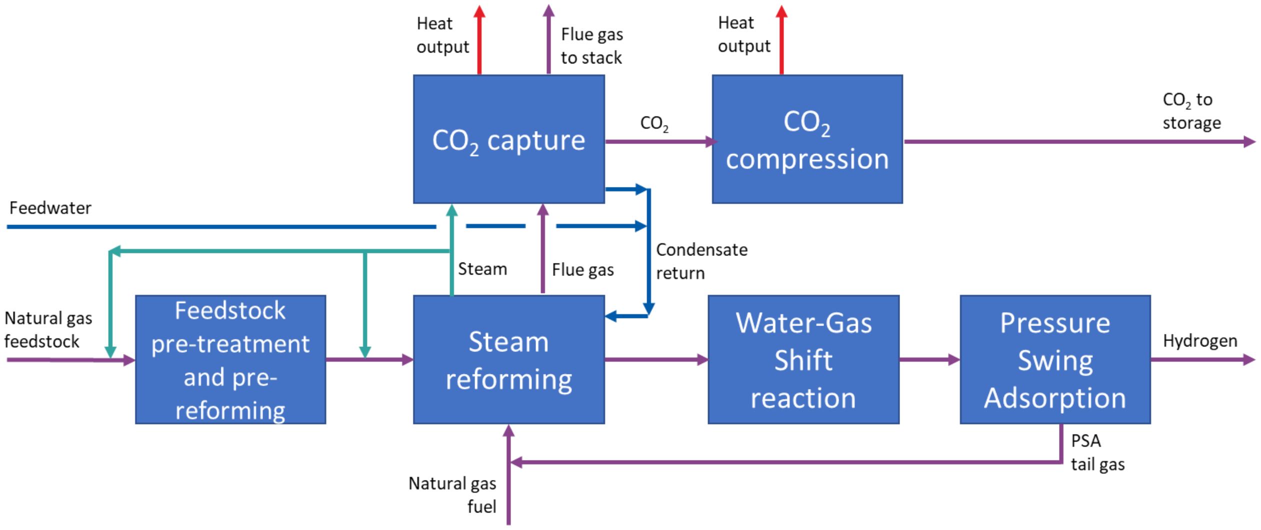
Due to the higher development level of the technology compared to competing ones, and the lower cost of hydrogen production, this analysis is based on a SMR plant with capture of CO_2 from the flue gases.

4.1.1 Overall process

The selected blue hydrogen production process consists of six main sections, as shown in Figure 4-2.

1. Feedstock pre-treatment
2. Steam reformer
3. Water-gas shift reactor
4. Pressure Swing Adsorber (PSA)
5. CO_2 capture plant
6. CO_2 compression system.

Figure 4-2: Block diagram of the Steam Methane Reforming process with carbon capture and compression



Firstly, the natural gas feedstock is pre-treated to remove contaminants from the natural gas and reacted with steam (pre-reformed) to decompose long-chain hydrocarbons into methane.

The refined methane stream is then fed into the primary reformer where it reacts with high pressure steam. The reforming reaction is endothermic. To allow the reaction to progress, heat is provided by the combustion of additional natural gas.

The resulting synthesis gas (syngas) is then passed to the shift reactors where the WGS reaction converts most of the carbon monoxide into hydrogen. The WGS reaction is exothermic, and the heat generated in this step is recovered and used within the plant to increase the overall efficiency.

The hydrogen gas that is generated is finally separated from the by-products in a Pressure Swing Absorption (PSA) unit. The PSA tail gas, which contains the unreacted gases and impurities like methane, carbon monoxide, some hydrogen, nitrogen as well as some water vapour, is combusted to provide heat for the reforming reaction. The purity of hydrogen in output from the PSA is typically above 99.9%[59].

Carbon dioxide is produced during the WGS reaction, as well as during the combustion of natural gas and PSA tail gas to provide heat for the reforming reaction. Ultimately, all the CO_2 generated is collected in the flue gas stream, which is sent to the CO_2 capture plant. In this stage, the flue gases are cooled and put in contact with a solvent (typically monoethanolamine, or MEA), which absorbs the CO_2. The flue gases, containing about 10% of the original CO_2, are sent to the stack for release to the atmosphere. The CO_2-rich MEA is instead regenerated in a stripping column and separated from the CO_2 so to be reused in the capture process.

The pure stream of CO_2 coming from the CO_2 capture plant is then dried, cooled and compressed to high pressure so to facilitate its transport to the storage site.

The SMR + CCS process is also highly integrated with a water/steam cycle. Steam is not only required as feedstock for the SMR reactions, but also for the regeneration (stripping) of the MEA. The energy required for the steam generation is provided by the heat generated by the WGS reaction and by the combustion of additional natural gas in the steam reformer furnace.

4.2 Assumptions and design basis

The International Energy Agency Greenhouse Gas R&D Programme (IEAGHG) analysed in detail the technical and economic aspects of hydrogen production from natural gas. In the 2017 report ‘Techno - Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS’[60], IEAGHG provided detailed information on the performance of different SMR plants configurations, including a case analysing the capture of CO_2 from the reformer’s flue gases to achieve an overall 90% CO_2 capture rate[61].

The design presented by the IEAGHG is a reference for the performance of future blue hydrogen plant, and it was used as the basis for this analysis Table 4-1 summarises the key performance parameters of the process.

Table 4-1: Basis of design for the blue hydrogen production plant

System basis of design	Unit	Value
Hydrogen production capacity	kg/h	8994
Hydrogen purity	%	>99.99%
Hydrogen delivery pressure	barg	25
Carbon capture rate	%	90%
Carbon absorption solvent	-	Methylethanolamine (MEA)
Carbon dioxide delivery pressure	barg	110

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[59] ETH Zürich, 2018, Project: Enabling a Zero-Carbon Economy via Hydrogen and CCS - Report on optimal plants for production of low-carbon H_2 with state-of-the-art technologies

[60] International Energy Agency, 2017, Techno - Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS. https://ieaghg.org/exco_docs/2017-02.pdf

[61] Case 3 – SMR Plant with capture of CO2 from SMR flue gas using MEA

4.3 Summary of water requirements

The water consumption in the SMR + CCS process is due to two reasons:

- Feedstock water consumed in the reforming and WGS reactions
- Water required for cooling, if applicable.

Utilisation of water cooling can significantly increase the amount of water usage in a system. A breakdown will be provided of water required for evaporative closed loop cooling, once-through seawater cooling or air cooling. While water requirements for once-through cooling are significantly higher than for evaporative cooling, this water is not consumed in the process and can be returned to the environment, provided impacts are appropriately managed. An overview of the differences between these cooling systems is presented in Section 2.

4.3.1 Feedstock water

Feedstock water is required in the form of pure steam to participate in the reforming and WGS reactions. Based just on the stoichiometry of these reactions, the water consumed is 4.5 litres per kilogram of hydrogen produced[62]. However, the total water consumption is greater for the following reasons:

- The steam generating process is responsible for additional losses via the continuous and intermittent blowdown of the steam cycle water as well as from the boiler feedstock water deaerator
- The water added to the steam generating boiler must be purified to avoid fouling, corrosion, and the introduction of contaminants in the reactor. The required water treatment process leads to additional water losses and therefore increased water consumption.

Water losses for blowdown and deaeration account for an additional 15% water consumption compared to the requirement dictated by the stoichiometric need, for a total of 5.2 litres of feedstock water per kilogram of hydrogen[60].

Table 4-2: Feedstock water requirements for blue hydrogen production

Process Units	**Water requirement (*Litres/kg hydrogen*)**
SMR process	4.5
Boiler (blowdown)	0.3
Utilities e.g deaerator	0.3
Total	**5.2**

4.3.2 Cooling requirement

The heat rejection from the condenser in the MEA cycle is responsible for the largest share of the cooling requirements for the blue hydrogen production process. Together with the cooling required for the inter-refrigeration in the CO_2 compression process, it accounts for virtually 100% of the heat dissipation demand.

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[62] The exact value varies slightly depending on the composition of natural gas.

Carbon capture with MEA

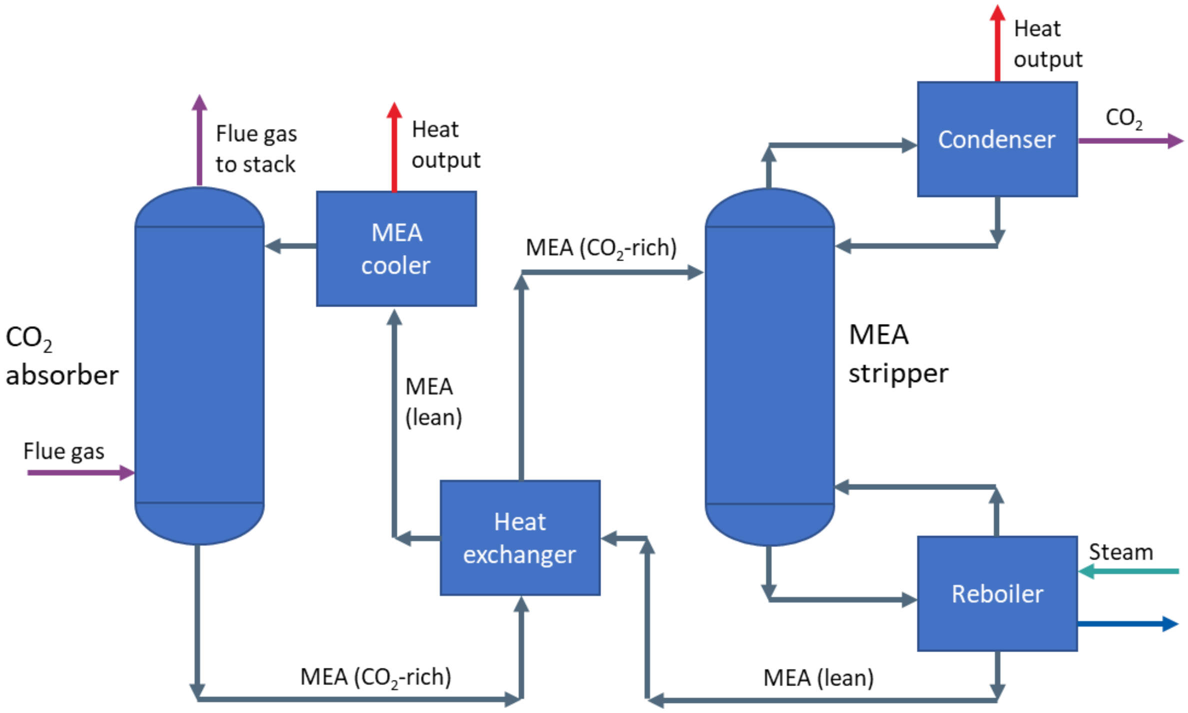
The process of carbon capture with MEA consists primarily of an absorber, a heat exchanger and a stripper, as presented in Figure 4-3. CO_2 in the flue gas enters to the bottom of the absorber where it is put in contact with a stream of lean MEA flowing in the opposite direction. The MEA solvent selectively absorbs the CO_2 in an exothermic reaction. The CO_2-rich MEA leaves the absorber and is pre-heated in a MEA/MEA heat exchanger. It then enters to the top of the stripper column where it desorbs the CO_2. The CO_2 is captured at the top of the stripper while the lean MEA is removed from the bottom. The regenerated lean MEA is cooled in the MEA/MEA heat exchanger and then further reduced in temperature in the MEA cooler. The regenerated lean MEA then enters the absorber to repeat the absorption cycle.

Finally, the reboiler provides the heat required to desorb the CO_2 from the MEA, while the condenser separates the gaseous stream of CO_2 by condensing the MEA vapours at the top of the stripper column.

The absorption and desorption processes are driven by controlling the temperature (and to a lesser extent the pressure) in the absorber and stripper. Low temperature and high pressure favour the absorption of CO_2 in the MEA, while the reverse process is achieved with high temperature and low pressure. While the heating and cooling requirements are partially satisfied by the MEA/MEA heat exchanger, the carbon capture system requires additional continuous supply and withdrawal of heat. Heat is provided via the reboiler, where steam is the energy vector. On the other hand, the system cooling is provided by cooling water exchanging heat with the process streams at the condenser and at the MEA cooler.

The heat rejection from the condenser and MEA cooler is responsible for the largest share of the cooling requirements in the blue hydrogen production process. According to the results in the IEAGHG case study used as reference, the specific cooling requirement for the carbon capture process is 28.7 MJ per kilogram of hydrogen produced.

Figure 4-3: Block diagram of the CO_2 capture process from SMR flue gases.



Carbon dioxide compression

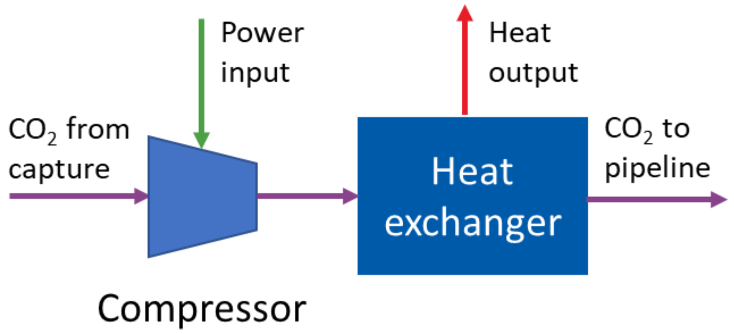
To complete the carbon capture and storage process, the CO_2 extracted from the SMR flue gas must be transported to the storage location and injected underground at high pressure. Since the CO_2 leaves the carbon capture process at low pressure, a compression stage is required. CO_2 is typically transported as a high-density fluid in liquid or supercritical phase. For this analysis, in accordance with the IEAGHG case study, the final pressure of the CO_2 is selected at 110 barg.

The compression of CO_2 is performed in a multi-stage compressor up to 80 barg. Above this pressure, and at temperatures below 31°C, the CO_2 is a liquid and can be further increased in pressure using a pump.

As it is compressed, the CO_2 increases its temperature. To limit the maximum temperature in the system and to reduce the power consumption of the compressor, the CO_2 temperature is reduced in a heat exchanger after each compression stage (inter-refrigeration). By adding several similar sections in series, the CO_2 can be brought to high pressure while maintaining a relatively low temperature. Figure 4-4 shows the block diagram of one inter-refrigerated compression stage.

The specific cooling requirement for the CO_2 compression process, according to the results in the reference IEAGHG case study, is 5.7 MJ per kilogram of hydrogen produced.

Figure 4-4: Block diagram of a single-stage CO_2 compression process.



Total cooling requirement

The carbon capture and compression processes are responsible for virtually all the cooling requirements in the blue hydrogen production plant. The remaining cooling loads are linked to the cooling of small waste streams (e.g., the continuous blowdown from the steam boiler) and account for less than 1% of the total.

Table 4-3 presents a summary of the process cooling loads. The total specific cooling requirement is equivalent to 34.4 MJ per kg of hydrogen.

Table 4-3: Breakdown of the cooling requirement for blue hydrogen production

Process units	**Cooling load (*MJ/kg hydrogen)***
MEA condenser	28.7
CO_2 compression	5.7
Other	<0.1
Total	**34.4**

4.4 Summary of treated water requirements

The summary of treated water consumption in blue hydrogen production is presented in Table 4-4, including variability in cooling water consumption across dry zones and wet zones in Australia. For an evaporative water-cooled system, the total water consumption including process water is 24 litres per kg of hydrogen in a dry zone and 20 litres per kilogram of hydrogen in a wet zone. For an air-cooled system, the only water consumed is the process water, which is 5.2 litres of water per kilogram of hydrogen.

Table 4-4: Summary of treated water requirements in blue hydrogen production

Parameter	SMR		Unit
	Dry Zone	Wet Zone	
Rated System Cooling Load per kg	10	10	kW/kg H_2 produced
Process H_2O Consumption per kg H_2	5.2	5.2	liters H_2O/kgH_2
Cooling H_2O Consumption per kg H_2 (evaporative water cooling)	19	15	liters H_2O/kgH_2
Cooling H_2O Required per kg H_2 (once-through cooling)	866	866	liters H_2O/kgH_2
Total H_2O Consumption per kg H_2 (air cooling)	5.2	5.2	liters H_2O/kgH_2
Total H_2O Consumption per kg H_2 (evaporative water cooling)	24	20	liters H_2O/kgH_2
Total H_2O Required per kg H_2 (once-through cooling)	871	871	liters H_2O/kgH_2

4.5 Critical treated water quality parameters

In determining critical treated water quality parameters in producing steam required for the SMR process, the 'ASME Consensus Operating Practices for the Control of Feedwater and Boiler Water Chemistry in Modern Industrial Boilers' was used Table 4-5 summarises feed/makeup water chemistry recommended for boilers with operating range between 3 to 25 bar pressure.

Table 4-5: Feed/Makeup water for watertube, high duty, primary fuel fired drum type boilers

Drum Operating Pressure	**Psig (0 – 300)** **MPa (0 – 2.07)** **bar (0 – 20.7)**	**Psig (301 – 600)** **Mpa (2.08 – 4.14)** **bar (20.8 – 41.4)**
Recommended water chemistry limits		
Feed/makeup water		
Dissolved oxygen (mg/L of O_2)	<0.007	<0.007
Total iron (mg/L)	<0.1	<0.05
Total copper (mg/L)	<0.05	<0.025
Total hardness (mg/L)	<0.5	<0.3
pH @ 25 °C	8.3 – 10.5	8.3 – 10.5
Nonvolatile TOC (mg/L)	<1	<1
Oily matter (mg/L)	<1	<1
Estimated total dissolved solids (mg/L) based on boiler 30 cycle of concentration of boiler water TDS threshold	108	85
Boiler water		
Silica (mg/L)	<150	<90
Total alkalinity (mg/L as $CaCO_3$)	<1000	<850
Free OH alkalinity (mg/L as $CaCO_3$)	Not specified	Not specified
Specific conductance (µS/cm) 25°C without neutralization	<7000	<5500
Equivalent TDS (mg/)	**<3241**	**2546**

Table 4-5 provides critical water parameters in feed or make up water to the boilers that used in SMR process. Feed or makeup water TDS was calculated based on an assumed cycles of concentration (30 was used) using the maximum threshold of TDS that the boiler's construction material can withstand. For the purpose of calculation in this technical paper, water chemistry for boiler operating at between 20.8 to 41.4 bar will be used as the basis in determining total water requirement for hydrogen production.

5. Water requirements for hydrogen liquefaction

Liquefaction of hydrogen is also required water for process cooling. **Cooling water demand per kg of hydrogen is ranging from 13 – 31 litres**. This will also add to the total treated water usage per kg of hydrogen being produced.

5.1 Process overview

In a similar way to liquefied natural gas, hydrogen can be liquefied to increase its volumetric density and facilitate its transport and storage. The main drawback of the liquefaction process is its high energy intensity.

The large energy requirement and other challenges of hydrogen liquefaction are due to specific physical characteristics of hydrogen.

Firstly, to be liquefied at atmospheric pressure, hydrogen must be cooled to extremely low temperatures, below -253°C. The low temperature makes the liquefaction process inherently inefficient.

In addition, hydrogen cannot be cooled down from ambient temperature just by ‘throttling’, as it is instead the case for most other gases. Throttling refers to the sudden reduction in pressure of a compressed gas through a throttling valve (isenthalpic Joule-Thomson expansion). While most gases at room temperature experience a temperature drop during the throttling process, hydrogen experiences a slight increase in temperature. To cool hydrogen by throttling, it must first be cooled to temperatures below its Joule-Thomson inversion temperature (-73°C). Below this temperature, hydrogen behaves like most other gases.

Finally, hydrogen presents two different spin isomers: para-hydrogen and ortho-hydrogen[63]. At ambient temperature, the equilibrium is reached when the para-hydrogen concentration is 25% and the ortho-hydrogen fraction is 75%[64]. While this balance remains constant for most temperatures, at very low temperature the equilibrium shifts towards 100% concentration of para-hydrogen. This characteristic is important when dealing with liquefied hydrogen, because the transition from ortho-hydrogen to para-hydrogen generates heat and can destabilise the liquid hydrogen and increase hydrogen losses during storage. To solve this issue, the liquefaction processes typically include ortho- to para-hydrogen converters.

There is not a unique process to perform hydrogen liquefaction, with several different designs and degrees of system complexity. The specific process design depends on several factors including liquefaction capacity, project-specific engineering requirements as well as site-dependent conditions such as costs for electricity and availability of refrigerants.

The simplest hydrogen liquefaction design is the Linde-Sankey process. Compressed hydrogen is firstly cooled with liquid nitrogen to bring it below its inversion temperature. Then, the hydrogen is rapidly expanded in a throttling valve and as a result, part of the hydrogen liquefies. The remaining vapour fraction is recirculated back with the hydrogen feed.

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[63] Ortho-hydrogen is defined as a hydrogen molecule in which the protons in the nuclei of both hydrogen atoms spin in the same direction. Conversely, para-hydrogen refers to a molecule in which the two protons spin in opposite directions.

[64] Hydrogen composed of 25% para-hydrogen and 75% ortho-hydrogen is defined as ‘normal hydrogen’

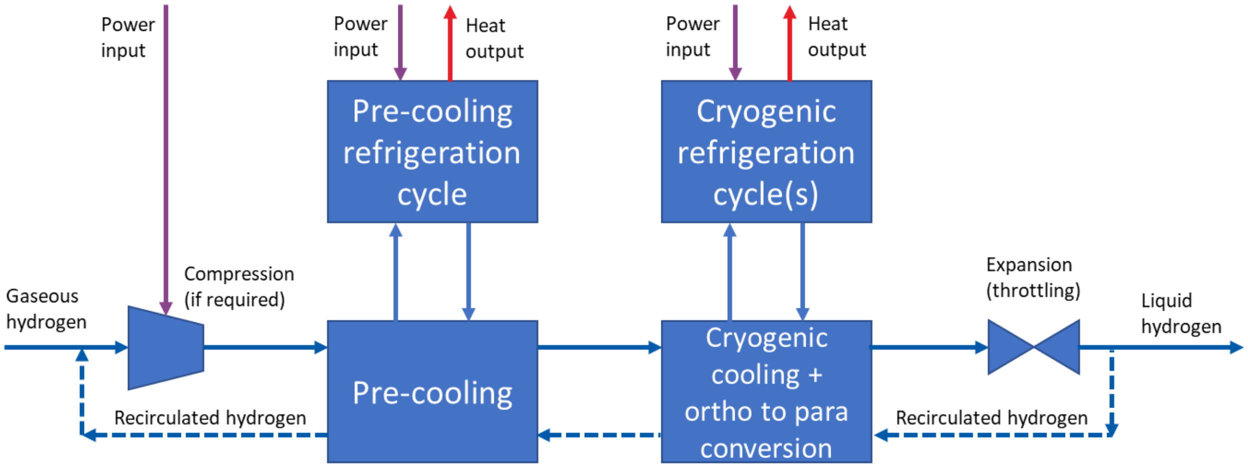
A more sophisticated design is represented by the Claude process, the technology implemented by most large-scale hydrogen liquefaction plants in operation today[65]. This process is similar to the Linde-Sankey process, with the addition of a refrigeration stage based on an expansion engine. The expansion engine provides additional cooling before the throttling valve, increasing the overall efficiency of the process.

More refined designs have been proposed to achieve better efficiency performances. The main differences are the number of refrigeration cycles and type of refrigerant fluids, and the addition of one or more expansion engines to increase the overall system efficiency.

The general design can be summarised by the following steps, as represented in Figure 5-1.

1. Hydrogen pre-compression (if required)
2. Pre-cooling of the hydrogen gas from ambient temperature to around 80 K
3. Cryogenic cooling of the hydrogen gas down to 20-30 K, including ortho-to-para-hydrogen conversion
4. Final Joule-Thomson expansion and liquefaction of the hydrogen
5. Recirculation of the vapour portion of the cooled hydrogen[66].

Figure 5-1: Simplified process flow diagram for hydrogen liquefaction.



5.1.1 Specific Energy Consumption of hydrogen liquefaction

Hydrogen liquefaction is based on the application of the refrigeration cycle (reverse Carnot cycle). Electrical energy is required to power the compressors within the refrigeration cycles. The total electrical energy in input to the hydrogen liquefaction process is identified by the SEC, or Specific Energy Consumption[67].

The ideal work required for the liquefaction of hydrogen at 20 bar of feed pressure is 2.9 kWh/kg. However, due to inefficiencies in the process, the actual energy required is significantly higher. As an example, the German hydrogen liquefaction plants of Linde, a leading industrial gases

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[65] Krasae-in S., Stang J., Neksa P., 2010, Development of large-scale hydrogen liquefaction processes from 1898 to 2009

[66] It is noted that liquefaction processes that do not require throttling and hydrogen recirculation have been proposed

[67] The energy entering the process is slightly smaller than the SEC due to some energy losses in the compressors' motors.

manufacturing company, have SECs between 11.9 kWh/kg and 13.6 kWh/kg[68]. Praxair, another industrial gas manufacturer, operates hydrogen liquefaction plants in the U.S.A. with SECs between 12.5 kWh/kg and 15 kWh/kg[69].

To facilitate a future large-scale hydrogen economy, new hydrogen liquefiers must be designed to produce liquid hydrogen more efficiently and at reduced costs. Higher efficiencies are technically possible in the near term. Existing industrial hydrogen liquefaction plants were often designed with the goal of minimising initial capital expenses rather than achieving high efficiencies. Consequently, there is great potential to improve the hydrogen liquefaction process and thus reduce the SEC for large-scale hydrogen liquefiers.

A high number of conceptual design studies on highly efficient large-scale hydrogen liquefaction plants have been published in the literature. IDEALHY, a European Union-funded program for the development of a high-efficiency liquefaction process, proposed a design for a liquefaction process with SEC of 6.8 kWh/kg[70]. The U.S. Department of Energy selected 6.0 kWh/kg (21.6 MJ/kg) as their target for hydrogen liquefaction SEC[71].

A summary of reference values for the SEC of hydrogen liquefaction is presented in Table 5-1.

Table 5-1: Specific energy consumption reference values for hydrogen liquefaction

Technology efficiency	**Specific Energy Consumption (*kWh/kg*)**
Theoretical minimum work[72]	2.9
Current design – high-efficiency	11.9
Current design – low-efficiency	15.0
Future design – target efficiency	6.0

5.2 Assumptions and design basis

The cooling requirement of hydrogen liquefaction can be determined in a rather straightforward way, despite the complexity and variability of the actual process. This can be calculated by looking at the energy balance of the entire process.

Considering that the total energy within the liquefaction process is constant at any point in time, according to the law of conservation of energy, the energy in output from the system must be equal to the energy in input.

The four key energy flows that cross the boundary of the liquefaction system are:

- the enthalpy of the gaseous hydrogen in input

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[68] Integrated Design for Demonstration of Efficient Liquefaction of Hydrogen (IDEALHY), 2012, Report on Technology Overview and Barriers to Energy- and Cost-Efficient Large Scale Hydrogen Liquefaction

[69] Drnevich R. Hydrogen delivery – liquefaction & compression. Praxair, strategic initiatives for hydrogen delivery workshop – May 7, 2003. Available from: http://www1.eere.energy.gov/ hydrogenandfuelcells/pdfs/liquefaction_comp_pres_praxair. pdf

[70] Integrated Design for Demonstration of Efficient Liquefaction of Hydrogen (IDEALHY), 2013, Hydrogen liquefaction report

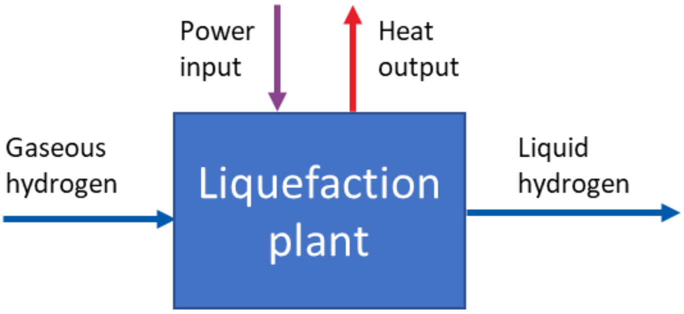
[71] https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-delivery

[72] Hydrogen initial conditions: Gas, 300K (27°C), 20 bar abs, normal hydrogen (25% para-hydrogen). Hydrogen final conditions: Liquid, 20K (-253°C), 1.01 bar (abs), 100% para-hydrogen.

- the enthalpy of the liquefied hydrogen in output
- the electrical energy in input to power the compressors in the refrigeration cycles
- the heat rejected in the coolers and refrigeration cycles.

The hydrogen enthalpy is a physical property that only depends on the input and output conditions of the hydrogen. If the power input is known, it is then possible to calculate the heat in output (cooling requirement).

Figure 5-2: Simple representation of the key energy and mass flows that cross the liquefaction plant's boundary



The characteristics and properties of the hydrogen flow in input and output from the liquefaction process are summarised in Table 5-2. The input pressure is in line with the typical hydrogen input pressure in existing liquefaction plants and is sufficiently low to not require pre-compression after the hydrogen production from a typical PEM electrolyser or SMR+CCS plant. The hydrogen enthalpy variation between inlet and outlet conditions is 3310.7 kJ/kg (3.3 MJ/kg).

Table 5-2: Hydrogen conditions and enthalpy at the inlet and outlet of the liquefication process

Hydrogen property	Unit	Input conditions	Output conditions
Temperature	°C	25	-253.4 (20.2 K)
Pressure	Bar (abs)	20	1.3
Phase	-	Gas	Liquid
Ortho/para ratio	%ortho / %para	75% / 25% (nomal hydrogen)	3% / 97%
Enthalpy	kJ/kg	0.7	-3310[73]

5.2.1 Cooling requirements

The amount of cooling required is equivalent to the sum of hydrogen enthalpy variation and the SEC, as calculated in Table 5-3.

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[73] Hydrogen enthalpy data retrieved from Zhang S., Li G., 2021, Design and performance analysis of a hydrogen liquefaction process

Table 5-3: Estimated cooling requirement for different hydrogen liquefaction process efficiencies

Technology Efficiency	Specific Energy Consumption (MJ/kg hydrogen)	Hydrogen enthalpy variation (MJ/kg hydrogen)	Cooling requirement (MJ/kg hydrogen)
Current design – high-efficiency	42.8 (11.9 kWh/kg)	3.3	46.1
Current design – low-efficiency	54.0 (15 kWh/kg)	3.3	57.3
Future design – target efficiency	21.6 (6 kWh/kg)	3.3	24.9

As shown in Table 5-4, the cooling requirement for hydrogen liquefaction is highly dependent on the SEC of the specific process (and therefore on its efficiency).

The expected drive towards reduced energy consumption in the future, together with the likely increase in the number and size of hydrogen liquefaction plants as the hydrogen economy develops, will lead to the achievement of considerably higher liquefaction efficiencies. Therefore, for the purpose of this analysis the efficiency of future hydrogen liquefaction plants is assumed to be between that of current high-efficiency plants and the U.S. Department of Energy efficiency target.

5.3 Summary of treated water requirements

While the hydrogen liquefaction process does not consume water in the process, it does require considerable cooling. If the heat rejection is provided by water cooling, then the liquefaction of hydrogen can be responsible for significant water demand.

The summary of treated water requirements for hydrogen liquefaction is presented in Table 5-4. For an evaporative water-cooled system, the total water consumption is 25 litres per kg of hydrogen at the current design efficiency and 13 litres per kg of hydrogen for future design efficiency (refer to Table 5-4). For once-through cooling, the calculated range is between 575 and 1105 litres per kg of hydrogen. If an air-cooled system is used, there are no water requirements for hydrogen liquefaction.

Table 5-4: Summary of treated water requirements in hydrogen liquefaction for current design efficiency and future design efficiency

Parameter	Technology Efficiency			Unit
	Current design – low efficiency	Current design – high efficiency	Future design – target efficiency	
Process H_2O Consumption per kg H_2	0	0	0	
Total H_2O Consumption per kg H_2 (air cooling)	0	0	0	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (evaporative water cooling)	31	25	13	litres H_2O/kgH_2
Total H_2O required per kg H_2 (once-through cooling)	1370	1105	575	litres H_2O/kgH_2

5.4 Critical treated water quality parameters

As there is no feedstock water required for hydrogen liquefaction, the critical treated water quality parameters are for cooling water only. Refer to Section 7.4.2.3 for water quality requirements for cooling water.

6. Water requirements for ammonia conversion

Hydrogen conversion to ammonia (Haber Bosch process) is also required water for process cooling. **Cooling water demand per kg of hydrogen is approximate 28 litres per kg of hydrogen during the conversion process to ammonia.** This will also add to the total treated water usage per kg of hydrogen being produced.

6.1 Process overview

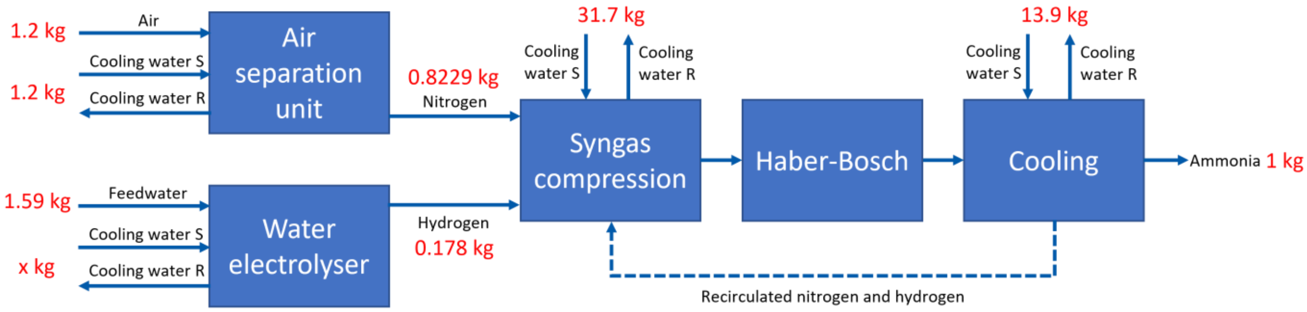
Ammonia has emerged as a promising medium for hydrogen storage. Consisting of 18% hydrogen by weight, ammonia has a relatively high volumetric energy density. As a liquid, its energy density of 12.9 MJ/L is higher than liquid hydrogen (8.49 MJ/L), yet it can be liquified easier than hydrogen – either by increasing the pressure to 10 bar at room temperature or by cooling to -33°C at atmospheric pressure[74]. Safer and easier to store and transport because of its low vapour pressure and high boiling point, ammonia can be used directly as a fuel source or converted back to hydrogen. A significant advantage of ammonia is that there is an existing infrastructure for the production, transport and distribution of ammonia worldwide, facilitating the way to an ammonia-based fuel industry.

Since ammonia has been used as a fertiliser for over a century, its manufacture is a well-established process. Through the Haber-Bosch cycle, hydrogen and nitrogen are converted into ammonia by means of high temperatures, high pressures, and a catalyst.

In Figure 6-1, the green and blue ammonia value chains differ in the hydrogen production method used; green ammonia being generated from water electrolysis and blue ammonia being generated from a conventional pathway, using fossil fuels, mainly through Steam Methane Reforming process (SMR).

Figure 6-1 represents a simple block diagram of Green Ammonia production process. The values in red represent the mass of air, water, nitrogen and hydrogen to produce 1 kg of ammonia. Figure 6-1 also shows the cooling water Supply (S) and Return (R) streams.

Figure 6-1: Simplified process flow diagram for hydrogen to ammonia conversion



Once the hydrogen and nitrogen gases are produced and any impurities removed, they are combined to form the synthesis gas known as the "syngas" and compressed. The reaction pressure normally ranges between 150-250 bar[75]. The compressors required to increase the pressure are based on multi-

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[74] Chatterjee, S.; Parsapur, R. K.; Huang, K.-W. Limitations of Ammonia as a Hydrogen Energy Carrier for the Transportation Sector. *ACS Energy Lett.* **2021**, *6* (12), 4390–4394.

[75] Eggeman, T. Ammonia. In Kirk-Othmer Encyclopedia of Chemical Technology; John Wiley & Sons, 2001; pp 261–291.

stage design with water-cooled intercoolers between stages to reduce the compression work and to keep the compression discharge temperature below a practical limit.

6.1.1 Haber-Bosch Synthesis Loop

After the syngas is compressed, it enters the Haber-Bosch synthesis loop. Equation 1 gives the reaction for the formation of ammonia from hydrogen and nitrogen that takes place in the reactor.

Equation 1:

$$N_2 + 3H_2 \rightleftharpoons 2NH_3$$

The flow rates of reactants and products through the ammonia production can be calculated from the stoichiometry of ammonia. At present, most ammonia plants produce 200-1500 tpd, with some plants designed for over 3000 tpd [76]. For a typical 300 tpd ammonia plant the flow rates of nitrogen, and hydrogen and the ratio factors per 1 kg H_2 are summarised in Table 6-1.

Table 6-1: Summary of flow rates for production of 300 tpd ammonia

Process	Component	Amount (tpd)	Flow rate (kg/h)	Ratio factor (kg/kg H_2)
Air separation	N_2	246.7	10,279	4.63 (N_2/H_2)
Electrolysis	H_2	53.3	2,221	1 (H_2/H_2)
Ammonia	NH_3	300	12,500	5.62 (NH_3/H_2)

Due to catalyst limitations and the unfavourable thermodynamic equilibrium of Equation 1, only 10-30% of the syngas is converted per pass to ammonia [77], so the unreacted syngas is recycled. The reactor operates at temperatures in the range of 350-550 °C, which is controlled by heating the syngas along with additional heat released by the exothermic synthesis of ammonia. Circulating cooling water is required in the Haber-Bosch synthesis loop to separate gaseous ammonia from the unconverted syngas. Cooling decreases the temperature of the gas so that ammonia condenses out of the mixture. The unconverted syngas is then supplemented with fresh makeup gas and returned as feed to the ammonia synthesis reactor. There will be far fewer impurities in a green ammonia plant such as the inert gases argon and methane than in a conventional ammonia plant, because the synthesis gases are derived from air separation and water electrolysis, not natural gas, which produce high purity nitrogen and hydrogen, respectively. Not only does this improve the ammonia yield, but it also results in negligible pollutant emissions [78].

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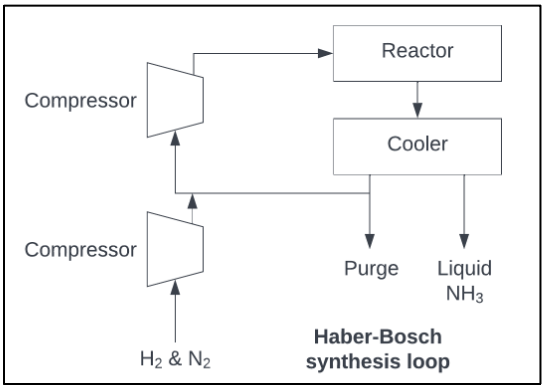
[76] Ammonia plant capacities in the U.S. Statista. https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states/ (accessed 2022-04-14).

[77] Ammonia Synthesis. In Synthetic Nitrogen Products: A Practical Guide to the Products and Processes; Maxwell, G. R., Ed.; Springer US: Boston, MA, 2004; pp 163–198. https://doi.org/10.1007/0-306-48639-3_6.

[78] European Commission. Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals - Ammonia, Acids and Fertilisers, 2007

Figure 6-2: Flow diagram of a Haber-Bosch synthesis loop showing the major components



6.1.2 Nitrogen Production

Ammonia synthesis requires ultra-high-purity (99.999%) nitrogen gas. Cryogenic air separation is currently the most efficient and cost-effective technology for producing large quantities of nitrogen [79]. An air separation unit (ASU) using a conventional, multi-column cryogenic distillation process produces high-purity nitrogen from compressed air at high recoveries and volumetric flowrates, in an all-electric process.

Cryogenic air separation is an established technology utilised in industry-standard ammonia plants with capacities from 200 to over 2000 tpd [80]. Cryogenic ASUs separate atmospheric air into its three main components – nitrogen, oxygen and argon – by exploiting their boiling point differences, which are -196 °C, -183 °C and -186 °C, respectively. The basic processes that take place in an ASU are:

1. Air compression: Atmospheric air is filtered to remove dust particles and compressed by a multi-stage compressor and cooled with intercoolers.
2. Air cooling and purification: The air is cooled with water in a direct contact cooler and water-soluble impurities are removed. The chilling of the cooling water is achieved using dry nitrogen waste gas from the distillation columns. Impurities such as CO_2 and water are removed by molecular sieve adsorbers.
3. Cold production and internal product compression: The dry air is further cooled in the main heat exchanger with counter current gas streams from the distillation process, as well as using Joule-Thomson cooling in an expander.
4. Cryogenic distillation: Cooled and liquefied air is separated into oxygen, nitrogen and argon using multiple distillation columns. The cold gases are sent through the heat exchanger to be warmed-up before being released.

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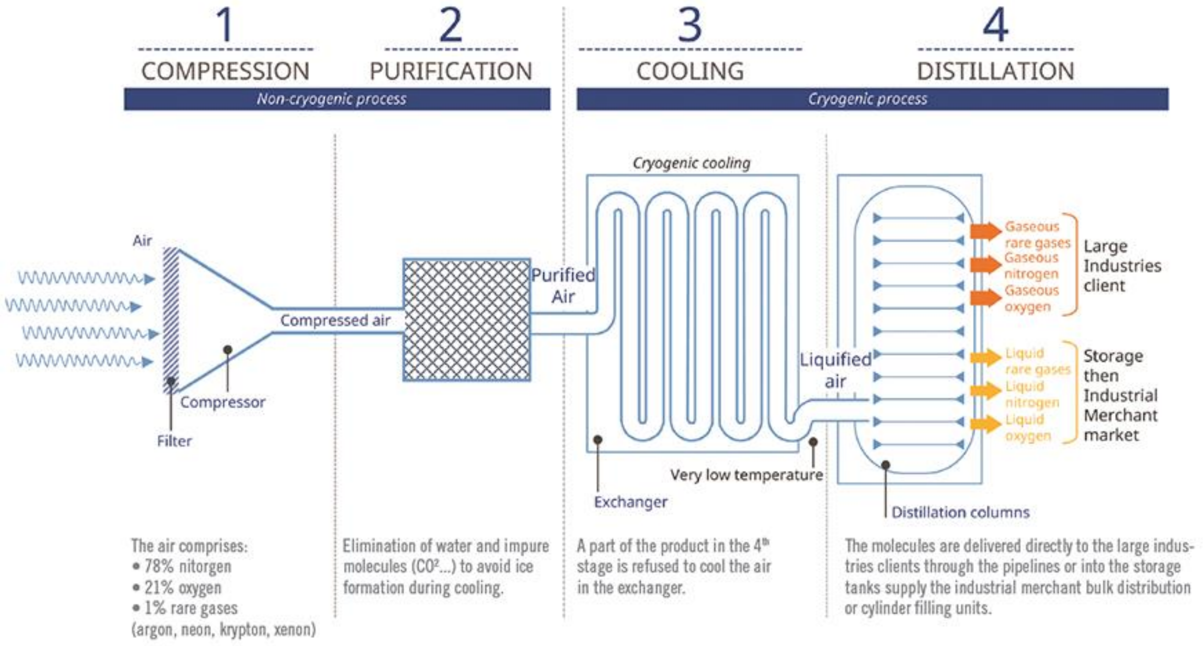
[79] Smith, A. R.; Klosek, J. A Review of Air Separation Technologies and Their Integration with Energy Conversion Processes. Fuel Process. Technol. 2001, 70 (2), 115–134. https://doi.org/10.1016/S0378-3820(01)00131-X.

[80] Pattabathula, V.; Richardson, J. Introduction to Ammonia Production, 2016.

Figure 6-3 Simplified process design of an air separation unit.

The ASU uses a series of distillation towers to separate liquefied air, under high pressures and cryogenic temperatures, into its constituent components [81].



The assumptions of the ASU are: (a) the intake temperature of the air is 293 K and the pressure is 1 bar, (b) there are three stages of compression to raise the pressure to approx. 6 bar and (c) the recovery ratio of nitrogen gas is 70% by volume. The last assumption is critical because it determines the flow rate of nitrogen gas produced by the ASU. A 300 tpd ammonia plant requires 246.7 tpd of nitrogen.

For an air separation unit with nitrogen production rate of 100 t/d (4.16 tph) of nitrogen, up to 887 m3/h (887tph) circulating water is required, which equates to 213 kg water per one kg nitrogen. Assuming a 10°C temperature increase and 5 cycles of concentration, 4.8 kg of water per kg of nitrogen would be required as make-up to the cooling water in circulation.

As per Table 6-1, applying the ratio factor of 4.63 kg N2/kg H_2, the water requirement for nitrogen production will be:

- Total circulation water: 213 x 4.63 = 986 kg water/ kg H_2
- Total make up water required: 22.2 kg water / kg H_2

6.1.3 Water Requirement for Ammonia Synthesis Loop

The estimates of water consumption were calculated for a medium size 300 tpd green ammonia plant.

Ammonia synthesis loops can be configured in myriad ways. However, there are some basic assumptions valid for any synthesis loop that are adopted for this analysis [82]:

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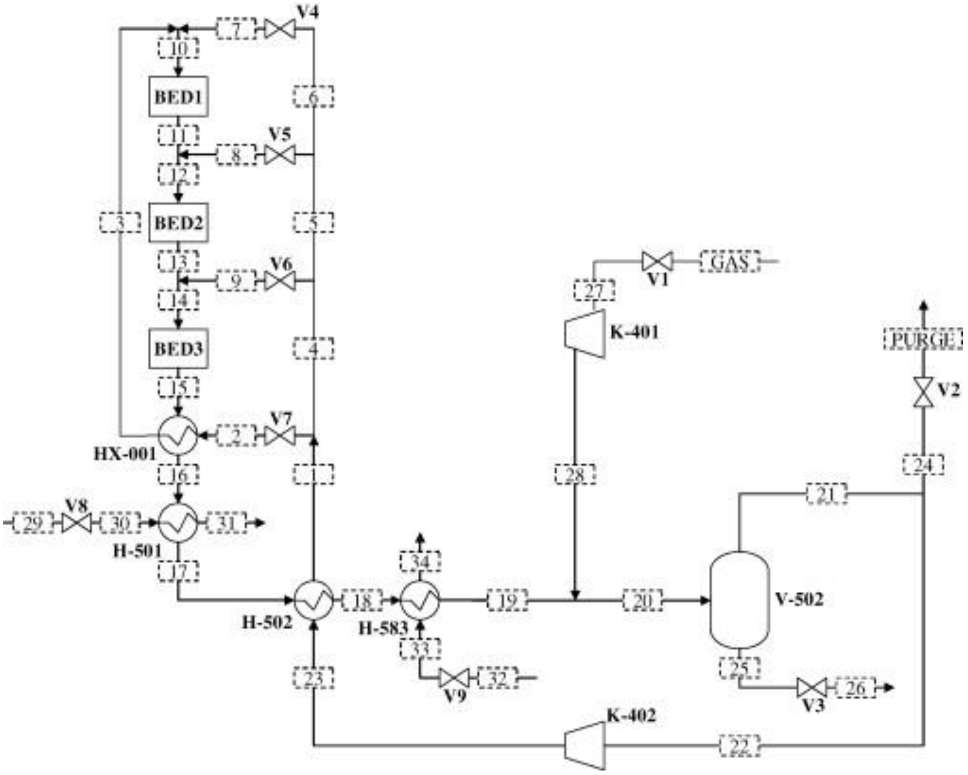
[81] Eng, B.; Martin, A.; Kantara, F.; Burgio, B. Air Liquide benefits from next-generation MPC. Control Global. https://www.controlglobal.com/articles/2021/air-liquide-benefits-from-next-generation-mpc/ (accessed 2022-04-21).

[82] Morgan, E. Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind. Open Access Diss. 2013. https://doi.org/10.7275/11kt-3f59.

1. The feed syngas is compressed by a centrifugal compressor train from 1 bar to operating pressure.
2. A recycle compressor compensates for pressure drops in the loop.
3. The operating pressures and temperatures are valid for any size ammonia plant.
4. The flow rate alone can be used to approximate the sizes of equipment.
5. There are four major heat exchangers. Only two of them require water cooling and are used to cool the product stream.

Here we consider the ammonia synthesis loop design given in Figure 6-4, which is a simplified version of an actual industrial plant [83]. There are four major heat exchangers: HX-001, H-501, H-502 and H-583. Heat exchangers HX-001 and H-502 preheat the reactor feed. Heat exchanger H-583 water-cools the syngas so that it can be condensed in the knockout drum. The cooling water's inlet temperature is 5 °C and there is a temperature increase of 10 °C. The original model was based on an industrial natural gas ammonia plant, and thus H-501 is intended to generate low pressure steam from the ammonia synthesis reaction heat. However, low pressure steam is not required for a green ammonia plant powered with electricity so the temperature change of the cooling water through H-501 is assumed to be 50 °C and the water remains liquid [82].

Figure 6-4: An ammonia synthesis loop with a three-bed catalytic reaction [84].



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[83] Morud, J. C.; Skogestad, S. Analysis of Instability in an Industrial Ammonia Reactor. AIChE J. 1998, 44 (4), 888–895. https://doi.org/10.1002/aic.690440414.

[84] Araújo, A.; Skogestad, S. Control Structure Design for the Ammonia Synthesis Process. *Comput. Chem. Eng.* **2008**, *32* (12), 2920–2932.

A five-stage compressor train is utilised to compress the syngas before it enters the synthesis loop. The heat transferred to the syngas by the compressors is removed by intercoolers. The cooling power required by one intercooler is given by Q in Equation 3. It is assumed that the cooling water is available at 5 °C and increases by 10 °C. Using the specific heat capacity of water, of 4.18 kJ/kgK, the mass flow rate of water through one intercool is given by Equation 3:

$$H_2O_{cool=\frac{Q}{C_{p_{H2O}}(T_2-T_1)}} = 27.5\ kg/s$$

Since the last compressor is not cooled because hot gases are required in the synthesis loop, the result is multiplied by four to get the total cooling water flow rate for all intercoolers. Using the same equation, the flow rate of water through the two other water-cooled heat exchangers in the synthesis is found to be 48.25 kg/s.

Hence, the total circulating cooling water requirement for a 300 tpd ammonia production is around 160 kg/s (576,000 kg/h). This equates to 46 kg water per 1 kg ammonia. Assuming a 10°C temperature increase and 5 cycles of concentration, 1.0 kg of water per kg of nitrogen would be required as make-up to the cooling water in circulation.

Accounting for ratio factor of 5.62 ammonia/H_2, (see Table 6-1), the water requirement per 1 kg of hydrogen is:

- Total circulation water = 46 x 5.62 = 259 kg water/ kg H_2
- Total make up water required = 5.8 kg water / kg H_2

6.2 Summary of treated water requirements

The water requirement for green ammonia production will consist of three main components:

- Water required for producing hydrogen via electrolysis, this has been discussed in detail in section 2.
- Water required for producing Nitrogen
- Water required for ammonia synthesis loop

Table 6-2: Water requirement breakdown for Green Ammonia production

Process	Resulted Component	Circulation Water required kg water / kg H_2	Makeup water required kg Water/ kg H_2
Air separation	N_2	986	22
Electrolysis	H_2	See Section 2	See Section 2
Ammonia Loop	NH_3	260	6

The summary of treated water requirements for green ammonia conversion is presented in Table 6-3. For an evaporative water-cooled system, the total water consumption including process water is 63 litres per kg of hydrogen. Note that this excludes the water that is used in the electrolysis process, which is captured separately in Section 2.

Table 6-3: Summary of treated water requirements in green ammonia production

Parameter	Ammonia conversion	Unit
Total H_2O required per kg H_2 (once-through cooling)	1246	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (air cooling)	0	litres H_2O/kgH_2
Total H_2O Consumption per kg H_2 (evaporative water cooling)	28	litres H_2O/kgH_2

7. Raw water sources and treatment options

Source water available for use by hydrogen projects will vary by location considering social, environmental, regulatory, and economic factors. The water quality of raw water sources is highly variable. Water sources considered include recycled water, surface water, groundwater, brackish water, and seawater. The water quality specifications of hydrogen production processes inputs also vary for green hydrogen (e.g for PEM electrolysis: Demineralised ASTM Type II water), Hydrogen process cooling water, Blue Hydrogen – boiler feed makeup water.

Water sources have been categorised by their water quality and associated treatment needs to meet the input requirements for each hydrogen production method assessed, using total dissolved salts (TDS) as an indicator.

In summary the ranking of preferred raw water sources for the production of hydrogen, based on water recovery and energy efficiency considerations is as follows:

- Advanced recycled water (Class A water with RO treatment)
- Surface water & ground water with low salinity (TDS < 800 mg/L)
- Class A water (without additional treatment by RO), brackish water, and
- Seawater

Where advanced recycled water is available, this is considered the most sustainable water source by the study as it requires the least treatment, whereas seawater requires the highest treatment.

This section will detail the raw water sources and treatment processes used to supply treated water for hydrogen production and conversion.

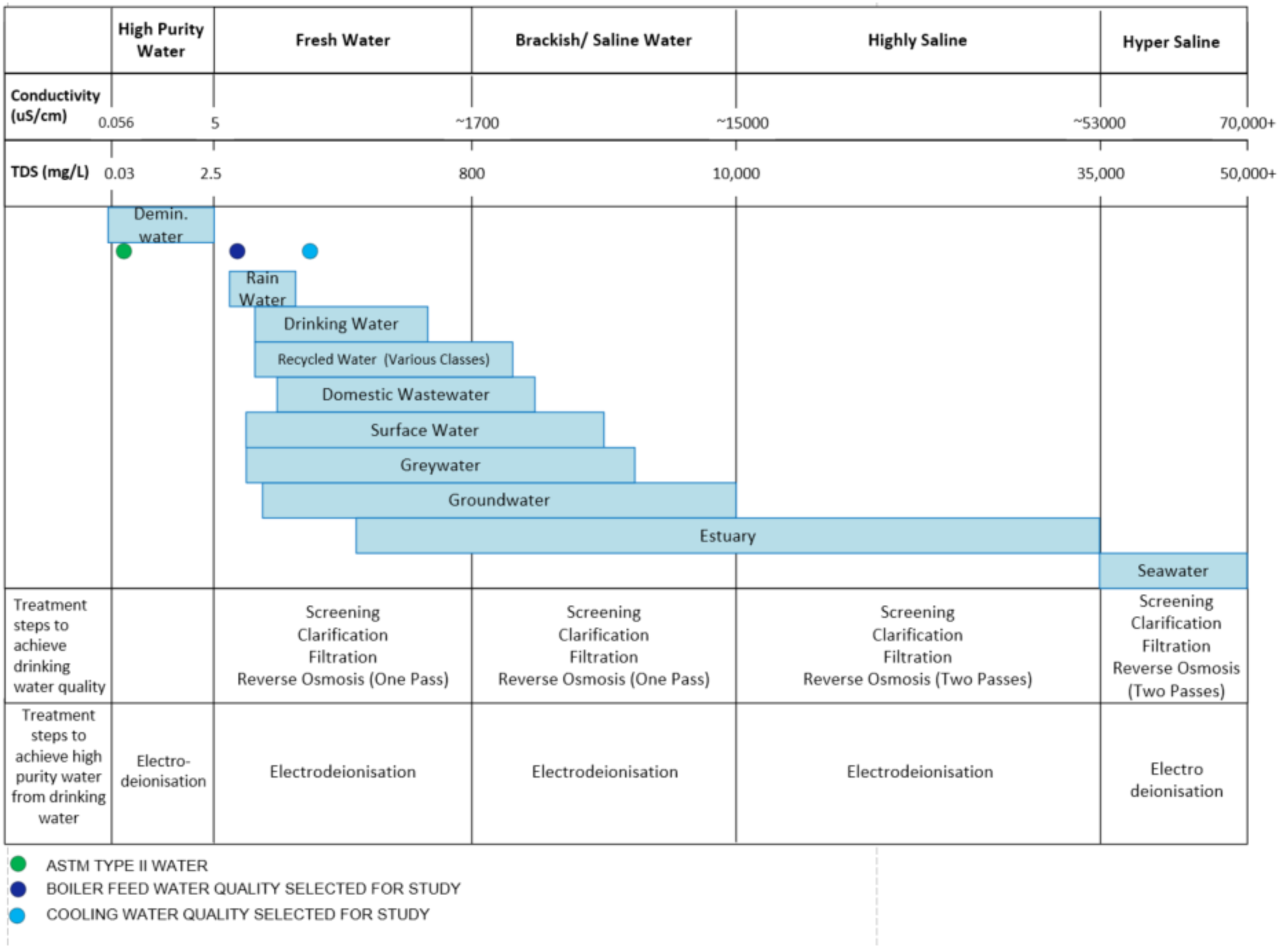
7.1 Overview of raw water sources

Water for use in hydrogen production is typically generated by treating a raw water source. Raw water can be drawn from a range of sources, including:

- Surface water (e.g., lakes, dams, rivers and creeks)
- Groundwater (e.g., well water, aquifers and bore water)
- Recycled water (e.g., treated wastewater effluent)
- Brackish water sources (e.g., saline surface water and groundwater)
- High salinity water sources (e.g., seawater, estuary water).

These water sources can be classified by various characteristics. For the application of hydrogen production where conductivity is one of the critical parameters in demineralised water, it will be useful to classify these raw sources by their conductivity or its equivalent represented by Total Dissolved Solids (TDS). Figure 7-1 below outlines typical ranges of TDS and conductivity for various water sources, together with the treatment steps required for purification. Appendix A: Typical Water Source TDS outlines the sources of these values.

Figure 7-1: Water sources, typical TDS ranges and treatment requirements



	High Purity Water	Fresh Water	Brackish/ Saline Water	Highly Saline	Hyper Saline
Treatment steps to achieve drinking water quality		Screening Clarification Filtration Reverse Osmosis (One Pass)	Screening Clarification Filtration Reverse Osmosis (One Pass)	Screening Clarification Filtration Reverse Osmosis (Two Passes)	Screening Clarification Filtration Reverse Osmosis (Two Passes)
Treatment steps to achieve high purity water from drinking water	Electro-deionisation	Electrodeionisation	Electrodeionisation	Electrodeionisation	Electro deionisation

7.2 Assumptions and design basis

The following assumptions were made in the development of the raw water envelopes and mass balances.

- Development of raw water quality envelopes are based on existing data available publicly or from previous Arup experience and is to be used only to provide a high-level understand to stakeholders of potential contaminants. It is assumed that this data would not be used for any specific projects or designs.
- Development of treated water quality envelopes are based on existing data available publicly or from previous Arup experience and is to be used only to provide a high-level understanding to stakeholders of potential treated water quality requirements. It is assumed that this data would not be used for any specific projects or designs, and that the site-specific requirements of each project would require a separate detailed investigation producing results which may differ from those provided by Arup.
- Development of environmental considerations shall be limited to projects within Australia. It is assumed that this shall provide a general overview to stakeholders and should not be used as an exhaustive list of planning, environmental and/or stakeholder engagement requirements.
- Raw water balances are only representative and will vary depending on project and location, so should not be used as a basis of design.

7.3 Representative water quality

To determine typical ranges of contaminants for these water sources, several data points of water quality from Australian raw water sources were collated to determine a water quality envelope for each type of raw water. Data from approximately 10-15 water sources from a range of sites around Australia were used for each type of raw water. The water quality data from each water source was analysed to highlight the minimum, maximum, median, and average of each of the contaminants of concern. Note that surface water and groundwater with an average total dissolved solids (TDS) > 800 mg/L has been categorised under saline water.

Water contaminants that are of particular concern to industrial water systems include:

- Algae and or organic matters (may cause biological fouling)
- Dissolved solids such as sulphate and chlorides (may be corrosive)
- Minerals such as calcium and magnesium, as well as high alkalinity (may cause scaling)
- High silica (may cause amorphous silica scale)
- Metal solids such as iron and manganese (may be oxidised to insoluble forms and precipitate in cooling systems)
- Turbidity (may cause fouling)
- Macro organisms such as clams and mussels (may cause blockages, damage to equipment)

The raw water quality envelopes developed for each of the defined water quality types are outlined in Table 7-1 to Table 7-5. These were developed based on the following assumptions:

- Although there are many contaminants of concern to be considered, not all contaminants are relevant to each type of water. For example, algae are a major concern of surface water and seawater, but not of groundwater sources. The contaminants chosen for each envelope directly reflect the risks of that water type.
- As previously outlined, for the purposes of categorising water sources, surface, or groundwater with TDS >800 mg/L has been defined as brackish water, with water sources with TDS>35,000 mg/L defined as highly saline water.
- The data for recycled water sources is a mixture of Class A, B and C recycled water.
- Raw water quality envelopes have been developed solely for the purpose of providing an indicative estimate of potential water quality for each raw water source covering the regions of interest for potential sites. Specific raw water quality envelopes should be developed for specific locations and sources and consider the site-specific conditions.
- Data points which were significant outliers from the entire data set and had a significant impact on average and median values were removed from the raw data.
- As data has been collated from various sources to develop the raw water quality envelope, the ionic composition of the water quality envelope does not balance as would typically occur from a single data source. This will alter values for TDS in surface and ground water sources when all ions have been balanced.

Table 7-1: Surface Water Raw Water Envelope

Contaminant	Units	Minimum	Maximum	Median	Average
Algal cell count	cells/1ml	46	117000	1670	5728
Alkalinity	mg/L as CaCO3	1.0	195.0	31.8	44.1
Calcium	mg/L	1.8	60.5	4.5	6.5
Total Hardness	mg/L as CaCO3	7.0	190.0	39.0	46.5
Chloride	mg/L	3.0	30.0	15.0	14.1
Copper	mg/L	0.0003	0.0302	0.0010	0.0022
Iron	mg/L	0.0	20.0	0.2	0.6
Magnesium	mg/L	0.5	170.0	3.3	11.2
Manganese	mg/L	0.00	3.00	0.02	0.10
pH	pH Units	4.0	10.1	7.3	7.3
SiO2	mg/L	2.6	18.4	2.7	4.3
Sodium	mg/L	1.4	81.0	9.6	17.5
Sulphate	mg/L	0.0	270.0	3.5	9.9
Total Dissolved Solids (TDS)	mg/L	13.0	410.0	57.5	101.0
Total Suspended Solids (TSS)	mg/L	1.0	553.0	4.0	17.9
Turbidity	NTU	0.10	1211	5.4	40.0

Table 7-2: Groundwater Raw Water Envelope

Contaminant	Units	Minimum	Maximum	Median	Average
Alkalinity	mg/L as CaCO3	2.0	330.0	125.5	128.4
Calcium	mg/L	0.3	217.0	11.1	17.3
Chloride	mg/L	19.5	2700.0	84.5	155.2
Total Hardness	mg/L as CaCO3	21.0	289.0	202.5	173.2
Copper	mg/L	0.00	0.69	0.003	0.01
Iron	mg/L	0.0	109.0	0.1	0.6
Magnesium	mg/L	0.0	330.0	11.9	21.3
Manganese	mg/L	0.00	0.85	0.04	0.12
pH	pH Units	3.6	11.0	6.8	6.8
SiO2	mg/L	0.0	33.0	7.0	8.2
Sodium	mg/L	1.6	1575.0	65.2	82.5
Sulphate	mg/L	0.0	700	7.6	28.7
Total Dissolved Solids (TDS)	mg/L	59.0	6200	348.8	422.2
Turbidity	NTU	0.1	13.0	5.6	5.3

Table 7-3: Recycled Water Raw Water Envelope

Contaminant	Units	Min	Max	Median	Ave
Alkalinity	mg/L as CaCO3	4.0	137.6	80.5	70.1
Calcium	mg/L	0.1	32.7	25.2	21.3
Chloride	mg/L	2.0	208.0	85.0	95.0
Copper	mg/L	0.001	0.219	0.005	0.009
Iron	mg/L	0.001	0.066	0.010	0.021
Magnesium	mg/L	0.1	23.4	14.9	12.4
Manganese	mg/L	0.001	0.239	0.002	0.015
pH	pH Units	6.0	9.8	7.4	7.4
SiO2	mg/L	6.0	9.9	6.9	7.1
Sodium	mg/L	2.0	301.0	90.7	101.9
Sulphate	mg/L	1.0	91.0	35.5	40.8
Total Dissolved Solids (TDS)	mg/L	72.0	800.0	415.0	403.7
Total Suspended Solids (TSS)	mg/L	1.0	29.0	3.5	3.9
Turbidity	NTU	0.02	97.0	0.2	0.8

Table 7-4: Brackish Water Raw Water Envelope

Contaminant	Units	Min	Max	Median	Ave
Alkalinity	mg/L as CaCO3	68.3	1100.0	277.0	381.1
Calcium	mg/L	4.0	206.0	57.0	80.9
Total Hardness	mg/L as CaCO3	270.0	1100.0	312.0	590.4
Chloride	mg/L	0.001	7490.0	548.0	1851.4
Copper	mg/L	0.001	0.080	0.003	0.005
Iron	mg/L	0.0	56.2	0.1	7.1
Magnesium	mg/L	4.7	1600.0	70.7	162.2
Manganese	mg/L	0.00	1.07	0.06	0.14
pH	pH Units	3.6	9.1	7.8	7.8
SiO2	mg/L	0.001	93.0	15.0	22.7
Sodium	mg/L	21.3	4200.0	306.0	880.8
Sulphate	mg/L	4.0	2444.0	199.8	324.2
Total Dissolved Solids (TDS)	mg/L	234.1	26000.0	1310.0	2284.4
Total Suspended Solids (TSS)	mg/L	15.8	25.0	15.8	15.8
Turbidity	NTU	0.0	2200.0	2.0	164.9

Table 7-5: Seawater Raw Water Envelope

Contaminant	Units	Min	Max	Median	Ave
Algal cell count	cells/1ml	0.0	500.0	250.0	250.0
Alkalinity	mg/L as CaCO3	123.0	146.0	136.0	134.4
Calcium	mg/L	405.0	662.0	422.5	475.9
Total Hardness	mg/L as CaCO3	6353	7000	6932	7013
Chloride	mg/L	19000	28000	20185	22048
Copper	mg/L	0.001	0.005	0.002	0.002
Iron	mg/L	0.001	0.348	0.016	0.027
Magnesium	mg/L	1300.0	1920.0	1380.0	1489.7
Manganese	mg/L	0.001	0.033	0.005	0.006
pH	pH Units	7.3	8.8	8.1	8.1
SiO2	mg/L	0.1	8.0	1.0	2.5
Sodium	mg/L	9800.0	16500.0	11350.0	12384.5
Sulphate	mg/L	2700.0	5370.0	2810.0	3177.0
Total Dissolved Solids (TDS)	mg/L	35000	49000	37250	39494
Total Suspended Solids (TSS)	mg/L	0.9	9.0	3.5	3.5
Turbidity	NTU	0.0	88.0	1.8	2.3

7.4 Basis of Design for Water Treatment Plant

The objectives for the water treatment plant are to produce the following type of water and quality as detailed in the subsequent sections.

7.4.1 PEM electrolyser feed water quality

PEM electrolyser will be used as the basis for production of green hydrogen and as per Section 3.4, ASTM Type II water quality has been recommended by some electrolyser vendors, case studies and Arup past projects. Table 7-6 below provides the parameters and their limits for ASTM Type II water, and this will be the basis for treatment technologies selection in subsequent sections of this report. Note that for ASTM Type II water, pH is not included in this specification because this grade of water does not contain constituents in sufficient quantity to significantly alter the pH.

Table 7-6 ASTM Type II Water Quality

Parameters	Unit	Type II
Electrical conductivity	µS/cm at 298 K (25°C)	1.0
Electrical resistivity	Min.Mcm at 298 K (25°C)	1.0
pH	pH at 298 K	N/A
Total organic carbon (TOC) max	µg/L	50
Sodium, max.	µg/L	5
Chlorides, max	µg/L	5
Total silica, max	µg/L	3

7.4.2 Water Cooling System

There are three basic types of cooling water systems: once-through, closed recirculating (non-evaporative), and open recirculating (evaporative) systems. Each system has different requirements for water quality.

7.4.2.1 Once through cooling system

Once through cooling water systems (also known as single pass cooling) use large volumes of water as they immediately discharge the water after it has been used for cooling. As such, there is little evaporation, so the water quality requirements are less strict. Often, raw water sources such as surface water and seawater are used, with limited treatment required before use. Unlike the high purity water required for electrolysis, only limited treatment is required to screen large objects which may damage equipment.

7.4.2.2 Evaporative and non-evaporative cooling systems

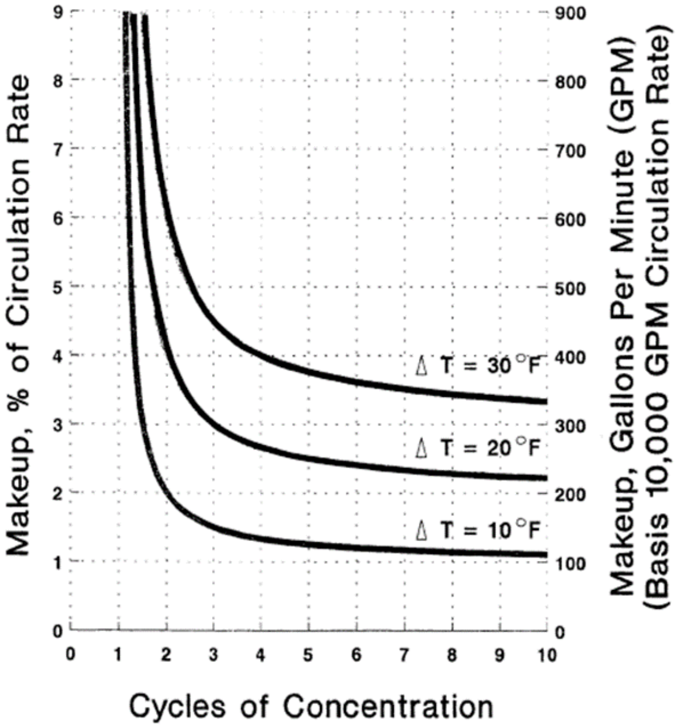
In open recirculating/evaporative cooling technology, heated water is cooled by exchanging with cooler recirculating water over contacted areas, which evaporates a small portion of the recirculating water as it flows through the unit. Evaporative cooling systems require less raw water than once through cooling, although there is more concern regarding the cooling water quality.

A particular concern to evaporative cooling systems is cycles of concentration (CoC). As cooling water is circulating, some proportion of the water is lost through evaporation or blowdown (discharging of water from cooling system). As makeup water is added to replace water lost, the concentration of dissolved solids increases. This is detrimental to cooling performance as these solids can cause corrosion and fouling. The CoC refers to cycle of concentration of dissolved solids in the blowdown water in comparison to the concentration in the makeup water. E.g., at 3 CoC, the blowdown water is 3 times more concentrated than the makeup water. Blowdown is required to manage the concentration in the cooling water. Figure 7-2 highlights the impact of CoC on the percentage of makeup water.

As such, evaporative cooling systems have the strictest requirements for water quality, as the concentration of dissolved solids in the feed water quickly increases due to cycles of concentration.

In closed recirculating/non-evaporative cooling systems, water is circulated in a closed cycle with no water loss to evaporation. As such, non-evaporative cooling systems have a much smaller amount of makeup water required and less of a concern for cycles of concentration. As such, the requirements for water quality are lower than in evaporative cooling systems.

Figure 7-2: Effect of cycles of concentration on makeup water



7.4.2.3 Cooling Water Quality

As there is variation in types of cooling water systems used, there are variations in recommended water quality. It is recommended to contact cooling system suppliers for the specific requirement for water quality needs.

For this technical paper, the basis of design is an evaporative cooling system and 5 CoC is selected as the basis. Upper limiting concentration for various water quality parameters have been collated from various suppliers and shown in Table 7-7, and the derived makeup water quality parameters are shown in Table 7-8.

Table 7-7 Water Quality Requirements from Various Evaporative Cooling Tower Suppliers

Parameters	**Unit**	**Baltimore**			**Evapo**			**Marley**	**SPX**
Material of construction		Galvanised Steel	SS304	SS316	Galvanised Steel	SS304	SS316	Galvanised Steel	Stainless Steel
pH	pH	6.5 – 9.0	6.5 – 9.2	6.5 – 9.5	7 – 8.8	6.0 – 9.5	6.5 – 9.5	6.5 – 9.0	6.5 – 9.0
Total Suspended Solids	mg/L	25	25	25	25	25	25		
Total Dissolved Solids	mg/L	1500	2050	2050					5000
Conductivity	µS/cm	2400	3,300	4000	2400	4000	5000		
Alkalinity	mg/L as $CaCO_3$	500	600	600	75 – 400	600	600		100 – 500
Calcium Hardness	mg/L as $CaCO_3$	50 – 600	50 – 750	50 – 750	50 – 500	600	600	500	800
Chloride	mg/L	250	300	750	300	500	2000	500	450
Sulfate	mg/L	250	350	750				250	800
Silica	mg/L	150	150	150	150	150	150		150
Iron	mg/L								3
Manganese	mg/L								0.1

Table 7-8 Basis of makeup water quality for evaporative cooling system running at 5 CoC

Parameters	**Unit**	**Selected maximum tolerable values**	**Makeup Water quality**
Material of construction		Galvanised Steel	Stainless Steel
pH	pH	6.5 – 9.0	6.5 – 9.0
Total Suspended Solids	mg/L	25	5
Total Dissolved Solids	mg/L	1500	300
Conductivity	µS/cm	2400	480
Alkalinity	mg/L as $CaCO_3$	500	100
Calcium Hardness	mg/L as $CaCO_3$	500	100
Chloride	mg/L	300	60
Sulfate	mg/L	250	50
Silica	mg/L	150	30
Iron	mg/L	3	0.0
Manganese	mg/L	0.1	0.03

7.4.3 Water Quality for SMR and Boiler Feed Water

For SMR process, steam at 700 – 1000 deg °C and at 3 – 25 bar pressure reacts with natural gas in presence of a catalyst to produce H_2 and CO_2. The chemical reactions in the SMR process are shown below.

1. Steam methane reforming reaction

$$CH4 + H2O + heat\ input \rightarrow\ CO + 3H2$$

2. Water gas shift reaction

$$CO + H2O\ \ \rightarrow CO2 + H2 + small\ amount\ of\ heat\ released$$

In determining critical treated water quality parameters in producing steam required for the SMR process, the ‘Table 2 in the ASME Consensus Operating Practices for the Control of Feedwater and Boiler Water Chemistry in Modern Industrial Boilers’ was used. Table 7-9 summarises feed/makeup water chemistry recommended for boilers with operating range between 3 to 25 bar pressure from the source.

Table 7-9 Recommended water chemistry limits for feed/makeup water for watertube, high duty, primary fuel fired, drum type boilers

Parameter	**Drum Operating Pressure**	
	Psig (0 – 300) **MPa (0 – 2.07)** **bar (0 – 20.7)**	**Psig (301 – 600)** **Mpa (2.08 – 4.14)** **bar (20.8 – 41.4)**
Feed/makeup water		
Dissolved oxygen (mg/L of O_2)	<0.007	<0.007
Total iron (mg/L)	<0.1	<0.05
Total copper (mg/L)	<0.05	<0.025
Total hardness (mg/L)	<0.5	<0.3
pH @ 25 °C	8.3 – 10.5	8.3 – 10.5
Non-volatile TOC (mg/L)	<1	<1
Oily matter (mg/L)	<1	<1
Estimated total dissolved solids (mg/L) based on boiler 30 cycle of concentration of boiler water TDS threshold	108	85
Boiler water		
Silica (mg/L)	<150	<90
Total alkalinity (mg/L as $CaCO_3$)	<1000	<850
Free OH alkalinity (mg/L as $CaCO_3$)	Not specified	Not specified
Specific conductance (µS/cm) 25°C without neutralization	<7000	<5500
Equivalent TDS (mg/)	<3241	2546

Feed or makeup water TDS in Table 7-9 was calculated based on an assumed 30 cycles of concentration, calculated from the maximum threshold of TDS that the boiler’s construction material can withstand. For the purpose of calculation in this technical paper, water chemistry for boiler operating at between 20.8 to 41.4 bar will be used as the basis in determining total water requirement for hydrogen production.

7.4.4 Basis for Mass Flow Balance

One of the objectives for the technical paper is to provide an estimate quantity of raw water required in the production (blue and green) and conversion (liquefaction and ammonia) of hydrogen. The water quality products required for each of these processes can be covered by ASTM Type II and boiler feed/cooling water quality. As there are five raw water sources and two product water quality products to be considered, the approach to undertake mass and flow balance for each raw water source is as followed:

- Estimate the quantity of raw water source required to produce 1ML/d of ASTM type II water as per Table 7-6.
- Estimate the quantity of raw water source required to produce 1ML/d of cooling water with quality as per Table 7-7 and Table 7-8.
- Estimate the quantity of raw water source required to produce 1ML/d of boiler feed water with quality as per Table 7-9.

The above unit rate for the three product streams can then be used to estimate the total raw water requirement in the green or blue hydrogen production process when the estimated quantity of water for ASTM Type II, cooling and boiler feed water are available.

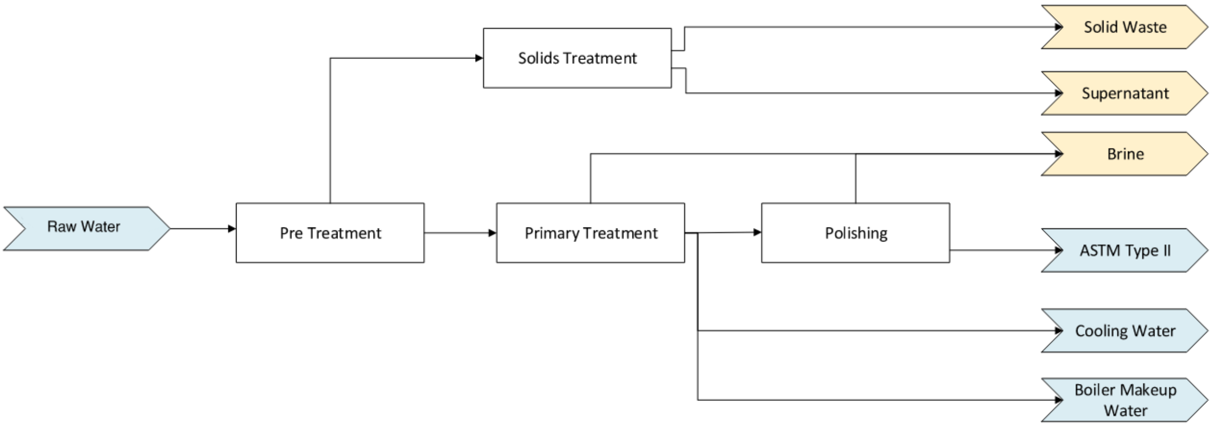
7.5 Treatment steps

A treatment process train was developed for each raw water source based on the major contaminants of concern in each source and the targeted water quality for hydrogen production facilities. The treatment train has been split into three treatment steps:

- Pre-treatment – Screening for removal of large debris to prevent damage to equipment
- Pre-treatment – chemicals flocculation and clarification for reduction of turbidity, colour and organics
- Pre-treatment – filtration for removal of suspended solids
- Primary treatment – for reduction of total dissolved solids
- Final polishing – further reduction of total dissolved solids if required to meet demineralised water grade

Depending on the characteristic of the raw water sources, some or all of the treatment steps above can be required. Figure 7-3 summarises these treatment steps, treated water output (ASTM Type II electrolyser water, cooling water and boiler makeup water) and waste streams (Solid waste, supernatant, and brine).

Figure 7-3: Treatment Steps Block Flow Diagram



Water quality assessment was undertaken for each of the water sources to identify potential pollutants that could impact the process and operational performance of the treatment plant. Typical technologies were suggested for each of the treatment stages, based on our familiarity and experience for treating that water type. Table 7-10 below summarises these treatment trains and key design considerations for each water type.

Table 7-10 Treatment Train Summary for Each Raw Water Source

	Surface water (TDS <800)	**Ground water (TDS <800)**	**Recycled Water (TDS<800)**	**Brackish Water (TDS 800 to < 10,000)**	**High salinity water (TDS >10,000 to 35,000)**
Target contaminants	Algae, suspended solids, silica, metals	Silica, calcium, magnesium, metals	Silica, metals, suspended solids, organics,	Silica, chlorides, calcium, metals, potential algal content	Silica, chlorides, calcium, metals, potential algal content
Nominated technologies for treatment train	Coarse screen Lamella clarifier DAFF RO EDI	Conventional clarifier (for softening) Media filter RO EDI	Chloramination UF Dechlorination RO (Double pass) EDI	Coarse screen Media Filter RO (double-pass) EDI	Coarse screen Media Filter RO (double-pass) EDI
Selection considerations	DAFF was proposed to assist with algal removal as clarifier alone may not be sufficient. High silica removal is key driver behind RO selection over EDR. EDI was selected as no chemical consumption for final polishing compared to ion-exchange resin beds	High carbonate and magnesium concentrations in groundwater require softening through lime clarifier. High silica removal and rejection rate are key driver behind RO selection over EDR. EDI was selected as no chemical consumption for final polishing compared to ion-exchange resin beds	Clarification optional if water is high in solids and algae. Chloramination reduces UF biofouling. High silica removal and rejection rate are key driver behind RO selection over EDR. EDI was selected as no chemical consumption for final polishing compared to ion-exchange resin beds	High silica removal and rejection rate are key driver behind RO selection over EDR. EDI was selected as no chemical consumption for final polishing compared to ion-exchange resin beds	High silica removal and rejection rate are key driver behind RO selection over EDR. EDI was selected as no chemical consumption for final polishing compared to ion-exchange resin beds

A comparison of the total raw water inputs and volume of wastes generated for each raw water sources are presented in Table 7-11. These values assume total production of 1 ML of ASTM Type II water, 1 ML cooling water and 1ML boiler feed makeup water. Further detail and discussion are provided in the subsequent sections.

Table 7-11 Comparison of Raw Water Inputs and Waste Streams generated for various raw water sources

Water Source	Raw Water Input Required (ML)	Waste Streams Including Brine, Supernatant, Solid Waste (ML)
Surface Water	4.08	1.08
Ground Water	5.24	2.24
Recycled Water	7.55	4.55
Brackish Water	7.06	4.06
High Salinity Water	7.72	4.72

Detailed discussion on treatment for each of the raw water sources is detailed in the following sections

7.5.1 Surface Water Treatment

This process treats surface water and produces the following treated water streams: ASTM Type II demineralised water for electrolysers, boiler feed water and cooling water make-up. The process is outlined in the process flow diagram, in Appendix B: Process Flow Diagrams. In summary, the process is as follows: Flow from the surface water will first be screened with a coarse screen. Screened flow will then be dosed with lime (for softening), carbon dioxide (for pH adjustment) and sodium hypochlorite (to precipitate metals) inline and with ferric chloride (coagulant) and cationic polymer (flocculant) dosed directly into a rapid mixing tank. This flow then gravitates into the lamella clarifier for sediment clarification.

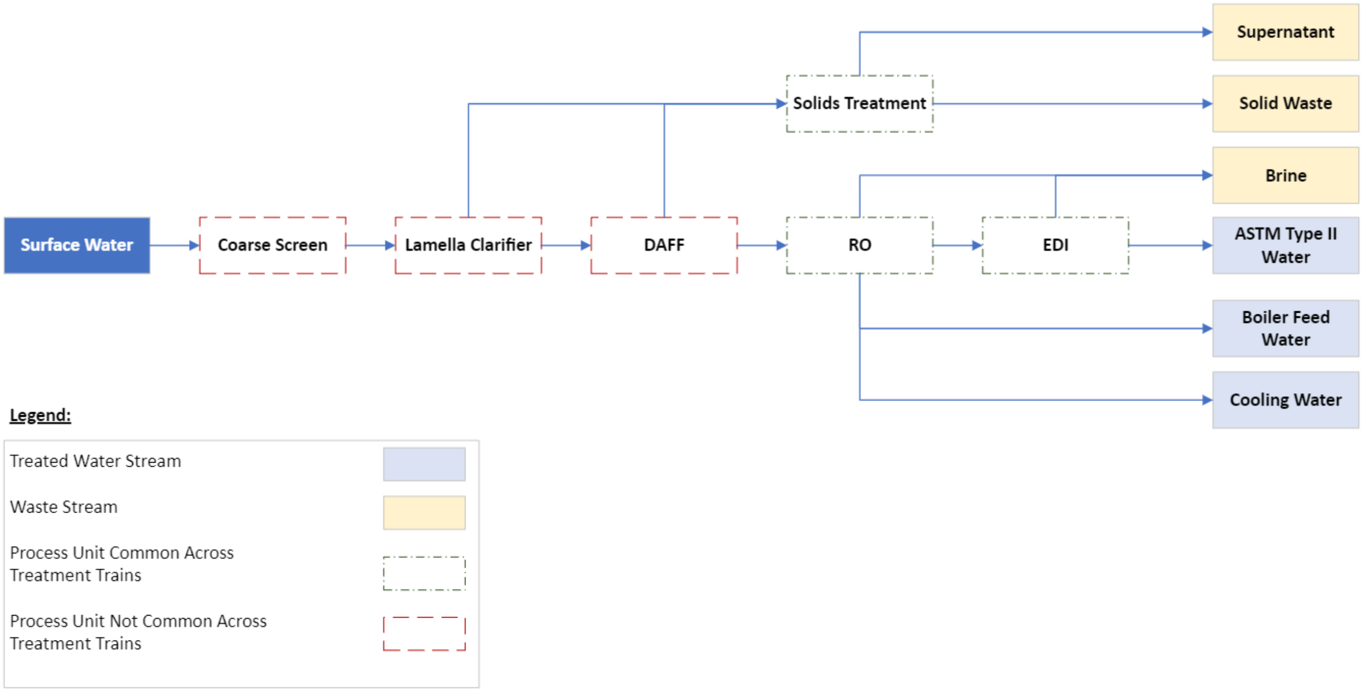
Clarified effluent will then gravitate to the DAFF, with additional ferric chloride (coagulant) dosing upstream of the DAFF. The DAFF filtered effluent is then able to either be pumped directly to the cooling water balance tank, or if further treatment is required can be pumped to the reverse osmosis system. If water quality after pre-treatment does not meet cooling water quality, the cooling water stream can be comprised of a shandy of both RO treated effluent and DAFF effluent, in a proportion that will meet the treated water requirements for cooling water. This proportion of the two flow streams is calculated by considering the quality of the DAFF effluent and RO effluent, determining a proportion of the two flows that will meet the cooling water quality requirement when mixed. This is intended to reduce the amount of water required for RO treatment, to reduce operating costs. This cooling water is stored in a tank for use. For the RO treated flow required for demineralised water, this flow is then fed to EDI for further polishing. EDI polished effluent is then stored in a storage tank for use as demineralised water.

There are several streams for waste removal and treatment including screenings, solid waste, and brine. Screenings from the coarse screen are directed to a waste bin for offsite disposal. Clarified sludge and the DAFF waste stream are both pumped to a waste balance tank for thickening. The thickened sludge is dewatered to ~20% dried solids and will be temporarily stored on-site in a customised waste bin(s) before the solids is transported for off-site disposal at a prescribed waste landfill facility or alternative disposal site. Dewatering centrate is returned to the feed buffer tanks at the head of plant.

The brine from both RO and EDI flows to the brine lagoon and is then pumped for brine disposal depending on site specific requirement. This brine is also used to back wash filter in the DAFF to minimise raw water usage. There is also an option for the DAFF backwash water to be drawn from downstream of the DAFF if the brine quality is not sufficient e.g., during commissioning. Any remaining brine can then be pumped for brine disposal or treatment.

Figure 7-4 below outlines a simplified flow diagram of this process, highlighting the process items that are common and different across the treatment of different water sources.

Figure 7-4: Surface Water Treatment Simplified Flow Diagram



7.5.1.1 *Water balance for surface water treatment*

Table 7-12 provides a summary of water balance for a surface water treatment plant in producing:

- 1ML/d of ASTM type II water as per Table 7-6.
- 1ML/d of cooling water with quality as per Table 7-8.
- 1ML/d of boiler feed water with quality as per Table 7-9.

Details on the mass flow balance and stream summary developed for a surface water treatment plant is detailed in Appendix C: Mass Balance Details. This includes rejection and recovery rates used in developing the treatment system.

Table 7-12 Surface Water Treatment Water Balance

Treated Water Output	Raw Water Input Required (ML/d)	Waste Streams Including Brine, Supernatant, Solid Waste (ML/d)
1 ML/d ASTM Type II Water	1.64	0.64
1 ML/d cooling water	1.2	0.2
1 ML/d boiler feed makeup water	1.5	0.5
1 ML/d ASTM Type II water, 1 ML/d cooling water, 1ML/d boiler feed makeup water	4.2	1.2

7.5.2 Groundwater Treatment

This process treats surface water and produces the following treated water streams: ASTM Type II demineralised water for electrolysers, boiler feed water and cooling water make-up. The process is outlined in the process flow diagram, in Appendix B: Process Flow Diagrams.

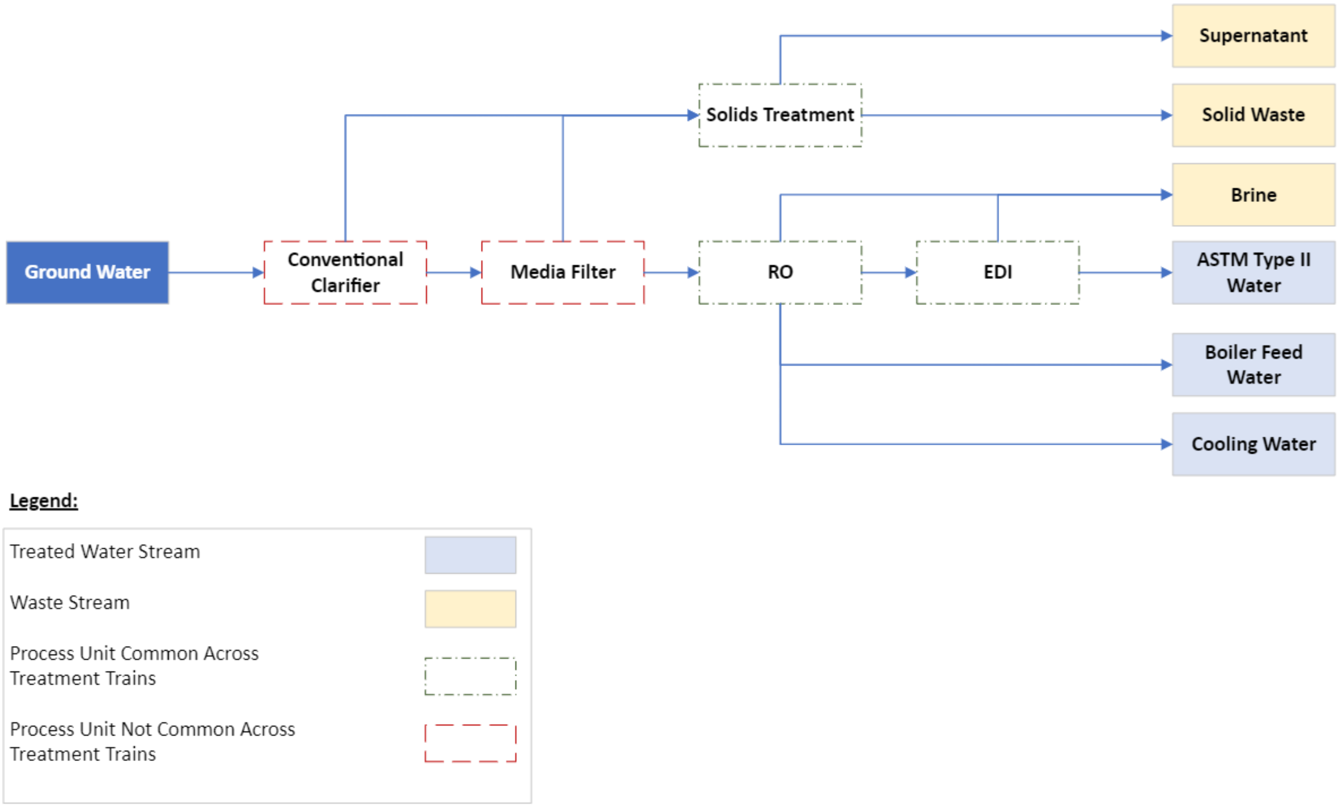
In summary, the process is as follows: Flow from the groundwater will not require screening. This flow will be dosed with lime (for softening), carbon dioxide (for pH adjustment) and sodium hypochlorite (to precipitate metals) inline and with ferric chloride (coagulant) and cationic polymer (flocculant) dosed directly into a rapid mixing tank. This flow then gravitates into the softening clarifier for sediment clarification and softening. Clarified effluent will then gravitate to the media filter, with additional ferric chloride (coagulant) dosing upstream of the filter. The filtered effluent is then able to either be pumped directly to the cooling water balance tank, or if further treatment is required can be pumped to the reverse osmosis system. The cooling water stream will be comprised of a shandy of both RO treated effluent and filter effluent, in a proportion that will meet the treated water requirements for cooling water. This is intended to reduce the amount of water required for RO treatment, to reduce operating costs. This cooling water is stored in a tank for use. For the RO treated flow required for demineralised water, this flow is fed to EDI for further polishing. EDI polished effluent is then stored in a storage tank for use as demineralised water.

There are several streams for waste removal and treatment including solid waste and brine. Clarified sludge and the filter waste stream are both pumped to a waste balance tank for thickening. The thickened sludge is dewatered to ~20% dried solids and will be temporarily stored on-site in a customised waste bin(s) before the solids is transported for off-site disposal at a prescribed waste landfill facility or alternative disposal site. Dewatering centrate is returned to the feed buffer tanks at the head of plant.

The brine from both RO and EDI flows to the brine tank and is then pumped for brine disposal depending on site specific requirement. This brine is also used as backwash water for media filter backwash. There is also an option for the filter backwash water to be drawn from downstream of the filter if the brine quality is not sufficient. Any remaining brine can then be pumped for brine disposal or treatment.

Figure 7-5 outlines a simplified flow diagram of this process, highlighting the process items that are common and different across the treatment of different water sources.

Figure 7-5: Groundwater Treatment Simplified Process Flow Diagram



7.5.2.1 *Water balance for groundwater treatment*

Table 7-13 provides a summary of water balance for a groundwater treatment plant in producing:

- 1ML/d of ASTM type II water as per Table 7-6.
- 1ML/d of cooling water with quality as per Table 7-8.
- 1ML/d of boiler feed water with quality as per Table 7-9.

Details on the mass flow balance and stream summary developed for ground water treatment plant is detailed in Appendix C: Mass Balance Details. This includes rejection and recovery rates used in developing the treatment system.

Table 7-13 Groundwater Treatment Water Balance

Treated Water Output	Raw Water Input Required (ML/d)	Waste Streams Including Brine, Supernatant, Solid Waste (ML/d)
1 ML/d ASTM Type II Water	1.9	0.9
1 ML/d cooling water	1.7	0.7
1 ML/d boiler feed makeup water	1.7	0.7
1 ML/d ASTM Type II water, 1 ML/d cooling water, 1ML/d boiler feed makeup water	5.4	2.4

7.5.3 Recycled Water Treatment

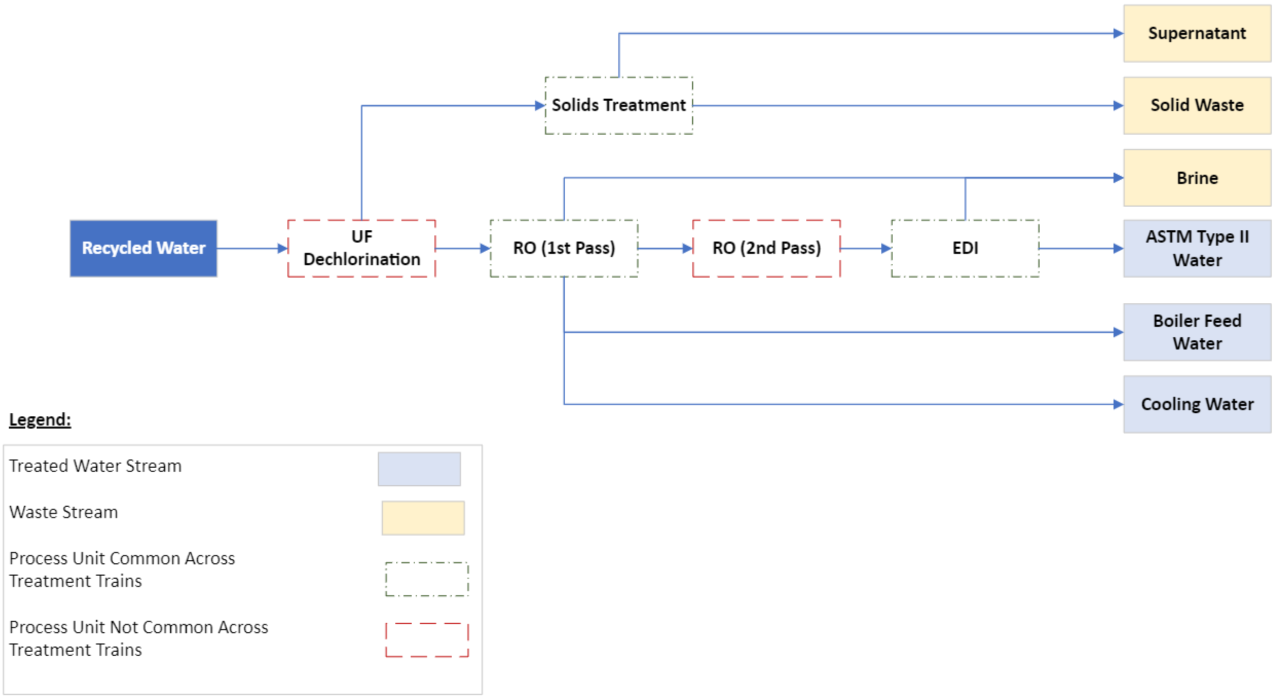
This process treats surface water and produces the following treated water streams: ASTM Type II demineralised water for electrolysers, boiler feed water and cooling water make-up. The process is outlined in the process flow diagram, in Appendix B: Process Flow Diagrams. Recycled water is dosed with sodium hypochlorite and/or aqueous ammonia to ensure any free chlorine or ammonia are converted to chloramine before passing through a fine strainer and collected in a feed buffer tank. Having chloramine (a weaker disinfectant to chlorine) in the feed water helps to reduce biofouling of the UF membranes. Flow from the buffer feed tank is then pumped to the UF units to remove finer suspended solids, bacteria, and some colour and organics. A small amount of coagulant may be dosed to enhance the filtration and colour removal process. Filtered recycled water will then be dosed with acid for pH correction before being stored in the RO feed tank. Prior to feeding the RO system, filtered recycled water will be dosed with sodium bisulphite to remove any chlorine (in the form of chloramine) as it would damage the membrane and followed by dosing of anti-scalant. The RO will require two passes. Cooling water and boiler feed water will be taken after the first pass of RO, while the remaining water will pass through the second pass. The flow from the second pass of the RO is then fed to EDI for further polishing. EDI polished effluent is then stored in a storage tank for use as demineralised water.

There are several streams for waste removal and treatment including solid waste and brine. Clarified sludge and the filter waste stream are both pumped to a waste balance tank for thickening. The thickened sludge is dewatered to ~20% dried solids and will be temporarily stored on-site in a customised waste bin(s) before the solids is transported for off-site disposal at a prescribed waste landfill facility or alternative disposal site. Dewatering centrate is returned to the feed buffer tanks at the head of plant.

The brine from both RO and EDI flows to the brine tank and is then pumped for brine disposal depending on site specific requirement. This brine is also used as backwash water for media filter backwash. There is also an option for the filter backwash water to be drawn from downstream of the filter if the brine quality is not sufficient. Any remaining brine can then be pumped for brine disposal or treatment.

Figure 7-6 outlines a simplified flow diagram of this process, highlighting the process items that are common and different across the treatment of different water sources.

Figure 7-6: Recycled Water Treatment Simplified Process Flow Diagram



7.5.3.1 Water balance for recycled water treatment

Table 7-14 provides a summary of water balance for a recycled water treatment plant in producing:

- 1ML/d of ASTM type II water as per Table 7-6.
- 1ML/d of cooling water with quality as per Table 7-8.
- 1ML/d of boiler feed water with quality as per Table 7-9.

Details on the mass flow balance and stream summary developed for a recycled water treatment plant is detailed in Appendix C: Mass Balance Details. This includes rejection and recovery rates used in developing the treatment system. Note that an ionic balance of the recycled water raw water source was undertaken for the purpose of mass flow balancing and RO projection.

Table 7-14 Recycled Water Treatment Water Balance

Treated Water Output (Class A water)	Raw Water Input Required (ML/d)	Waste Streams Including Brine, Supernatant, Solid Waste (ML/d)
1 ML/d ASTM Type II Water	2.8	1.8
1 ML/d cooling water	2.4	1.4
1 ML/d boiler feed makeup water	2.4	1.4
1 ML/d ASTM Type II water, 1 ML/d cooling water, 1ML/d boiler feed makeup water	7.5	4.5
Treated Water Output (Class A water+RO)	**Raw Water Input Required (ML/d)**	**Waste Streams Including Brine, Supernatant, Solid Waste (ML/d)**
1 ML/d ASTM Type II Water	1.1	.1
1 ML/d cooling water	1	0
1 ML/d boiler feed makeup water	1	0
1 ML/d ASTM Type II water, 1 ML/d cooling water, 1ML/d boiler feed makeup water	3.2	0.2

7.5.4 Brackish Water Treatment

This process treats surface water and produces the following treated water streams: ASTM Type II demineralised water for electrolysers, boiler feed water and cooling water make-up. The process is outlined in the process flow diagram in Appendix B: Process Flow Diagrams.

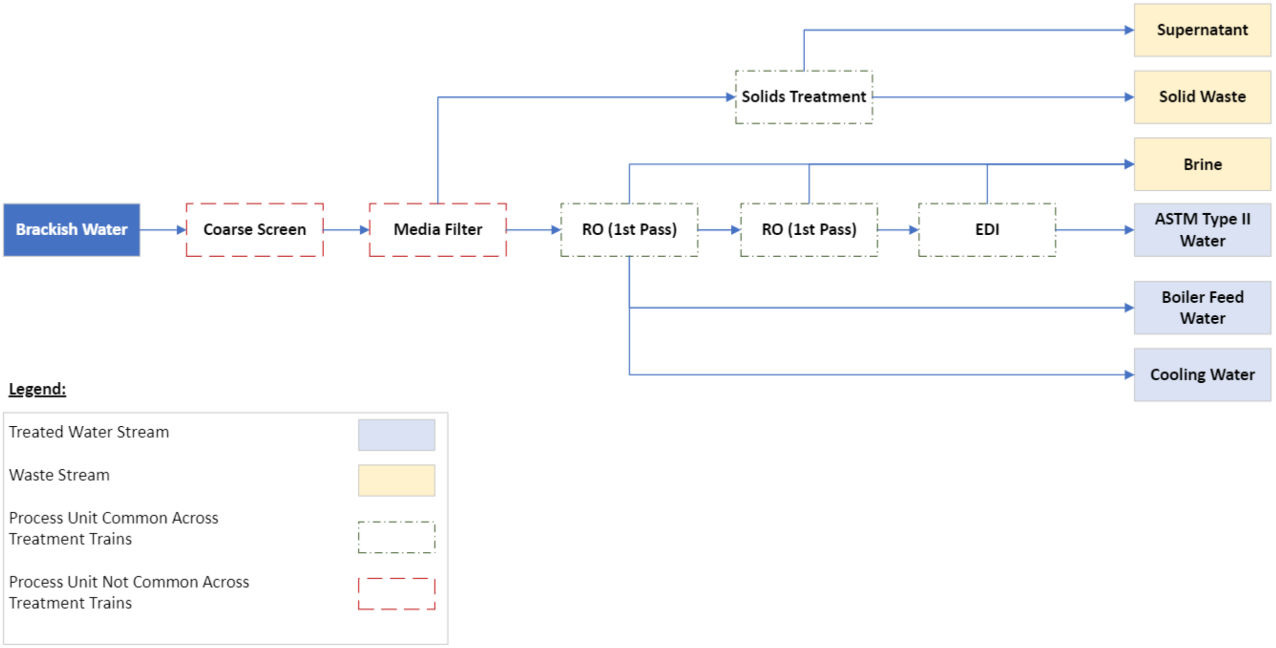
In summary, the process is as follows: Flow is first passed through a coarse screen. This flow will be dosed with sulfuric acid (for pH adjustment) and a coagulant. The flow then gravitates into the media filter for filtration. The filtered effluent is then dosed with anti-scalant and pumped through a cartridge filter before entering the RO system. For brackish water, the RO system will require two passes. Cooling and boiler feed water will be taken after the first pass of RO, while the remaining water will pass through the second pass. The flow from the second pass of the RO is then fed to EDI for further polishing. EDI polished effluent is then stored in a storage tank for use as demineralised water.

There are several streams for waste removal and treatment including screenings, solid waste, and brine. Screenings from the coarse screen are directed to a waste bin for offsite disposal. The dirty backwash water from the media filter is pumped to a waste balance tank for thickening. The thickened sludge is dewatered to ~20% dried solids and will be temporarily stored on-site in a customised waste bin(s) before the solids is transported for off-site disposal at a prescribed waste landfill facility or alternative disposal site. Dewatering centrate is returned to the feed buffer tanks at the head of plant.

The brine from both RO and EDI flows to the brine tank and is then pumped for brine disposal depending on site specific requirement. This brine is also used as backwash water for media filter backwash. There is also an option for the filter backwash water to be drawn from downstream of the filter if the brine quality is not sufficient. Any remaining brine can then be pumped for brine disposal or treatment.

Figure 7-7 below outlines a simplified flow diagram of this process, highlighting the process items that are common and different across the treatment of different water sources.

Figure 7-7: Brackish Water Treatment Simplified Process Flow Diagram



7.5.4.1 *Water balance for brackish water treatment*

Table 7-15 provides a summary of water balance for a brackish water treatment plant in producing:

- 1ML/d of ASTM type II water as per Table 7-6.
- 1ML/d of cooling water with quality as per Table 7-8.
- 1ML/d of boiler feed water with quality as per Table 7-9.

Details on the mass flow balance and stream summary developed for brackish water treatment plant is detailed in Appendix C: Mass Balance Details. This includes rejection and recovery rates used in developing the treatment system. Note that an ionic balance of the brackish raw water source was undertaken for the purpose of mass flow balancing and RO projection.

Table 7-15 Brackish water treatment balance

Treated Water Output	Raw Water Input Required (ML/d)	Waste Streams Including Brine, Supernatant, Solid Waste (ML/d)
1 ML/d ASTM Type II Water	2.6	1.6
1 ML/d cooling water	2.2	1.2
1 ML/d boiler feed makeup water	2.2	1.2
1 ML/d ASTM Type II water, 1 ML/d cooling water, 1ML/d boiler feed makeup water	7.1	4.1

7.5.5 High Salinity and Seawater Treatment

This process treats surface water and produces the following treated water streams: ASTM Type II demineralised water for electrolysers, boiler feed water and cooling water make-up. The process is outlined in the process flow diagram in Appendix B: Process Flow Diagrams. The process treatment train is identical to brackish water with the exception cooling and boiler feed water will be taken after the second pass RO. The mass flow balance and stream summary developed for highly saline and seawater is detailed in Appendix C: Mass Balance Details. This includes rejection and recovery rates used in developing the treatment system.

Figure 7-8 below outlines a simplified flow diagram of this process, highlighting the process items that are common and different across the treatment of different water sources.

Figure 7-8: High Salinity and Seawater Simplified Process Flow Diagram

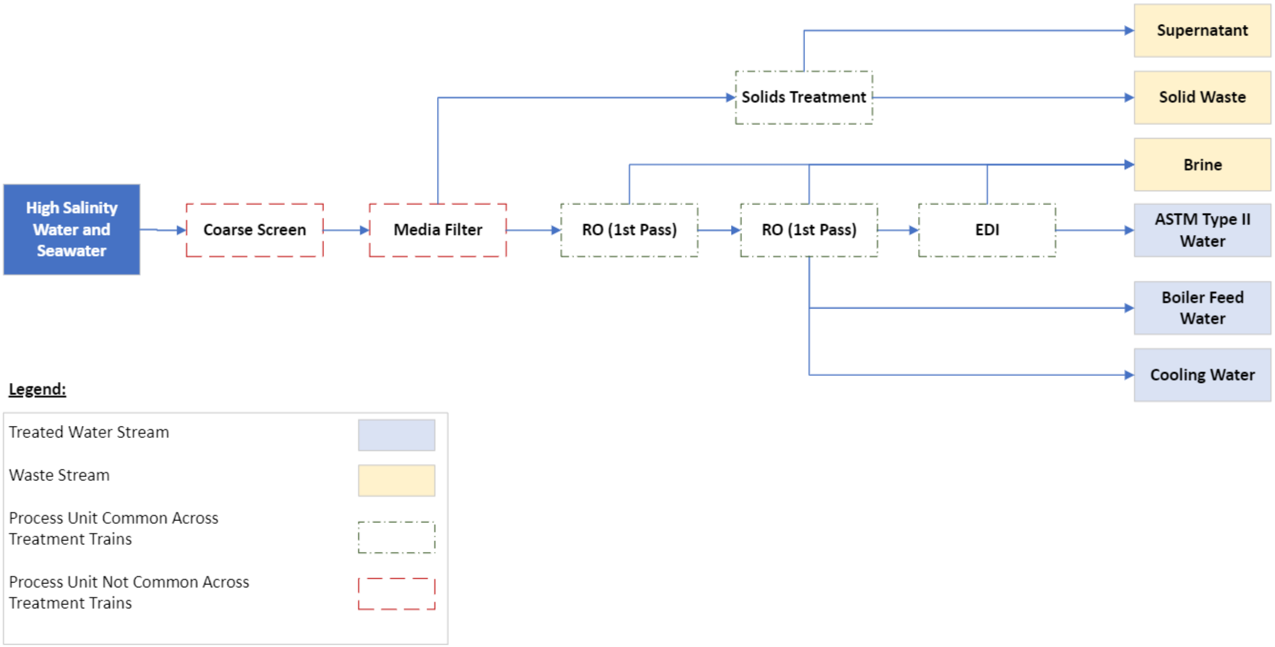


Table 7-16 provides a summary of water balance for a ground water treatment plant in producing:

- 1ML/d of ASTM type II water as per Table 7-6.
- 1ML/d of cooling water with quality as per Table 7-8.
- 1ML/d of boiler feed water with quality as per Table 7-9.

Details on the mass flow balance and stream summary developed for highly saline water treatment plant is detailed in Appendix C: Mass Balance Details. This includes rejection and recovery rates used in developing the treatment system. Note that an ionic balance of the highly saline raw water source was undertaken for the purpose of mass flow balancing and RO projection.

Table 7-16 Highly Saline Water Treatment Water Balance

Treated Water Output	Raw Water Input Required (ML/d)	Waste Streams Including Brine, Supernatant, Solid Waste (ML/d)
1 ML/d ASTM Type II Water	2.8	1.8
1 ML/d cooling water	2.5	1.5
1 ML/d boiler feed makeup water	2.5	1.5
1 ML/d ASTM Type II water, 1 ML/d cooling water, 1ML/d boiler feed makeup water	7.7	4.7

7.5.5.1 Water recovery for various water sources

Table 7-17 provides a summary of water recovery in using various water sources to produce treated water required for hydrogen production. It is shown that advanced recycled water has the highest recovery followed by surface water, ground water, brackish water and recycled water with seawater the lowest.

Table 7-17 Recovery from various water sources

Treated Water	Surface water ML	Ground water ML	Recycled water (Class A) ML	Advanced recycled water Class A +RO ML	Brackish water ML	Seawater ML
1 ML ASTM Type II Water	1.64	1.9	2.8	1.1	2.6	2.8
1 ML/d cooling water	1.2	1.7	2.4	1	2.2	2.5
1 ML/d boiler feed makeup water	1.5	1.7	2.4	1	2.2	2.5
1 ML/d ASTM Type II water, 1 ML/d cooling water, 1ML/d boiler feed makeup water	4.1	5.3	7.6	3.3	7.0	7.8

7.6 Energy consumption ranges

7.6.1 Context

The production of hydrogen requires several water streams, in particularly for cooling and as electrolyser feed water. The typically available raw water sources are not suitable for direct use and require some form of treatment. The primary driver for selection of treatment process is ability to remove the contaminants within the raw water source. This selection is discussed further in Section 7.5. However, given the green credentials associated with hydrogen production it is also important to consider the energy consumption associated with each treatment option.

Energy is consumed in the treatment process in several ways. The largest demand is typically the pumps required to move water through the treatment process. For simple conventional processes the energy demand is low as the operating pressures are also typically low. In contrast, seawater reverse osmosis systems require very high pressures to overcome the osmotic pressure of the saline water and thus have higher energy demands. Thermal desalination processes (eg. MED, MVC and TVC) also require significant inputs of energy in the form of electricity, steam or waste heat. Electricity is again used for pumping, but condensers and compressors also form significant demands while steam or waste heat is used as the heat source to facilitate evaporation.

7.6.2 Basis

Energy consumption is provided for treatment of four potential water sources: surface water (clean and brackish), groundwater, and seawater. The treatment technologies included for each water source are based on the most common options for removing the typical contaminants from the raw water source and achieving the required water quality. Further detail on the process selection is provided within Section 7.5.

The treatment processes and energy consumption are further separated into two categories – those required to produce water suitable for use in cooling system, and the additional treatment and energy required to produce high purity electrolyser feed water.

The figures presented in Table 7-17 have been derived from a combination of previous Arup design work, supplier estimates, and literature values.

7.6.3 Energy Consumption

Table 7-18 shows that there is a significant range in energy consumption for each treatment process. The actual energy consumption for a treatment plant can be influenced by:

- Plant design: in particular as a result of key process design decisions such as the use of pressurised or gravity filters, pump selection and piping design
- Site selection: including proximity to the hydrogen production, aquifer depths, and any elevation differences across the site which must be overcome
- Raw water quality: for the groundwater and clean surface water this is primarily driven by the concentrations of iron, manganese and other solids while for seawater and brackish surface water the primary drivers are salinity and temperature.
- Steam quality: the available flow, temperature and pressure of the steam are influential in determining the amount of additional electrical energy required for thermal processes.

Table 7-18 also highlights that for a given water source there is a wide variation in energy consumption between the treatment process options. This is of particular relevance for the seawater and brackish surface water where proponents may have a fundamental choice between reverse osmosis and the thermal desalination processes. The lower energy consumption for reverse osmosis is a driving factor behind its dominance in the global desalination industry. Thermal desalination is typically only used in the Middle East where the electricity prices are lower and thermal desalination projects can be combined with low-cost sources of steam such as power plants.

Finally, it can be seen that energy required to treat groundwater or “clean” surface water is substantially lower than the energy required to treat seawater or brackish surface water. While this may imply these are preferred raw water sources, proponents must consider the sustainability related issues of clean surface and groundwater extraction compared to the relatively abundant seawater. These issues are further discussed in Section 7.9.

Table 7-18 Energy consumption for various water treatment processes

	Cooling Water			**Electrolyser Feed**	
	Treatment Process	Electrical (kWh/m3)	Thermal (MJ/m3)	Treatment Process	Electrical (kWh/m3)
Seawater	RO (Seawater)	3 - 6		EDI	0.4 - 0.7
	MED	1.5 - 2.5	145 - 390	EDI	0.4 - 0.7
	MVC	6 - 17		EDI	0.4 - 0.7
	TVC	1.5 - 2.5	145 - 390	EDI	0.4 - 0.7
	MSF	3 - 6	190 - 390	EDI	0.4 - 0.7
Groundwater	Oxidation / Softening / Filtration	0.1 - 0.25		RO + EDI	1 - 2
Surface - Brackish / Turbid	RO (Brackish)	1.5 - 2.5		EDI	0.4 - 0.7
	MED	1.5 - 2.5	145 - 390	EDI	0.4 - 0.7
	MVC	6 - 17		EDI	0.4 - 0.7
	TVC	1.5 - 2.5	145 - 390	EDI	0.4 - 0.7
	MSF	3 - 6	190 - 390	EDI	0.4 - 0.7
Surface - Clean	Clarifier / DAFF	0.1 - 0.25		RO + EDI	1 - 2

Note: the energy consumption for electrolyser feed water is in addition to the energy required to produce cooling water.

7.7 Water Usage in Hydrogen Production and Carrier Conversion

Treated water consumed in hydrogen production and carrier conversion were calculated in Section 3 to 6 of the report. Mass and flow balances were carried out to determine the quantity of raw water required to produce treated water that consumed by the hydrogen production and carrier conversion processes. The results of the mass and flow balances for various raw water sources are outlined in Table 7-19 to Table 7-22.

Table 7-19: Raw Water Demand per kg Green Hydrogen

Water application	PEM electrolyser operating conditions			Treated water consumed @ point of use		Raw water requirement from source (L/kg of H_2)				
	Asset condition	Asset performance	Climate zone	(L/kg of H_2)	Ref. in report	Surface water	Ground water	Recycled water	Brackish water	Seawater
Process water	Beginning of Life	High end	Dry zone	9.1	Table 3-4	15.0	17.4	25.1	23.8	25.1
	Beginning of Life	Low end	Dry zone	9.2	Table 3-4	15.1	17.6	25.3	24.1	25.4
	End of Life	Low end	Dry zone	9.3	Table 3-5	15.3	17.8	25.6	24.4	25.6
	Beginning of Life	High end	Wet zone	9.1	Table 3-8	15.0	17.4	25.1	23.8	25.1
Evaporative cooling water	Beginning of Life	High end	Dry zone	23.0	Table 3-4	27.1	39.6	53.8	51.1	57.0
	Beginning of Life	Low end	Dry zone	43.0	Table 3-4	50.7	74	100.6	95.6	106.7
	End of Life	Low end	Dry zone	61.2	Table 3-5	72.2	105.3	143.2	136	151.9
	Beginning of Life	High end	Wet zone	14.0	Table 3-8	16.5	24.1	33.9	31.1	34.7
Total water requirement with evaporative cooling system	Beginning of Life	High end	Dry zone	32.1		42.1	57	78.9	74.9	82.1
	Beginning of Life	Low end	Dry zone	52.2		65.8	91.6	125.9	119.7	132.1
	End of Life	Low end	Dry zone	70.5		87.5	123.1	168.8	160.4	177.5
	Beginning of Life	High end	Wet zone	23.1		31.5	41.5	59	54.9	59.8
Total water requirement with air cooling system	Beginning of Life	High end	Dry zone	9.1		15.0	17.4	25.1	23.8	25.1
	Beginning of Life	Low end	Dry zone	9.2		15.1	17.6	25.3	24.1	25.4
	End of Life	Low end	Dry zone	9.3		15.3	17.8	25.6	24.4	25.6
	Beginning of Life	High end	Wet zone	9.1		15.0	17.4	25.1	23.8	25.1

Table 7-20: Raw Water Demand per kg Blue Hydrogen

Water application	**Site operating conditions**	**Treated water consumed @ point of use**		**Raw water requirement from source (L/kg of H_2)**				
	Site climate zone	**(L/kg of H_2)**	**Ref. in report**	**Surface water**	**Ground water**	**Recycled water**	**Brackish water**	**Seawater**
SMR - Process water	Dry zone	5.2	Table 4-4	8.6	9.9	14.3	13.6	14.3
	Wet zone	5.2	Table 4-4	8.6	9.9	14.3	13.6	14.3
SMR - Evaporative cooling tower - Makeup water	Dry zone	19.0	Table 4-4	22.4	32.7	44.4	42.2	47.1
	Wet zone	15.0	Table 4-4	17.7	25.8	35.1	33.3	37.2
Total water requirement with evaporative cooling system	Dry zone	24.0		31	42.6	58.7	55.8	61.4
	Wet zone	20		26.3	35.7	49.4	46.9	51.5
Total water requirement with air cooling system	Dry zone	5.2		8.6	9.9	14.3	13.6	14.3
	Wet zone	5.2		8.6	9.9	14.3	13.6	14.3

For green hydrogen production, the study assessed variables that affect system efficiency, as this impacts the water requirements. The variables assessed included different electrolyser types (PEM versus Alkaline), electrolyser design (Low end vs High end), climatic conditions (Dry zone versus Wet zone), age of equipment (Beginning of life versus End of life) and operating profile (Variable versus Constant).

For blue hydrogen, this study indicated that there was less variability in water requirements, with 5.2 litres of treated process water per kilogram of hydrogen and a range of 13-19 litres of treated water per kilogram of hydrogen if evaporative cooling is used, depending on the climatic zone (wet zone versus dry zone).

While the hydrogen liquefaction process does not consume any process water, it does require considerable cooling. There is variability in cooling load depending on the efficiency of the design.

Table 7-21: Raw Water Demand Per Kg of Hydrogen Liquefaction

Water application	**System Efficiency**	**Treated water consumed @ point of use**		**Raw water requirement from source (L/kg of H_2)**				
		(L/kg of H_2)	**Ref. in report**	**Surface water**	**Ground water**	**Recycled water**	**Brackish water**	**Seawater**
Hydrogen liquefaction – Process water	Not applicable as no process water involved							
Hydrogen liquefaction - Evaporative cooling tower - Makeup water = Total water requirement	Low	31	Table 5-4	36.6	53.3	72.5	68.9	76.9
	High	25	Table 5-4	29.5	43.0	58.5	55.6	62.0
	Future target	13	Table 5-4	15.3	22.4	30.4	28.9	32.3
Hydrogen liquefaction with air cooling system – Total water requirement				0	0	0	0	0

Table 7-22 Raw Water Demand Per Kg of Hydrogen for Conversion to Ammonia

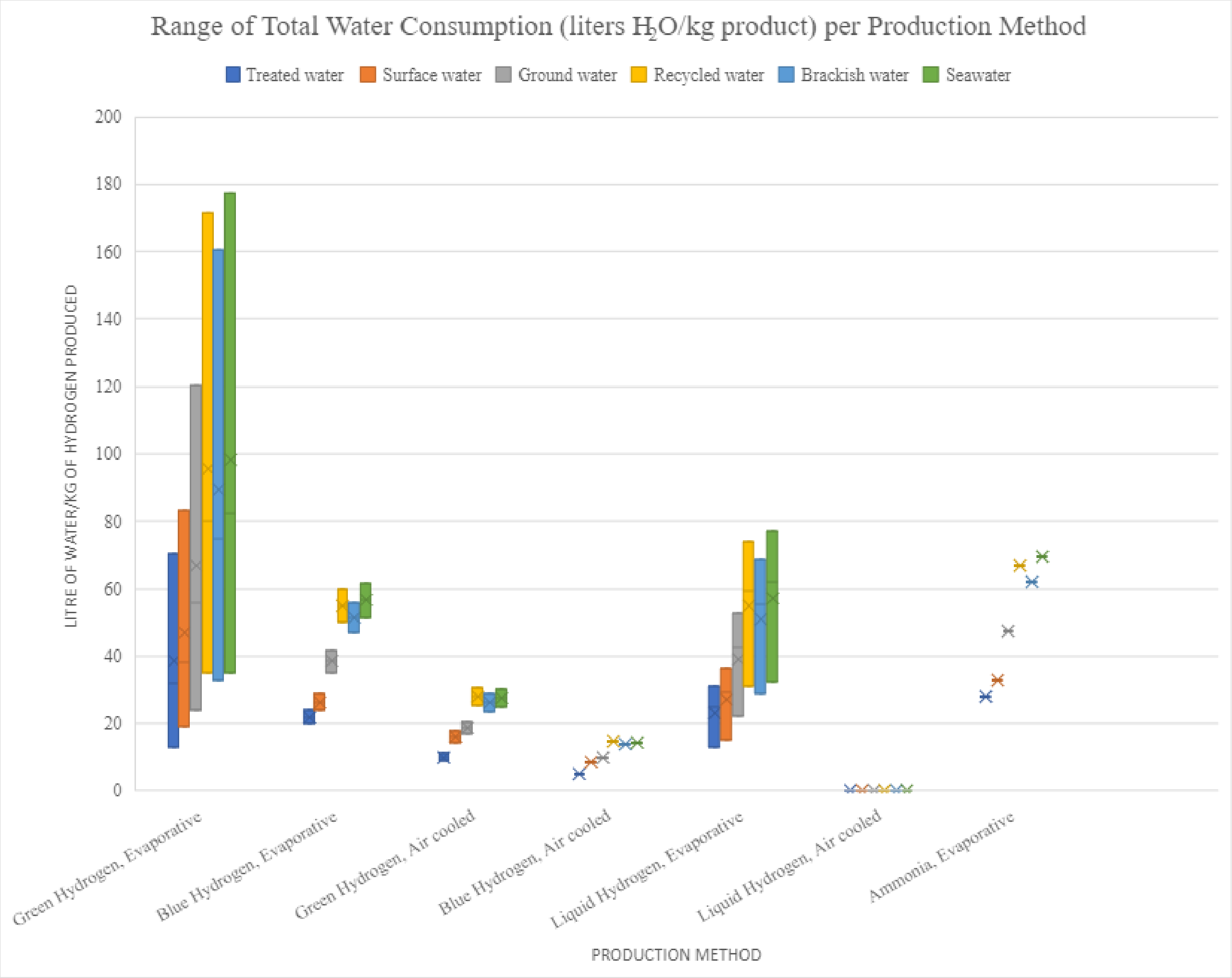
Water application	**Treated water req'd @ point of use**		**Raw water requirement from source (L/kg of H_2)**				
	(L/kg of H_2)	**Ref. in report**	**Surface water**	**Ground water**	**Recycled water**	**Brackish water**	**Seawater**
Ammonia conversion – process water	Not applicable as no process water involved						
Conversion to liquid ammonia via Haber Bosch process - Evaporative cooling tower - Makeup water	28.0	Table 6-3	33.0	48.2	65.5	62.2	69.5

7.8 Water Usage Summary

Following this, the total water usage for various types of hydrogen production and carrier conversion processes based on each raw water source, were calculated and the results are presented in Figure 7-9. The graphs in the figure also provide ranges of water usage for each hydrogen production process over different operating and climate zone conditions.

To determine the total water requirement for a complete hydrogen production chain of a particular raw water source, water requirement from hydrogen production must be added with the water requirement from carrier conversion process. This is illustrated in Table 7-23 to Table 7-25.

Figure 7-9: Range of total water consumption for production method assessed.



Note:

- Figure 7-9 summarises water consumption used in hydrogen production and carrier conversion processes for the source water categories assessed
- Water consumption volumes provided in the graph cover various climate zones, electrolyser design efficiency and electrolyser operating condition for each production method.
- For the total water consumption of a hydrogen carrier supply chain (liquified hydrogen or ammonia), the water consumed for hydrogen production needs to be added to the water consumed for hydrogen carrier conversion.
- Water returned to a source system such as in once through water cooling is not included in the Figure 7-9 water consumption graph. Water requirement including for once through cooling is provided in the water requirement calculation tables for each value chain in this report.

Table 7-23: Total water requirements in L per kg/H_2 produced - BOL, high efficiency & dry zone evaporation

Water application	Raw water requirement from source (L/kg of H_2)				
	Surface water	Ground water	Recycled water	Brackish water	Seawater
Green H_2	42.1	57	78.9	74.9	82.1
Green H_2 -LH_2-evap	71.6	100	137.4	130.5	144.1
Green H_2 -ammonia- evap	75.1	105.2	144.4	137.1	151.6
Blue H_2	31	42.6	58.7	55.8	61.4
Blue H_2 - LH_2- evap	60.5	85.6	117.2	111.4	123.4
Blue H_2- ammonia - evap	64	90.8	124.2	118	130.9

Table 7-24: Total water requirements in L per kg/H_2 produced - BOL, high efficiency & wet zone evaporation

Water application	Raw water requirement from source (L/kg of H_2)				
	Surface water	Ground water	Recycled water	Brackish water	Seawater
Green H_2	31.5	41.5	59	54.9	59.8
Green H_2 -LH_2-evap	61	84.5	117.5	110.5	121.8
Green H_2 -ammonia- evap	64.5	89.7	124.5	117.1	129.3
Blue H_2	26.3	35.7	49.4	46.9	51.5
Blue H_2 - LH_2- evap	55.8	78.7	107.9	102.5	113.5
Blue H_2- ammonia - evap	59.3	83.9	114.9	109.1	121

Table 7-25: Total water requirements in L per kg/H_2 produced - BOL, high efficiency & dry zone air cooled

Water application	Raw water requirement from source (L/kg of H_2)				
	Surface water	Ground water	Recycled water	Brackish water	Seawater
Green H_2	15.0	17.4	25.1	23.8	25.1
Green H_2 -LH_2-evap	15.0	17.4	25.1	23.8	25.1
Green H_2 -ammonia- evap	15.0	17.4	25.1	23.8	25.1
Blue H_2	8.6	9.9	14.3	13.6	14.3
Blue H_2 - LH_2- evap	8.6	9.9	14.3	13.6	14.3
Blue H_2- ammonia - evap	8.6	9.9	14.3	13.6	14.3

Figure 7-10 to Figure 7-12 present the total water requirement for various hydrogen production scenarios, including Green H_2, Blue H_2, liquefaction and ammonia conversion. The cooling requirements can vary based on the type of cooling (evaporative or air cooling) and the climate zone (dry or wet).

Figure 7-10: Total water requirement for hydrogen production (Dry Zone)

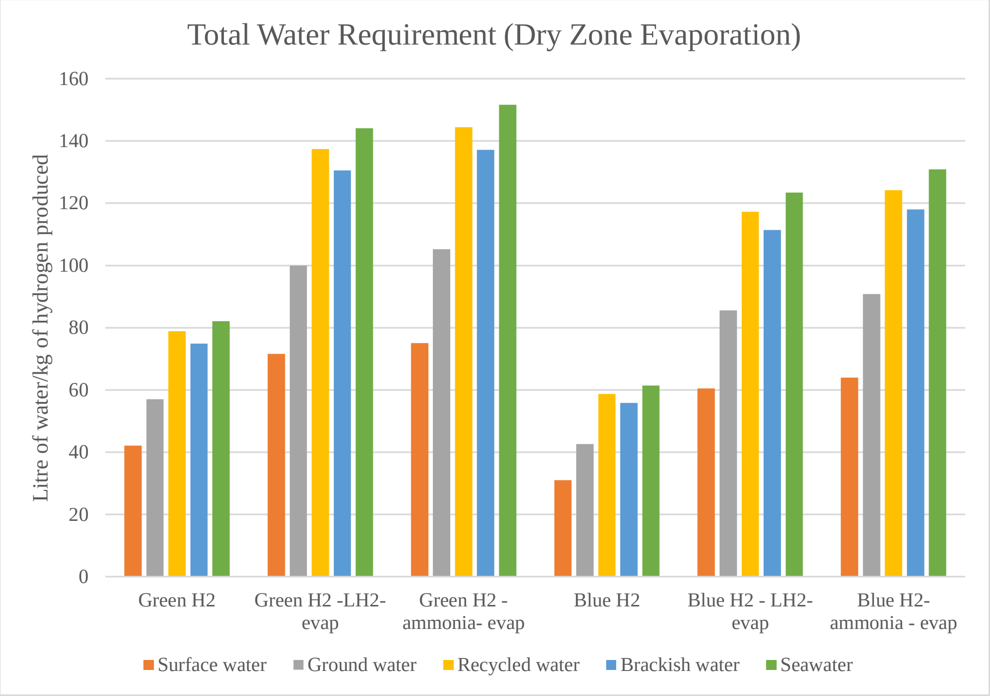


Figure 7-11: Total water requirement for hydrogen production (wet zone)

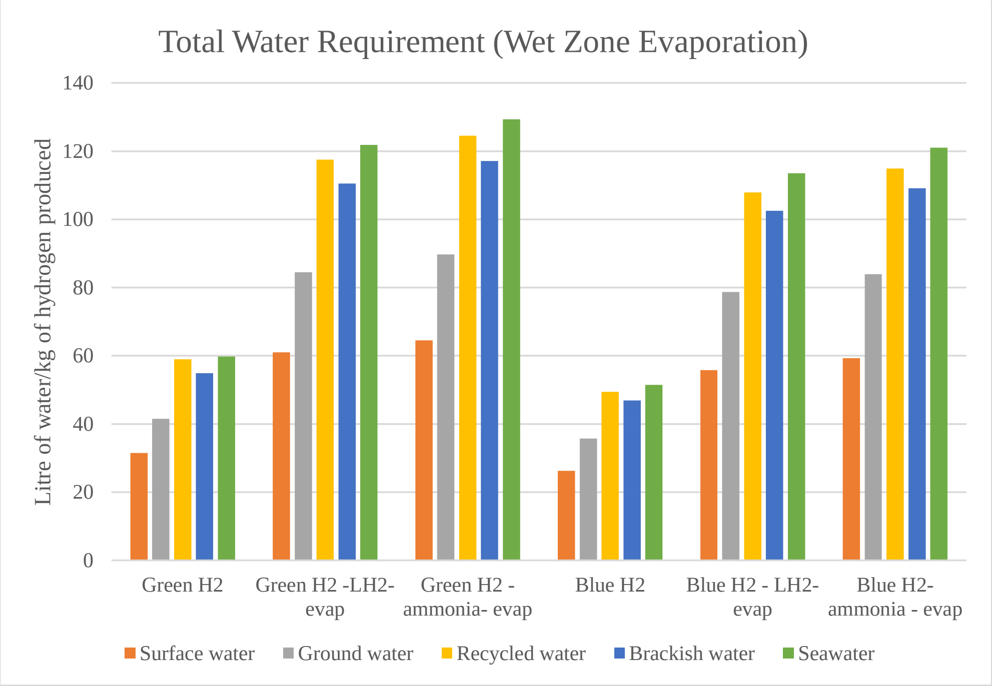
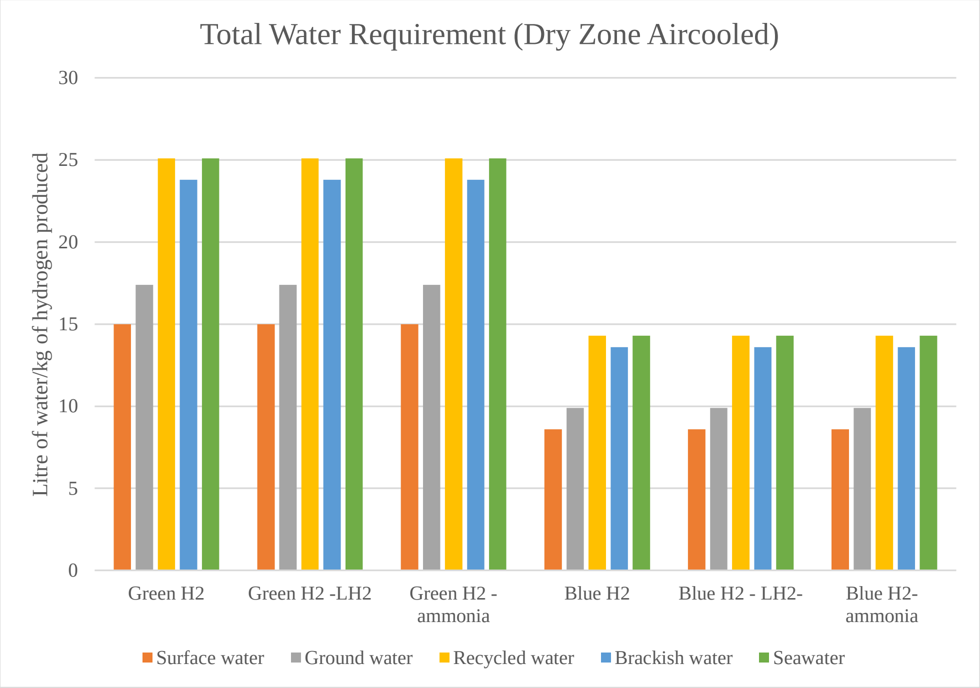


Figure 7-12: Total water requirement for hydrogen production (air cooled)



How much water is consumed and what can be recycled or reused needs to be considered during assessment of water requirement and its source. This will determine the net amount of water requires from the source, and how much can be safely returned to help the environment if reuse is not required.

Figure 7-13 to Figure 7-15 provide a breakdown of water requirements for green hydrogen production only (without liquefaction or conversion to ammonia) using evaporative and air-cooling systems under wet and dry climate zones. Below is the summary of the assessment:

- Air-cooling system has lower water usage than evaporative cooling system, however advantages and disadvantages of various cooling technologies should be considered in the overall assessment,
- Cooling water makeup contribute a large portion on water usage, and site within wet climate zone tends to have lesser water usage than dry zone,
- To produce 1kg of H2, the order from lowest to highest on volume of water used is:
    - Surface water
    - Ground water
    - Brackish water
    - Recycled water
    - Seawater
- From a sustainable, social licencing, community acceptance and environmental benefit perspective, recycled water seems to be the most suitable raw water source to be used in hydrogen value chain where possible,
- Seawater has the highest water usage with the least recyclable water as the waste streams from the treatment processes are to saline for reuse. This is similar to brackish water.

Figure 7-13: Total Water Requirement Breakdown (Dry Zone)

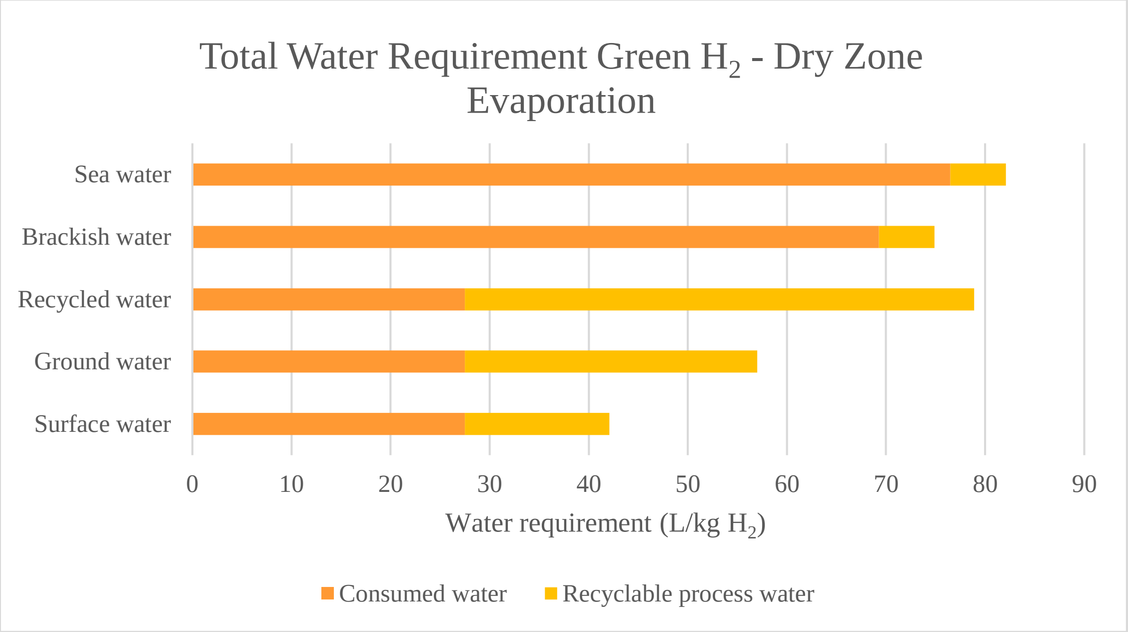


Figure 7-14: Total Water Requirement Breakdown (Wet Zone)

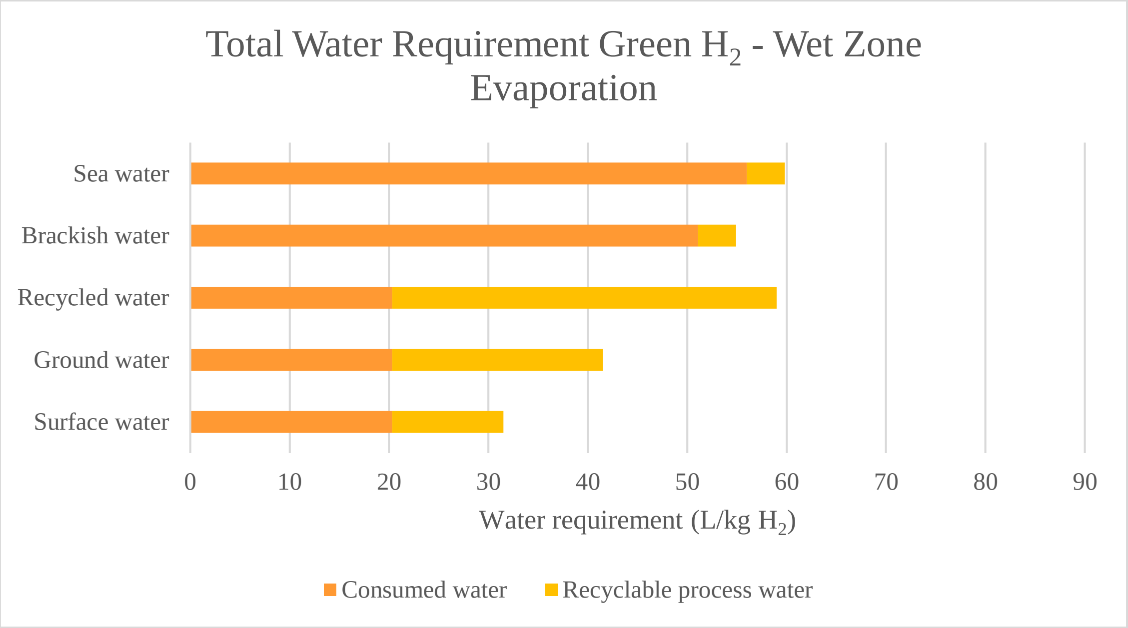
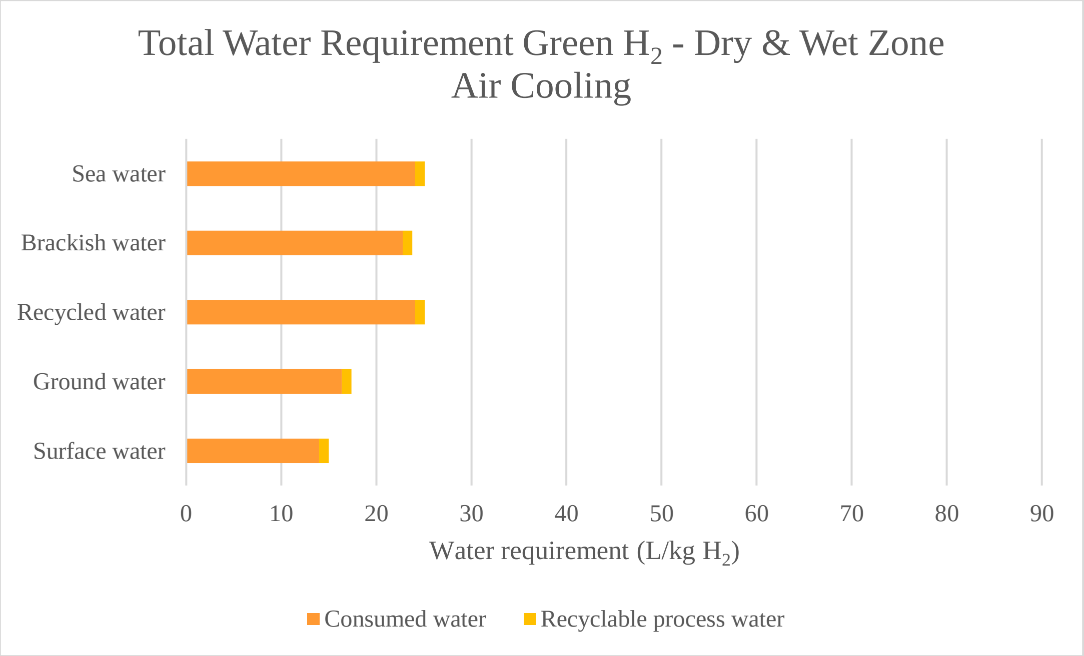


Figure 7-15: Total Water Requirement Breakdown (Air Cooled)



7.9 Environmental considerations and waste management

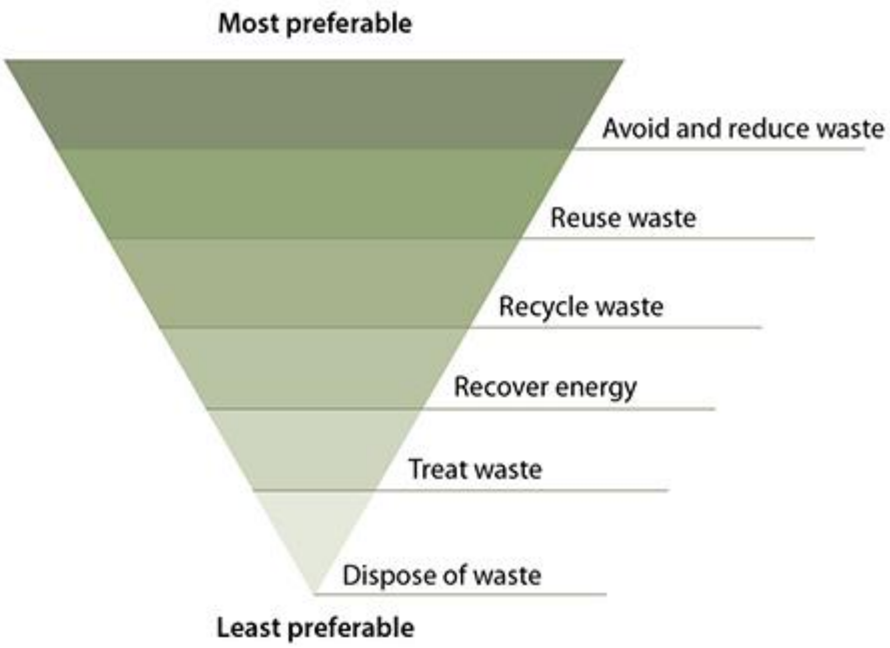
The environmental considerations relating to water use during the production of hydrogen are varying and complex and span areas such as water source selection, water treatment selection, construction impacts, operational impacts, waste management and environmental discharge. The scope of this work is focused on the environmental impacts related to waste management and environmental discharge.

This section outlines matters to consider in the siting and design of such developments to avoid, minimise or otherwise manage potential impacts from solid and liquid wastes to the environment. This will focus solely on the management and disposal of the various liquid and solid waste streams during the operational phase, including brine and solid wastes (such as filter waste and screenings).

7.9.1 Waste hierarchy

In Australia, current best practice around efficient use of resources looks to the waste hierarchy to guide decisions around waste management (see Figure 7-16). The waste hierarchy is a set of priorities for the management of waste, where avoiding and reducing waste is the most preferable outcome and disposal of waste is the least preferable outcome. Resource recovery, including re-use, recycling, reprocessing, and energy recovery sit in between. The objectives of the waste hierarchy are to reduce the use of raw resources, minimise the volume of waste going to landfill and generally support a more circular economy.

Figure 7-16: Waste hierarchy (National Waste Policy 2018)



In the context of water use on hydrogen projects, it is envisaged that the waste hierarchy will be used as a lens with which to consider the feasibility of various treatment options and/or raw water sources. For example, can utilising a different raw water source reduce the volume of waste needed to be managed? Can solid wastes be reused or recycled to divert them from landfill?

Consideration of waste streams at the project feasibility stage will have the biggest impact on reducing project waste and will need to consider the available water sources, local waste regulations, local treatment and/or disposal options and the sensitivity of the receiving environment. Ultimately, decisions on the nature and fate of waste products will not be made based on environmental impacts in isolation and will include consideration of cost, available technology and workforce, safety, reputation and legislative requirements.

7.9.2 Waste management considerations

The impacts of waste originating on site during operation need to be considered across various stages, all of which have the potential to interact with the local and regional environment in different ways:

- Onsite waste storage
- Transport
- Offsite treatment
- Offsite disposal
- Discharge to the environment.

When considering the potential environmental impacts at each of these stages it is important to note that the overall aim is to avoid impacts where possible. Where this is not possible, we would look to then minimise and finally manage these to the lowest extent practicable. The following sections outline matters to consider at each stage in order to avoid, minimise and manage the potential impacts to the environment on a site-by-site basis.

Onsite waste storage - leaks and spills

Where wastes are to be reused, recycled, treated or disposed of off-site they will need to be stored, at least temporarily, on site. The storage of waste materials on site, along with the loading of materials for delivery, presents the risk of leaks or spills to the local environment.

Management of the temporary onsite storage of waste includes avoiding, where possible, the number and type of wastes stored on site, avoiding siting the facility within a particularly sensitive receiving environment, minimising the volume and time wastes are stored on site, best practice design of storage and transfer facilities and employing appropriate segregation as well as spill and containment practices.

Offsite reuse, recycle, treatment or disposal

Where it has been determined that waste streams cannot be discharged to the environment without causing unreasonable harm to the receiving environment then such waste streams will need to be removed from site and either reused, recycled, treated or disposed of to a licenced landfill. The decision on the fate of the waste will need to consider the nature of the waste, the waste hierarchy, the availability and proximity of local receiving facilities as well as indirect impact such as greenhouse gas emissions (including the energy intensity of incinerating waste).

Environmental considerations that would influence decisions around waste management options would include assessing the potential to reduce the volume of waste needed to be managed, the potential for reuse, recycling and energy recovery and triggers around disposal to landfill versus onsite treatment. It will also be important to understand the indirect environmental impacts from waste reuse, recycle, treatment or disposal such as transportation emissions or the energy required for incineration.

Discharge to the environment

Another potential waste management option, particularly for liquid wastes such as brine, is to discharge it to the environment.

When considering facilities that will discharge to marine or groundwater environments it is important to consider the sensitivity of the receiving environment when going through the site selection process. That is, sites close to significant or highly sensitive ecosystems (such as Ramsar listed wetlands or conservation areas) should be avoided. To this end, socially or culturally significant landscapes (such as commercial fishing grounds) should also be avoided. Potential environmental impacts from discharging liquid wastes to marine or groundwater environments will relate to the salinity (and other chemical concentrations where present) compared to background concentrations, the velocity of its release as well as the temperature and colour of the brine discharge. These factors all influence the potential ecological impact in the vicinity of the discharge point. In addition to these factors, the existing physical conditions of the receiving environment, such as depth, distance from shore and prevailing currents, will all impact the extent of the “mixing zone” or impact zone.

Through these considerations we would be looking to minimise the size and sensitivity of the impact area through both the concentration and volume of discharge as well as the dissipation capacity of the receiving water. It is also important at this stage to consider the direct construction impacts caused by construction of the outfall structure itself and again, avoiding particularly sensitive ecosystems and minimising the impact footprint. Controls to minimise the impacts may include dilution targets, designating an “impact zone” outside of which impacts will not be measurable for agreement with the local environmental regulator, use of diffusers at the outlet to aid mixing and developing a monitoring program including baseline monitoring and monitoring of control sites to identify any impacts early.

Discharging waste to the environment, on large scales, is likely to trigger both state and national environment approval pathways. For example, significant impacts to a matter of national environmental significance, such as Ramsar wetlands or to the Great Barrier Reef Marine Park, would trigger the need to refer the project under the *Environment Protection and Biodiversity Conservation Act 1999* resulting in lengthy and complex approval processes.

7.9.3 Waste streams from water treatment plants

Various type of wastes will be produced or generated from a water treatment plant which need to be managed for disposal, these include:

- Sludge and dewatered solids
- Chemicals waste stream
- Brine stream from reverse osmosis process, and
- Consumables such as spent media, used membrane elements or resins from various process equipment.

These sources are categorised under three type of waste streams:

Liquid Waste – containing liquid waste from pre-treatment and primary treatment and final polishing processes. Used Chemicals from cleaning in place (CIP) of membranes and other liquid waste stream from the treatment plant will be included under this category

Solid waste – removed solids from pre-treatment processes

Consumables – spent media, membranes, resin, and filters from various process equipment

Table 7-26 provides the type of waste generated from each of the treatment steps identified in Section 7.5, current treatment and disposal practice with further environmental and sustainability considerations as well as opportunities to integrate circular economy concepts to hydrogen production.

Table 7-26 Sources of waste, management options and environmental considerations

Treatment Step	Process Treatment	Type of Waste	Current Treatment Practice & Management	Environmental Consideration	Opportunity for Circular Economy to H_2 Production
Pre-treatment	Intake screening	Rocks, twigs, rags, foreign debris, weeds, shells and aquatic or marine animals trapped by screening	Dewater and dispose to landfill.	Screenings could be sorted into bio and non-biodegradable solids for composting and landfill respectively.	Not applicable.
	Chemical flocculation and clarification	Floating scum/algae from any flotation process equipment and sludge stream from clarifier	1. Dispose to sewer if available and effluent meets discharge limits 2. Thicken and dewater waste stream to produce drier solids and dispose to landfill 3. Sending the sludge waste stream to onsite sludge drying bed 4. Supernatant returned to head of plant or dispose to water body	Further sludge drying helps to reduce sludge volume and minimise nuisances and maximise the recovered value of sludge. As water treatment sludge is mostly inorganic matter and subject to local regulations, sludge cake material may be appropriate for re-use, for example as a replacement for raw materials in road base, backfill or concrete mix. However, consideration of residual contamination will be required.	Unused waste heat from H_2 production and conversion to ammonia facilities can be used for drying of sludge.
	Filtration	Filter backwash water that contains high level of suspended solids	1. Combined with the clarification sludge stream for further thickening and return the supernatant back to head of plant or back to water body 2. Sewer disposal if available and meeting trade effluent discharge	In connection to the above.	In connection to the above.
		Spent filter media	1. Reuse as fill material 2. Landfill	Subject to local regulations, certain components of the filter media (such as sand) may be appropriate for re-use, for example as a replace for raw	Not applicable.

Treatment Step	**Process Treatment**	**Type of Waste**	**Current Treatment Practice & Management**	**Environmental Consideration**	**Opportunity for Circular Economy to H_2 Production**
				materials in road base, backfill or concrete mix. However, consideration of residual contamination will be required.	
Primary Treatment	Reverse Osmosis	Brine stream	1. Ocean outfall 2. Evaporation pond (more for smaller scale plant and suitable environment & climate) 3. Zero liquid discharge by further reducing the brine stream quantity via RO or thermal evaporation and salts crystallization (not widely adopted due to high capital and operating costs) 4. Disposal to sewer, where applicable 5. Subsurface injection, where applicable 6. Land application	1. Find opportunity to co-discharge with nearby wastewater treatment plant facility if possible 2. The brine concentration, when compared to background concentrations, the velocity of its release, the temperature and colour of the brine discharge 3. The existing ecosystem, including the presence of significant or sensitive ecosystems 4. The depth, distance from shore and prevailing currents in the "mixing zone" 5. The presence of socially or culturally significant landscapes (e.g., commercial fishing grounds) 6. Availability of land 7. Risks associated with leaks to the underlying	1. Using brine stream from the RO process as cooling water for cooling system of the production facility. 2. Brine discharge to outfall can provide opportunity of hydro power to supply additional green energy to the facility 3. Opportunity for unused waste heat from H_2 facility to heat up brine stream in supporting lagoon evaporation 4. Opportunity for unused waste heat from production facility to assist with brine evaporation and crystallization

Treatment Step	**Process Treatment**	**Type of Waste**	**Current Treatment Practice & Management**	**Environmental Consideration**	**Opportunity for Circular Economy to H_2 Production**
				groundwater or pathways to nearby aquatic ecosystems 8. Seepage through land into groundwater, impacting groundwater conditions, any nearby bore extractors, flora and fauna	
		Waste stream from RO clean in place (CIP)	Neutralised and disposed together with the brine stream to ocean outfall or to sewer network.	Refer to brine stream	Refer to brine stream
		Used membrane elements from RO skids	1. Landfill disposal 2. Re-purpose of used RO membrane and transformed it into UF membrane for water filtration application	1. Part of the membrane accessories are recyclable and these to be considered when dispose 2. Membranes should be washed and drained free of liquids prior to disposal to limit the volume of waste 3. If the RO membranes are not able to be used for a higher value application, the material should be classified, according to local regulations, and disposed of to a licensed treatment facility or landfill	Opportunity to use re-purpose RO membrane as UF membrane for filtration of cooling water. Further investigation and assessment to be undertaken.
Polishing Treatment	EDI	Brine stream	As quality of brine stream from the polishing step is	Nil	Nil

Treatment Step	Process Treatment	Type of Waste	Current Treatment Practice & Management	Environmental Consideration	Opportunity for Circular Economy to H_2 Production
			sufficient, it can be recirculated to the RO feed stream or combined with the cooling water stream.		
		Spent membrane/resin will require replacement of individual stacks within the EDI system	The used stack is to be disposed of to landfill, however different states may differ in the regulation of landfill wastes. Opportunity to outline ability to return spent stacks to supplier during supply contract negotiation. Should waste be determined to not be acceptable by landfill (e.g., prescribed waste) this will require classification and transportation to be disposed of in accordance with statutory requirements by licensed transport and receival agencies. Similar to the spent RO membrane, there could be opportunity to repurpose the materials.	Stacks should be drained free of liquids prior to disposal to limit the volume of waste. Material should be classified, according to local regulations, and disposed of to a licensed treatment facility or landfill. Part of the membrane accessories are recyclable, and this should be considered during disposal.	Nil

8. Comparison with alternative fuels

A comparison of water usage for select transport end-use cases was undertaken. Hydrogen fuel cell electric vehicles (FCEV) and fossil fuel combustion engines (diesel & petrol) for both passenger car and bus applications were considered.

The assessment has provided ranges of water use per 100km travelled. The water use ranges are predominantly reflective of the variance in water usage in fuel production including process cooling as identified in this study for hydrogen and in Section 8.6 for petrol and diesel. The fuel consumption assumptions for vehicles are provided in Section 8.7. It is also noted that FCEV also produce water in the tailpipe however this was not assessed.

In summary, water consumption for hydrogen used in FCEV passenger cars and buses is generally within comparable ranges of fossil fuels used in traditional combustion engines.

For passenger vehicles, it is notable that the water consumption is comparable between an evaporative water-cooled system hydrogen production and traditional fuels, however if air cooling is used, then the water consumption for hydrogen is significantly lower.

Water consumption of diesel fuelled combustion engine buses is also generally considered within comparable range to FCEV for blue and green hydrogen using air cooling and also the lower range of evaporative cooling of blue hydrogen ie low evaporation (wet, cooler) conditions. Water usage for evaporative cooling processes for green hydrogen is considerably higher particularly when operating in the upper limits of high evaporation (hot and dry) environments of Australia.

8.1 Overview of alternative fuels

This section will cover the water consumption requirements associated with conventional liquid hydrocarbon fuel production from crude oil refining. The two fuels that will be covered specifically are petrol and diesel to demonstrate the relative difference in water consumption that is associated with the replacement of common fuels with hydrogen.

8.1.1 Overview of water consumption in petrol and diesel production

Water is used in the drilling and recovery operations during the production of crude oil. It is also used in the refining process, when converting to products such as diesel or petrol. Water is also naturally present in the rocks and may be extracted along with oil. This produced water needs to be treated and disposed or reused according to regulations and with consideration of environmental impact. The quantity and quality of water used, produced and disposed of varies depending on local geology, recovery technologies and regulations[85].

8.2 Assumptions and design basis

The following assumptions were made to verify the water consumption of diesel and petrol.[86]

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[85] American Geosciences: Water in the Oil and Gas Industry, 2018 https://www.americangeosciences.org/geoscience-currents/water-oil-and-gas-industry

[86] Estimation of U.S. refinery water consumption and allocation to refinery products https://www.sciencedirect.com/science/article/pii/S0016236117309511

- The scope of this assessment includes water consumption during crude oil production and the refining of crude oil to product (diesel or petrol), including any ancillary water streams required for cooling or other services.
- Water required for down-hole processes during the drilling and production at the well site and produced oily water vary greatly from site to site and will be stated as a range.
- Crude oil production may have impacts on groundwater sources, including contamination. This has been excluded from the scope.
- For the purpose of this report, the consumption of water is defined as the amount of “fresh” (not the circulating rate) withdrawal of water that is taken into the geographic limit of a refinery and is not returned to the environment in a liquid water form (with similar or improved quality). In other words, this water is chemically consumed and/ or lost to evaporation.
- Water consumption from the refinery boundary system will include cooling water evaporation loss, water embedded with product (chemically consumed), and other losses such as steam trap losses, steam venting losses, firewater main leaks to ground, evaporation from open water usage during maintenance, and evaporation from open water ponds in the wastewater treatment plant. For clarity, the term “other loss” will be used in the following sections to refer to the sum of water consumption from the aforementioned sources.

The design basis used in this study includes refinery configurations of cracking, light coking (Lt Coking) and heavy coking (Hvy Coking), as there is variability in water consumption between these configurations. Cracking refers to fluid catalytic cracking (FCC) and does not have a delayed coker and tends to process lighter crudes, producing residual fuel oil. Coking also has an FCC and processes heavier crude and has minimal production of residual fuel. Coking refineries can be further delineated based on the type of crude to the refinery. LT Coking refinery configurations are required for processing light crude whereas Hvy Coking processes heavy crude.

8.3 Water consumption in crude oil production

Water consumption in crude oil production depends on the type of oil field, oil recovery technology, age of the oil well and degree of produced water recycling.

Early in field life, primary oil recovery uses the natural pressure of the well to produce a mixture of oil, gas and produced water. As wells age, secondary recovery (or water flooding) becomes the major recovery technology, which involves the injection of water into the formation. To enhance recovery of trapped oils that cannot be produced via secondary recovery, tertiary or enhanced oil recovery is used. Tertiary recovery can involve injection of carbon dioxide and a surfactant to reduce surface tension, or steam injection to reduce viscosity contrasts. The water consumption of crude oil recovery depends on what combination of recovery technologies are used.[87]

The produced water, which is a by-product of oil production, is sometimes recycled and used in recovery processes, which decreases the amount of water consumption for oil recovery. Produced water can also be treated and beneficially reused, such as in irrigation. If not reused or recycled, the produced water adds to the water consumption of oil production. The amount of produced water recycling varies between regions and with regulations.

The water consumption of oil production that can be attributed to petrol and diesel depends on the yield of product to crude oil. There is a process gain of approximately 6% with 170 litres of refined

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[87] Consumptive water use in the production of ethanol and petroleum gasoline, Argonne National Laboratory, 2009 https://www.researchgate.net/publication/236532942_Consumptive_water_use_in_the_production_of_ethanol_and_petroleum_gasoline

petroleum products obtained from 159 litres of crude oil[88]. This is a result of the product having a lower specific gravity compared to the initial crude. This results in a lower water consumption per litre of petroleum product compared to per litre of crude oil.

An estimated range for water consumption associated with crude oil production and petroleum products is provided in Table 8-1.

Table 8-1 Water consumption of crude oil recovery[89]

	U.S. Conventional Oil (Onshore)	Saudi Arabian Conventional Oil
Water consumption (L/L crude oil)	2.1 - 5.4	1.4 - 4.6
Water consumption (L/L petroleum product)	2 – 5.1	1.3 – 4.3

8.4 Water consumption in refining of crude oil to petrol

Petrol is a highly processed fuel and utilises and consumes the most water per barrel of product (in comparison with other refinery products). For all three refinery configurations, the largest water consumers for petrol production are the Alkaline unit, followed by the reformer unit and then the FCC unit[86].

The breakdown of water consumption for petrol is shown in Table 8-2.

Table 8-2: Petrol Product Water Consumption

Petrol Product Water Consumption			
	Cracking	Lt Coking	Hvy Coking
Cooling water Evaporation (L/s)	41.9	52.0	47.5
Other losses (L/s)	8.4	-	-
Steam loss (L/s)	-	10.4	9.5
Coker factor (L/s)	-	0.4	0.7
SMR factor (L/s)	-	0	0
Total water consumption (L/s)	50.2	62.9	57.6
Water consumption L/L product	0.60	0.71	0.66
Water consumption (L/Kg product)[90]	0.79	0.94	0.87
Water consumption (L / 100 km based on average fuel consumption in Australia)[91]	6.5	7.7	7.1
Overall product consumption ratio %	67.7	64.4	55.9

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[88] Energy Education, University of Calgary, 2017 https://energyeducation.ca/encyclopedia/In_a_barrel_of_oil#cite_note-1

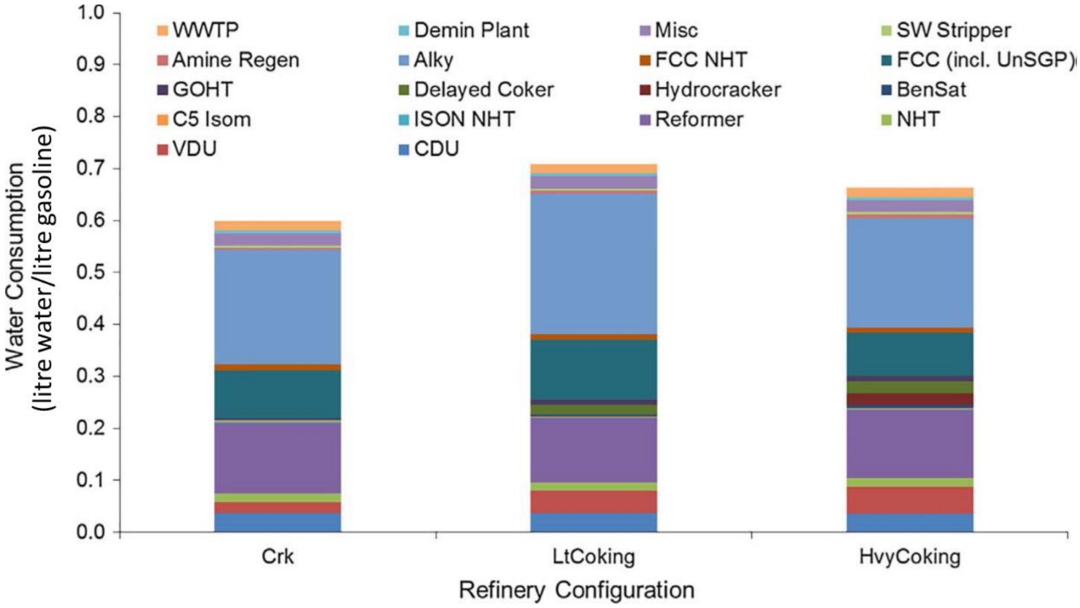
[89] Consumptive water use in the production of ethanol and petroleum gasoline, Argonne National Laboratory, 2009 https://www.researchgate.net/publication/236532942_Consumptive_water_use_in_the_production_of_ethanol_and_petroleum_gasoline

[90] Based on a typical petrol density of 0.755 kg/L

[91] Based on average fuel consumption of vehicles in Australia of 11.1 L petrol per 100 km in 2020. https://www.abs.gov.au/statistics/industry/tourism-and-transport/survey-motor-vehicle-use-australia/latest-release#fuel-consumption

Table 8-2 shows that for a cracking refinery, 1 litre of petrol produced consumes 0.60 litres of water. The water consumption increases to 0.71 litres for the typical Light Coking refinery and to 0.66 litres for typical Heavy Coking refinery.

Figure 8-1: Water Consumption Unit Contribution for Petrol Production[92]



8.5 Water consumption in refining of crude oil to diesel

The refinery configuration has a significant impact on diesel production. However, relative to petrol production, diesel production still consumes less water than petrol product does. The breakdown of water consumption (by refinery configuration) for diesel is shown in Table 8-3 and Figure 8-2.

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[92] Estimation of U.S. refinery water consumption and allocation to refinery products https://www.sciencedirect.com/science/article/pii/S0016236117309511

Table 8-3: Diesel Product Water Consumption

Water consumed in process	Process		
	Cracking	Lt Coking	Hvy Coking
Cooling water Evaporation, (L/s)	12.7	19.0	21.8
Other losses, (L/s)	2.5	-	-
Steam loss, (L/s)	-	3.8	4.4
Coker factor, (L/s)	-	0.4	0.7
SMR factor, (L/s)	-	3.8	9.9
Total water consumption, (L/s)	15.2	27.0	36.8
Water consumption L/L product	0.2	0.3	0.40
Water consumption (L/Kg product) [93]	0.23	0.35	0.47
Water consumption (L / 100 km based on average fuel consumption in Australia)[94]	3.7	5.5	4
Overall product consumption ratio %	20.5	27.7	35.7

Figure 8-2 shows a breakdown of water consumption for diesel production. Diesel production requires 0.2, 0.3, 0.4 litres of water per litre of product, for the Cracking, typical Light Coking, and Heavy Coking refinery.

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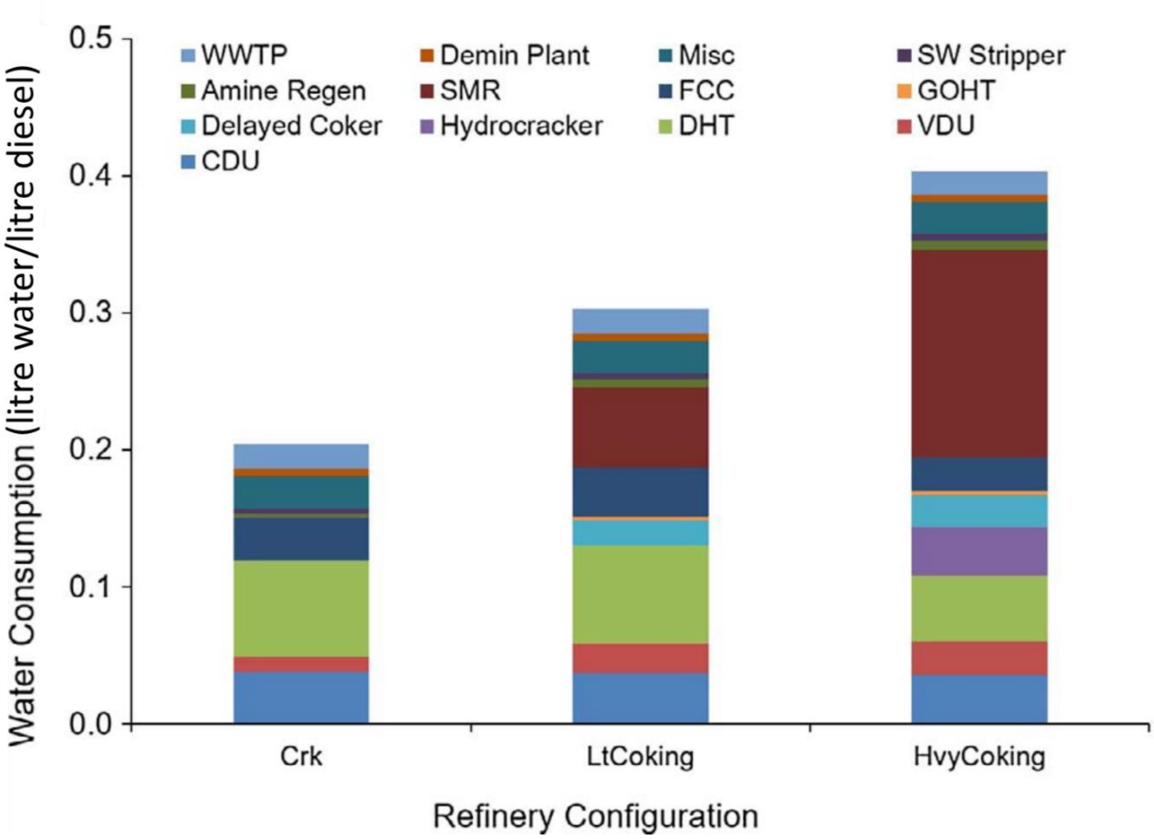
[93] Based on a typical diesel density of 0.85 kg/L

[94] Based on average fuel consumption of passenger vehicles in Australia of 11.4 L diesel per 100 km in 2020 https://www.abs.gov.au/statistics/industry/tourism-and-transport/survey-motor-vehicle-use-australia/latest-release#fuel-consumption

Figure 8-2: Water consumption unit contribution for diesel production[95]



8.6 Summary of water consumption

The results indicate that the water consumption of petrol and diesel is dominated by the water consumed during crude oil production, with 1.3 - 5.1 litres of water consumed per litre of petroleum product.

During refining, petrol refining consumes the largest amount of water, 0.60–0.71 L water/L petrol, due to the energy-intensive (and thus water-intensive) processing of petrol components (mainly sourced from alkylation, reformer, and fluid catalytic cracking units).

The water consumption of diesel is most sensitive to refinery configuration with 0.20, 0.30, and, 0.40 L water/L diesel for cracking, light coking and heavy coking configurations, respectively. This is mainly because as configuration complexity increases to process heavier and sourer crudes, a sizable burden of hydrogen production from steam methane reforming unit is allocated to diesel fuel production (including diesel sulfur removal). The trend of water consumption associated with these refinery products is consistent with the energy consumption for their production.

Figure 8-3 shows that for all three configurations the water consumption trend is consistent with the energy consumption trend associated with producing these refinery products. The correlation of these two quantities, water consumption and energy consumption, confirms the dominance of water loss sourced from energy-linked cooling water usage. In addition, energy consumption is correlated with CO_2 emissions, and this in turn leads to the correlation of water consumption with CO_2 emissions,

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[95] Estimation of U.S. refinery water consumption and allocation to refinery products https://www.sciencedirect.com/science/article/pii/S0016236117309511

implying the importance of addressing the interconnection of water, energy, and environment sustainability.

Figure 8-3: Refinery production water consumption in comparison with energy consumption and CO2 emission[96]

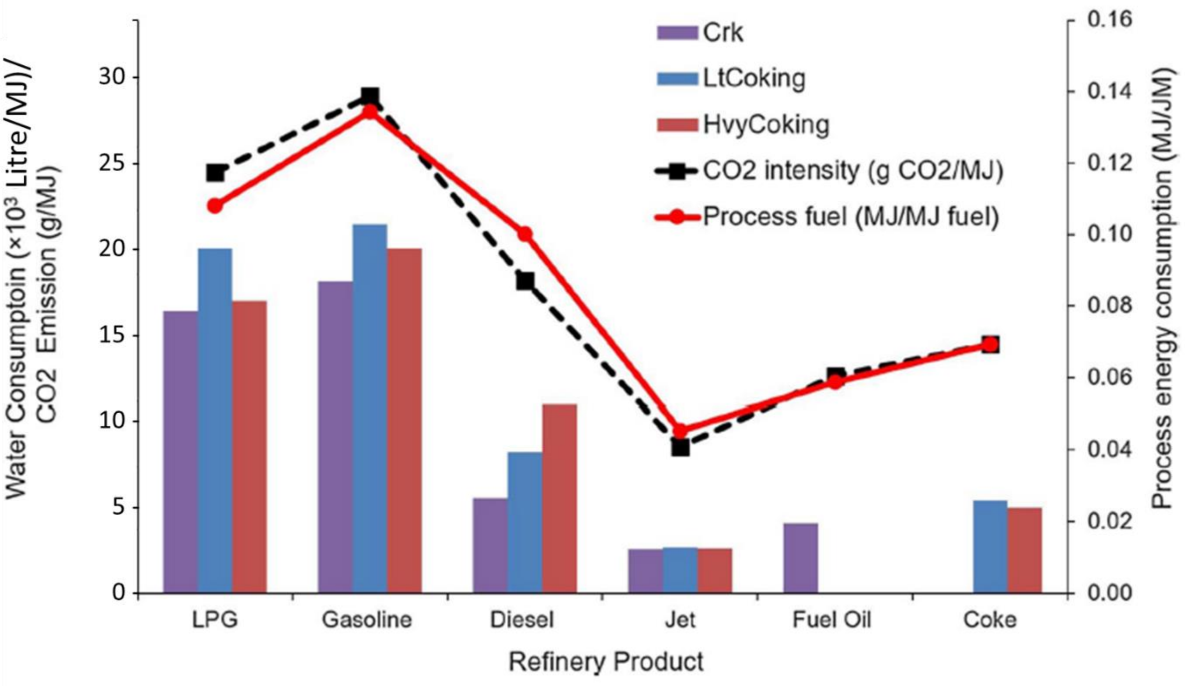

Figure 8-4 shows that of all the refinery products, petrol production consumes the most water, primarily because it requires the most processing and its components come from particularly energy-intensive units. On the other hand, jet fuel/kerosene production requires the lowest amount of water consumption due to their minimal processing required post-distillation in the crude tower.

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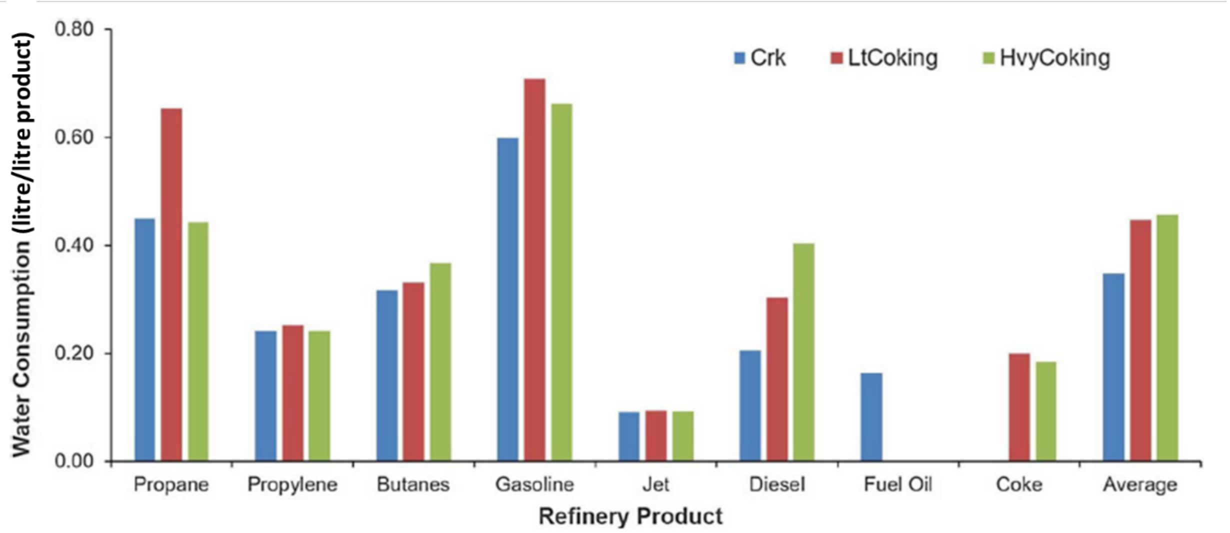
[96] Estimation of U.S. refinery water consumption and allocation to refinery products https://www.sciencedirect.com/science/article/pii/S0016236117309511

Figure 8-4: Refinery product water consumption unit contribution[97]



The total estimated water consumption of petrol and diesel including crude oil production and refining is shown in Table 8-4.

Table 8-4 Total water consumption of petrol and diesel including crude oil production and refining

	Petrol	**Diesel**
Water consumption during crude oil production (L/L petroleum product)	1.3 - 5.1	1.3 - 5.1
Water consumption during refining (L/L petroleum product)	0.6 - 0.71	0.2 - 0.4
Total water consumption (L/L petroleum product)	1.9 - 5.8	1.5 – 5.5

Comparison with water consumption for hydrogen production

Table 8-5 shows the water consumption of travelling 100 km using green or blue hydrogen in an electric fuel cell vehicle compared to a petrol or diesel combustion engine.

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[97] Estimation of U.S. refinery water consumption and allocation to refinery products https://www.sciencedirect.com/science/article/pii/S0016236117309511

Table 8-5: Comparison of water consumption of hydrogen with alternative fuels

	Fuel type					
Vehicle type	**Green hydrogen (air cooling)** [98]	**Green hydrogen (evaporative cooling)** [99]	**Blue hydrogen (air cooling)**	**Blue hydrogen (evaporative cooling)**	**Petrol**	**Diesel**
Passenger vehicle - Water consumption (L / 100 km)	Process water: 9 – 11	Process water and cooling water: 21 - 71	Process water: 5.2	Process water and cooling water: 18 - 24	From crude oil production: 14 - 57 From refining: 7 - 8	From crude oil production: 15 - 58 From refining: 2 - 5
Passenger vehicle – Total water consumption (L / 100 km)	**9-11**	**21 - 71**	**5.2**	**18 - 24**	**21 - 64**	**17 - 63**
Buses - Water consumption (L / 100 km)	Process water: 86 - 105	Process water and cooling water: 200 - 675	Process water: 49	Process water and cooling water: 171 - 228	-	From crude oil production: 55- 217 From refining: 9 - 17
Buses - Total Water consumption (L / 100 km)	**86 - 105**	**200 - 675**	**49**	**171 - 228**	**-**	**64 - 234**

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[98] Refer to section 3.3 for details on the range

[99] Refer to section 3.3 for details on the range

Fuel consumption per 100km travelled have been assumed as follows:

- Hydrogen Electric Fuel Cell Passenger Vehicle: 1 kg hydrogen per 100 km[100]
- Petrol Combustion Engine Passenger Vehicle: 11.1 L petrol per 100 km in 2020[101]
- Diesel Combustion Engine Passenger Vehicle: 11.4 L petrol per 100 km in 2020[102]
- Fuel Cell Electric Bus (FCEB): 9.5 kg hydrogen per 100 km in 2021[103]
- Diesel bus: 42.5 L diesel per 100km in 2021[104]

It is noted that fuel/energy consumption of all vehicles is dependent on a number of factors including driving conditions for metro or regional driving. For the purposes of this study vehicle fuel/energy consumptions have been selected from literature to reflect comparable Australian conditions where possible.

For passenger vehicles, it is notable that the water consumption is within comparable ranges between hydrogen FCEV and fossil fuels in traditional combustion engines. Green hydrogen production using evaporative water-cooled system is most similar to fossil fuels, whilst green hydrogen and blue hydrogen using air cooled processes are significantly lower water usage.

For heavier vehicles such as buses, the heavier the load that the vehicle is required to carry, the higher the fuel consumption. Water consumption of diesel fuelled combustion engine buses is also generally considered within comparable range to blue and green hydrogen using air cooling and also the lower range of evaporative cooling of blue hydrogen ie low evaporation (wet, cooler) conditions. Water usage for evaporative cooling processes for green hydrogen is considerably higher particularly in the upper limits of high evaporation (hot and dry) environments of Australia.

This highlights the need to consider water-efficient cooling system design in water-scarce and high evaporation regions.

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[100] Research on Hydrogen Consumption and Driving Range of Hydrogen Fuel Cell Vehicle, 2021 https://www.mdpi.com/2032-6653/13/1/9/pdf#:~:text=According%20to%20the%20data%20in,is%200.983%20kg%2F100%20km.

[101] Australian Bureau of Statistics - Survey of Motor Vehicle Use in Australia, 2020 https://www.abs.gov.au/statistics/industry/tourism-and-transport/survey-motor-vehicle-use-australia/latest-release

[102] Australian Bureau of Statistics - Survey of Motor Vehicle Use in Australia, 2020 https://www.abs.gov.au/statistics/industry/tourism-and-transport/survey-motor-vehicle-use-australia/latest-release

[103] Institute of Transport and Logistics Studies: Comparative assessment of zero emissions electric and hydrogen buses in Australia, 2021 https://www.sydney.edu.au/content/dam/corporate/documents/business-school/research/itls/zero-emission-electric-and-hydrogen-buses.pdf

[104] Institute of Transport and Logistics Studies: Comparative assessment of zero emissions electric and hydrogen buses in Australia, 2021 https://www.sydney.edu.au/content/dam/corporate/documents/business-school/research/itls/zero-emission-electric-and-hydrogen-buses.pdf

9. Conclusions

This technical study assesses water usage for a range of hydrogen production and hydrogen carrier conversion processes. The study considers both water quality and quantity requirements throughout the hydrogen value chain and identifies opportunities for process wastewater recycling and reuse to enable water savings.

Key findings from the study include:

- Water requirement for a hydrogen value chain varies substantially depending on**:** water source quality, water treatment method, climatic conditions, hydrogen production method, cooling method and hydrogen carrier conversion process.
- The water requirement for the production of green hydrogen is generally higher than blue hydrogen due to both feedstock water consumption and cooling water consumption/losses.
- When carrier conversion to liquid ammonia or liquefied hydrogen is required, there is additional water requirement. It is anticipated that future advancements in the liquefaction process technology may substantially reduce the water usage well below that for ammonia in the future.
- Cooling water requirements vary significantly depending on the cooling method and climatic conditions and often contribute a significant portion to the total water requirement for a hydrogen value chain. Air cooling, evaporative cooling and once-through cooling were assessed.
- As air cooling does not use water it can be adopted, where conditions are suitable, to reduce the overall water requirement. Once-through cooling has a high water requirement however almost all of the water is available to be recycled back to the raw water source. Evaporative cooling has a high water requirement and high water consumption / losses due to evaporation. Evaporative cooling is suited to a wide range of conditions, with dry climate conditions using more water through evaporative losses than wet climate conditions.
- Water quality requirements differ for each process of the hydrogen value chain. Water treatment is usually required for raw water quality to meet process specifications.
- For green hydrogen, high purity water is required as feedwater to the electrolyser. The study considered the effect of operational mode (constant versus variable) and efficiency of the electrolyser (beginning of life versus end of life) which were found to have a relatively low impact to total water requirement.
- The study also considered the amount of potentially recyclable water able to be reused in the system, to reduce water requirements. This was undertaken by identifying volumes consumed by the process (e.g feedstock consumption or evaporation) and categorising the waste and wastewater streams as either requiring limited treatment for reuse (recyclable water) or as waste streams.
- Of the five raw water sources considered (surface water, ground water, recycled Class A water/advanced Class A, brackish water and seawater), advanced recycled water is preferable because being of the highest source water quality it requires the lowest level of treatment and associated water consumption and energy consumption to produce the feedstock and cooling water. This source is then followed in order of by surface water, ground water, brackish water recycled Class A water with seawater requiring the most treatment.

- Seawater has the highest water usage with the least recyclable water availability as waste streams from the treatment processes are too saline for reuse. This is similar to brackish water.
- When considering water requirements as part of a hydrogen project feasibility assessment, it is important to remember that the outputs of this technical study should not be considered in isolation. Instead, a holistic approach should be taken and the overall water requirement should be evaluated together with the access to sustainable water sources, security of water supply, mitigation of environmental and social impacts associated with hydrogen use and any other co-benefits opportunities.
- Manufactured water sources such as from wastewater treatment plants (recycled water) and desalinated seawater provide sustainable supply and are less likely to compete with existing water use and thus gain community acceptance. Other impacts such energy consumption and brine waste management however need to be considered.
- As the industry moves from demonstration to commercial scale, real world information of water requirement for hydrogen production will become increasingly available and should be used to refine the outputs of this study.
- A comparison of water usage for select transport end-use cases was undertaken. Hydrogen fuel cell electric vehicles (FCEV) and fossil fuel combustion engines (diesel & petrol) for both passenger car and bus applications were considered.
- For passenger vehicles, water consumption for green hydrogen process with evaporative water-cooled system is comparable to traditional fossil fuels. For heavier vehicles such as buses, the results indicated that if air cooling is used or evaporative cooling system in a wet climate zone, water use in hydrogen production is comparable to diesel. However, if evaporative cooling is used in dry climate zone, the water consumption for green and blue hydrogen may be higher.

10. Glossary and Abbreviations

Table 10-1 Glossary of Terms

Term	Meaning
Ammonia Conversion	Producing ammonia from a hydrogen and nitrogen syngas using the Haber Bosch process. This process is a high-pressure chemical reaction with the following equation: $N_2 + 3H_2 \rightleftharpoons 2NH_3$
Basis of design	The assumed equipment configuration and battery limits of the assessment for the water usage in hydrogen study.
Blue Hydrogen	The production of hydrogen from the conversion of fossil fuels and using carbon capture and storage. Hydrogen is produced through processes such as Steam Methane Reforming (SMR), which also results in carbon emissions. Blue hydrogen then limits carbon emissions using Carbon Capture and Storage (CCS).
Carbon Capture and Storage	Carbon Capture and Storage (CCS) is a technology where the CO^2 emitted in carbon intensive processes is separated, transported and injected in underground formations. Here it can be stored for long periods of time, effectively avoiding its release to the atmosphere.
Carrier Conversion	Process that converts hydrogen gas to another form - such as liquefied hydrogen or liquefied ammonia - for cost effective storage and transport
Dry Zone and Wet Zone	Different climatic zones developed using the Bureau of Meteorology (BOM)'s average annual evaporation map. The extreme zones on the map were used to select a “wet zone” (lowest evaporation) and “dry zone” (highest evaporation). See Section 2.2.
Green Hydrogen	Hydrogen production where water is the primary feedstock. Hydrogen is produced by electrolysis, using renewable energy.
Hydrogen Liquefaction	Cooling hydrogen into a liquid to increase its volumetric density and facilitate its transport and storage.
Hydrogen process	A process that involves either production or conversion of hydrogen. In this report, hydrogen process refers to green hydrogen production, blue hydrogen production, hydrogen liquefaction or ammonia conversion.
Hydrogen Value Chain	Hydrogen gas production processes including conversion of hydrogen gas to other forms (carrier conversion).
Raw Water	Water coming directly from its source of origin without having been treated to meet the water quality requirement of a specific process. Types of raw water include river water, seawater, recycled water from a wastewater treatment plant.
Recyclable Water	Wastewater generated from water treatment or hydrogen processes that can be recycled or reused readily in the system (e.g. cooling water blow down or water treatment plant wastewater with low salinity).
Steam Methane Reforming	A process for producing hydrogen from fossil fuel. Methane is heated with steam and a catalyst to produce a mixture of hydrogen and carbon monoxide.
Syngas	Synthesis gas, a mixture of hydrogen, carbon monoxide and carbon dioxide
Treated water	Water that has undergone a water treatment process to meet the water quality requirements of a specific process
Waste Stream	Used water that is degraded in quality and not readily able to be recycled or reused in the process (e.g brine)
Water consumption	Amount of water withdrawn from a water source that is not returned to its source of origin because it is incorporated into the products, lost through evaporation, or discharged as waste stream due to its degraded quality.
Water quality requirement	Water quality standards for a defined use. Water quality requirements may differ depending on the process.

Water requirement	Amount of water usage in the defined hydrogen value chain. Water requirement is the sum of water consumption, recyclable water and waste stream. Water usage and water requirement are used interchangeably throughout the document.

Table 10-2 Table of Abbreviations

Abbreviation	Meaning
ASU	Air Separation Unit
Alky	Alkylation Plant
ASTM	American Society for Testing and Materials
AHC	Australian Hydrogen Council
ATR	Autothermal Reforming
Barg	Unit of gauge pressure
BOL	Beginning of Life
BOM	Bureau of Meteorology
C5 Isom	C5 isomerisation
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
CDU	Crude Distillation Unit
CoC	Cycles of Concentration
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DAFF	Dissolved Air Flotation over Filters
DHT	Distillate or Diesel Hydrotreater
EDI	Electro deionisation
EOL	End of Life
FCC	Fluid Catalytic Cracking
FCC-NHT	Fluidised Catalytic Cracking unit
GOHT	Gas oil hydrotreater
HX	Heat Exchanger
H_2	Hydrogen
IPP	Independent Power Producer
IEAGHG	International Energy Agency Greenhouse Gas R&D Programme
ISOM NHT	Isomerization Naptha Hydrotreating Unit
MVC	Mechanical Vapour Compression
MEA	Methylethanolamine
MED	Multiple-effect distillation
MSF	Multi-Stage Flash distillation
NHT	Naphtha hydrotreating
PEM	Polymer Electrolyte Membrane
PSA	Pressure Swing Adsorber
RES	Renewable Energy Systems
RO	Reverse Osmosis
SW Stripper	Sour Water stripper
SMR	Steam Methane Reforming
BenSat	The process that is undergone in a Benzene Reduction Unit
TVC	Thermo Vapour Compression
TDS	Total Dissolved Solids
UnSGP	Unsaturated Gas Plant
VDU	Vacuum Distillation Unit
WWTP	Wastewater Treatment Plant
WGS	Water-Gas Shift

Appendix A: Typical Water Source TDS

Table A-1 below outlines the classification of water by salinity[105].

Table A-1: Salinity Classification by TDS

Salinity Classification	TDS (mg/L)
Fresh	<800
Brackish	800-2,000
Saline	2,000-10,000
Highly Saline	10,000-35,000
Hyper Saline	>35,000

Table A-2 below outlines the typical range of TDS by water type with sources.

Table A-2: Water Type Typical Salinity Range

	TDS Min (mg/L)	**TDS Max (mg/L)**	**Source**
Demineralised		<10	Samco, "What are the properties of demineralized water?", https://www.samcotech.com/properties-demineralized-water-can-benefit-plant/
Rainwater	10	150	Industry standard.
Drinking Water	50	600	Level for good quality drinking water. Australian Government National Health and Medical Research Council, "Australian Drinking Water Guidelines 6 2011", https://www.nhmrc.gov.au/sites/default/files/documents/reports/aust-drinking-water-guidelines.pdf
Recycled Water	50	1,000	Developed from collated water quality envelopes.
Domestic Wastewater	150	1,200	Natural Resource Management Ministerial Council, Environment Protection and Heritage Council, Australian Health Ministers' Conference, "National Guidelines for Water Recycling: Managing Health and Environmental Risks", https://www.waterquality.gov.au/sites/default/files/documents/water-recycling-guidelines-full-21.pdf
Greywater	50	6,000	Natural Resource Management Ministerial Council, Environment Protection and Heritage Council, Australian Health Ministers' Conference, "National Guidelines for Water Recycling: Managing Health and Environmental Risks", https://www.waterquality.gov.au/sites/default/files/documents/water-recycling-guidelines-full-21.pdf
Surface water	10	5,000	Developed from collated water quality envelopes.
Groundwater	100	10,000	Developed from collated water quality envelopes.
Estuary	500	35,000	United States environmental Protection Agency, "Voluntary Estuary Monitoring Manual Chapter 14: Salinity", https://www.epa.gov/sites/default/files/201509/documents/2009_03_13_estuaries_monitor_chap14.pdf
Seawater	3,5000		Government of Western Australia, Department of Water and Environmental Regulation, https://www.waterquality.gov.au/sites/default/files/documents/water-recycling-guidelines-full-21.pdf

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[105] Source: Government of Western Australia, Department of Water and Environmental Regulation, https://www.waterquality.gov.au/sites/default/files/documents/water-recycling-guidelines-full-21.pdf

Appendix B: Process Flow Diagrams

Figure B-1: Process flow diagram for surface water treatment plant

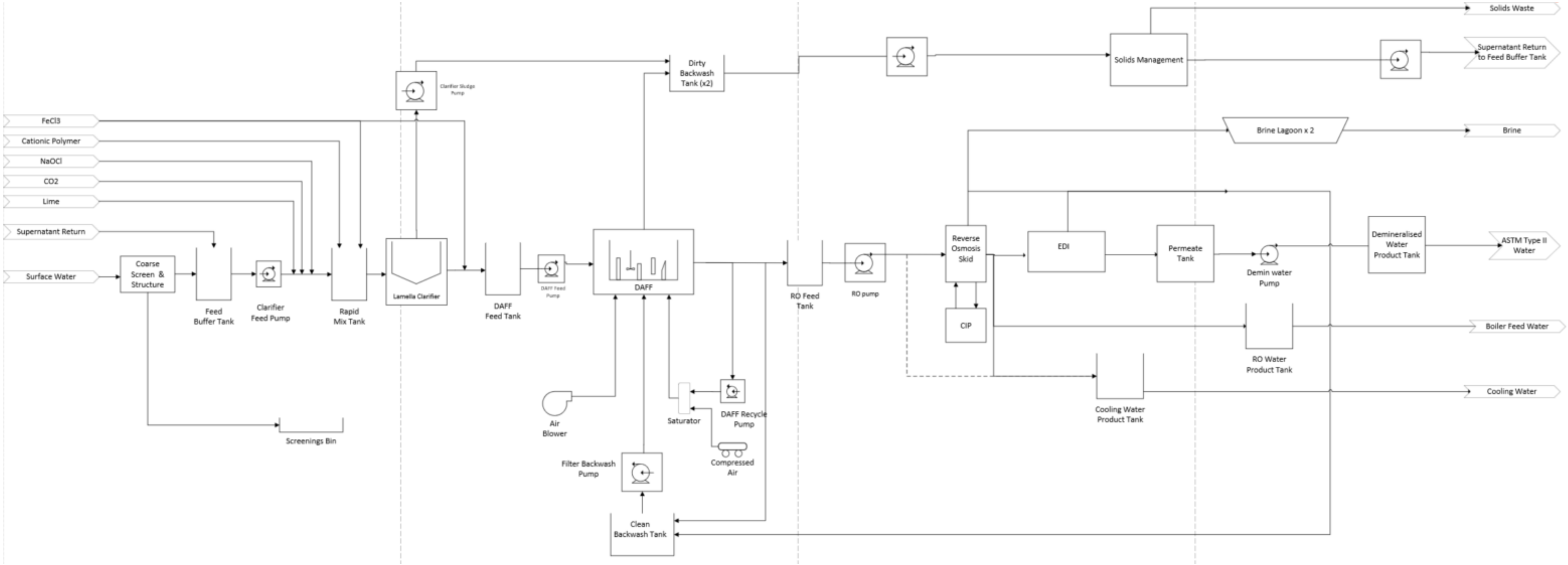


Figure B-2: Process flow diagram for groundwater treatment plant

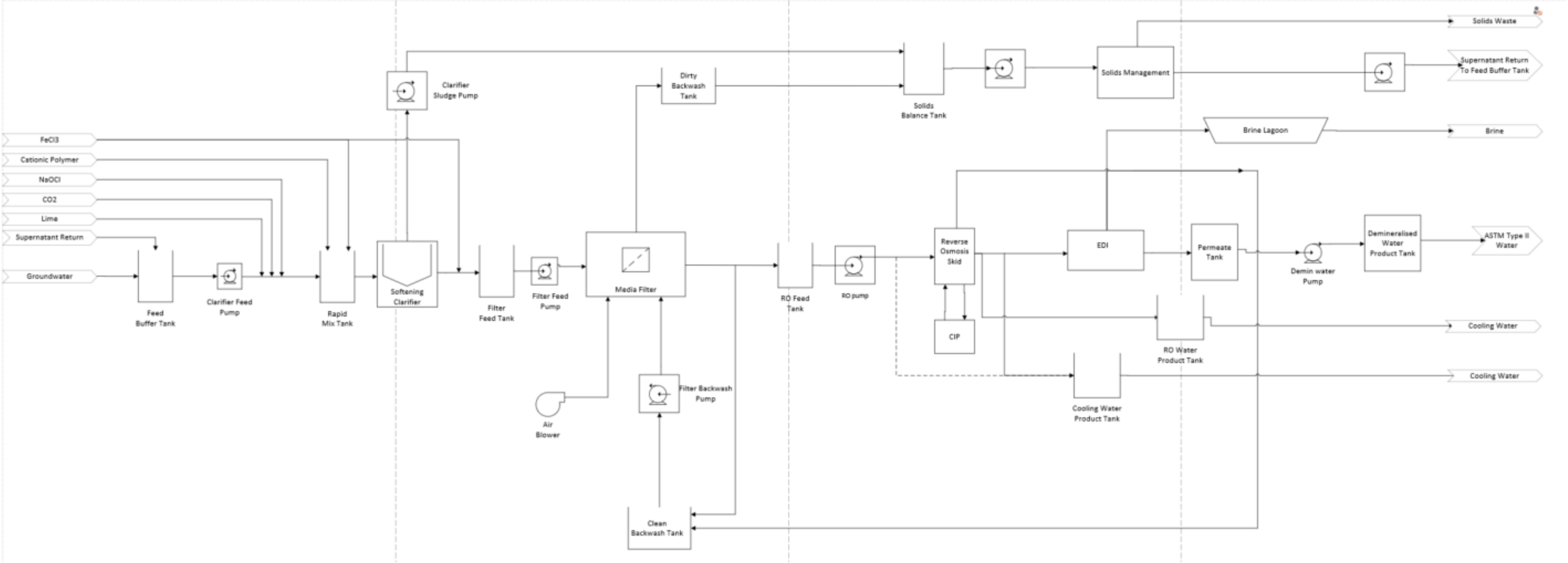


Figure B-3: Process flow diagram for recycled water treatment plant

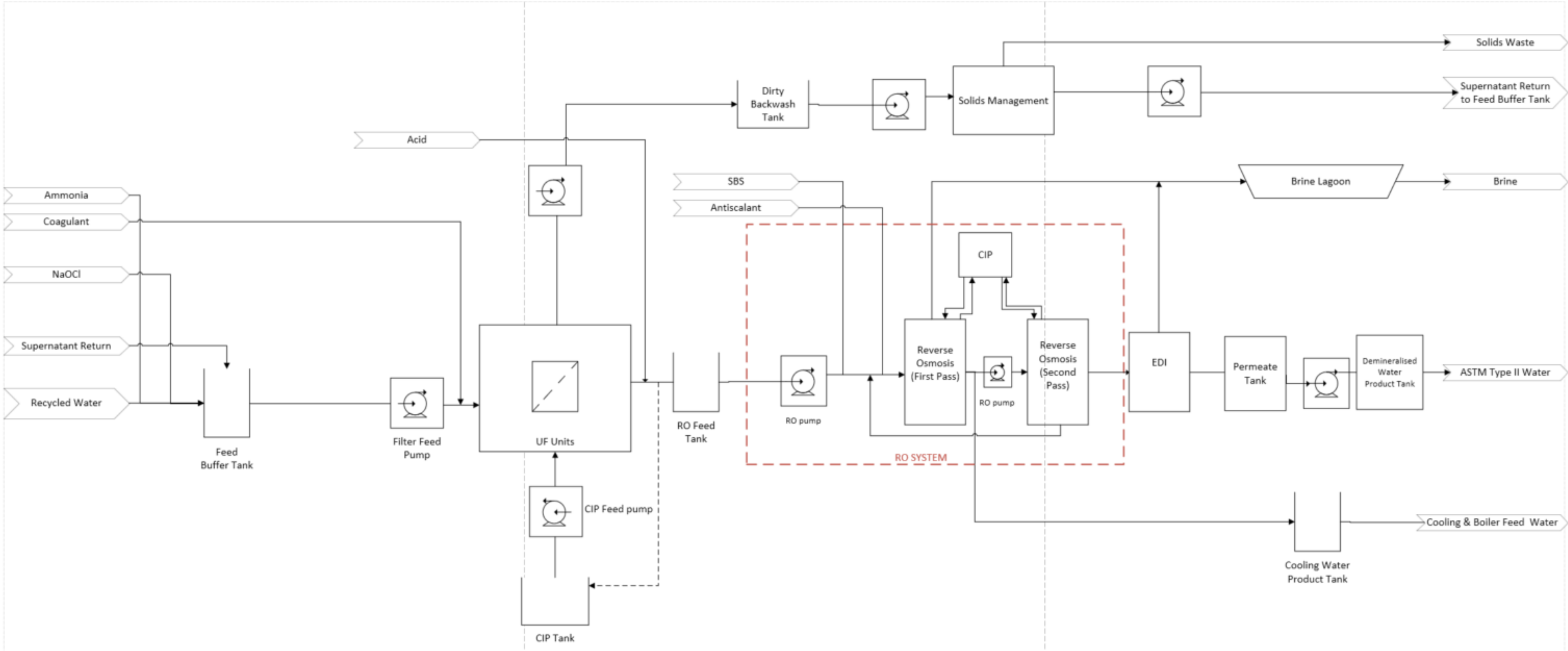


Figure B-4: Process flow diagram for brackish water

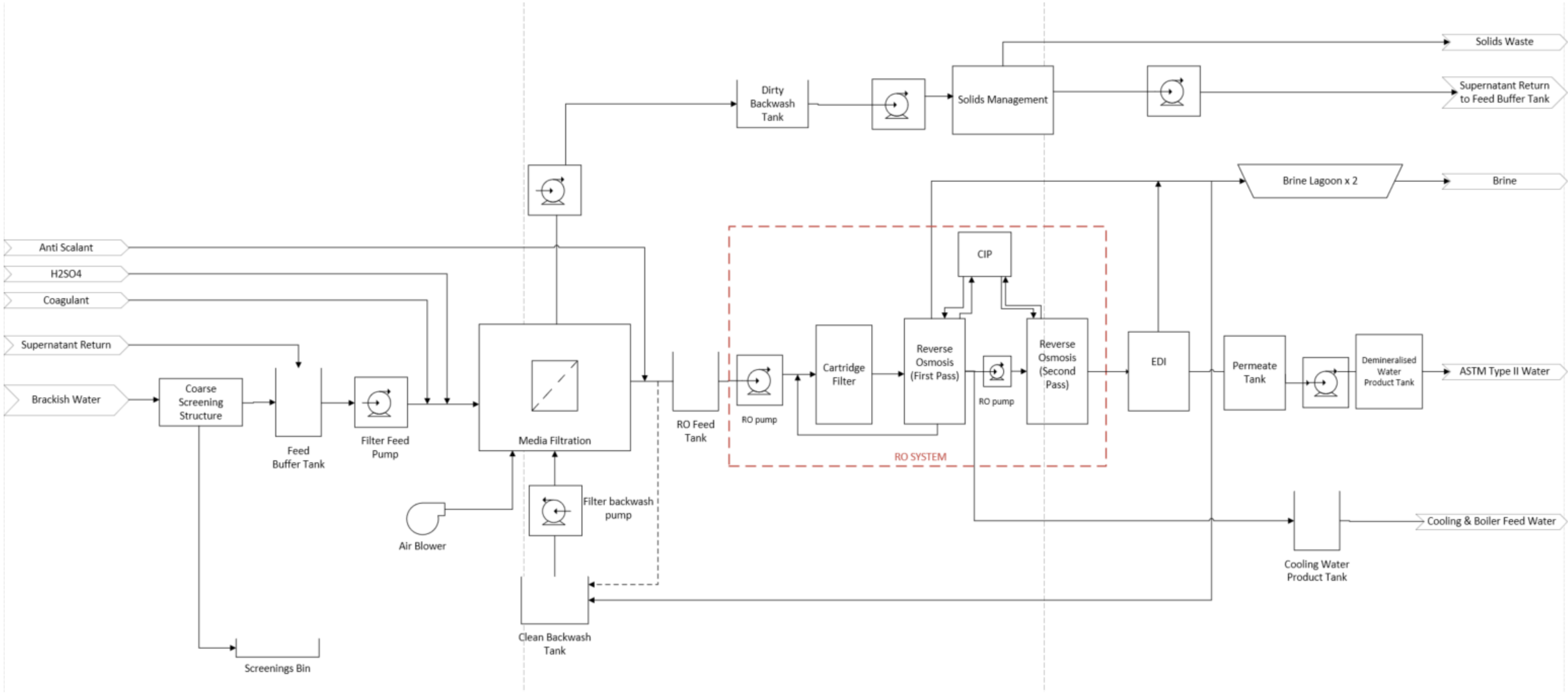
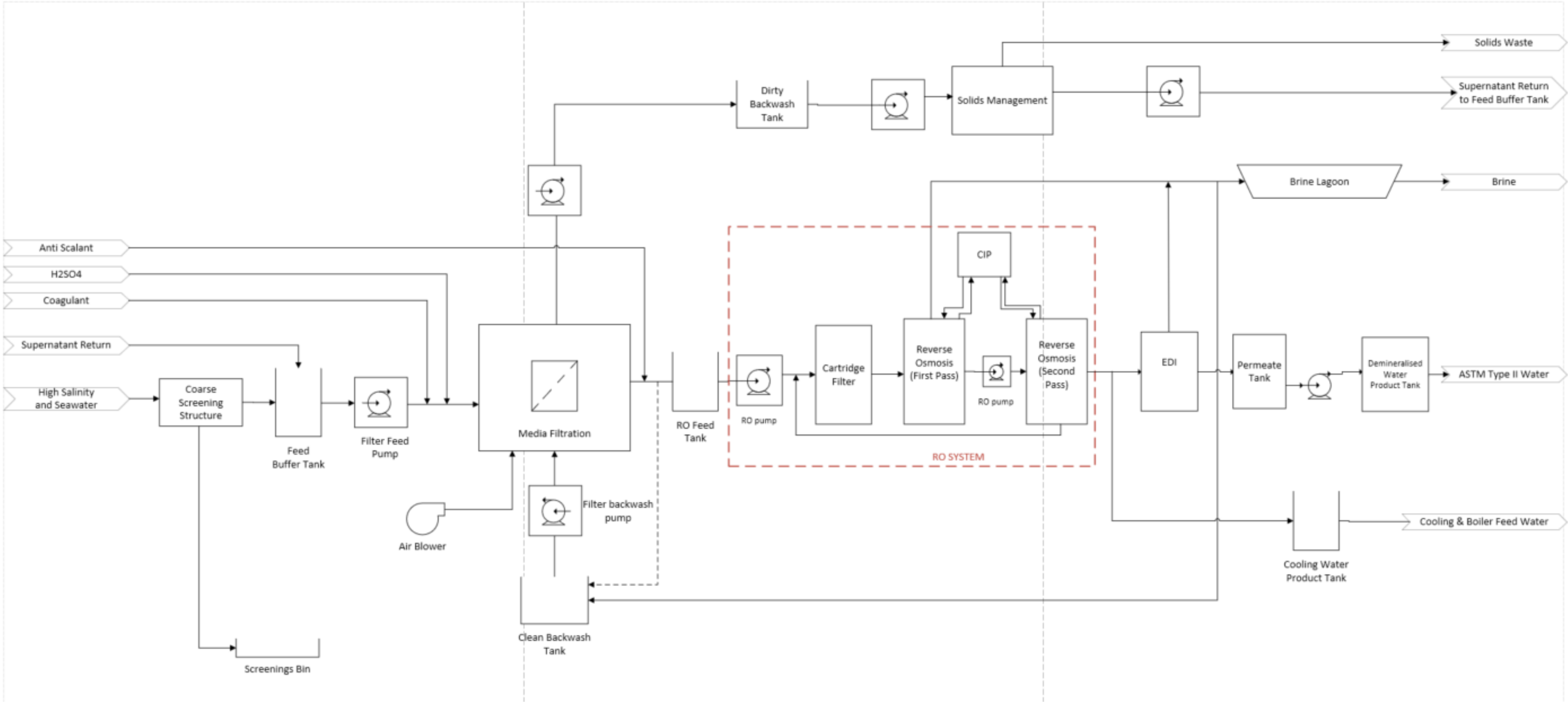
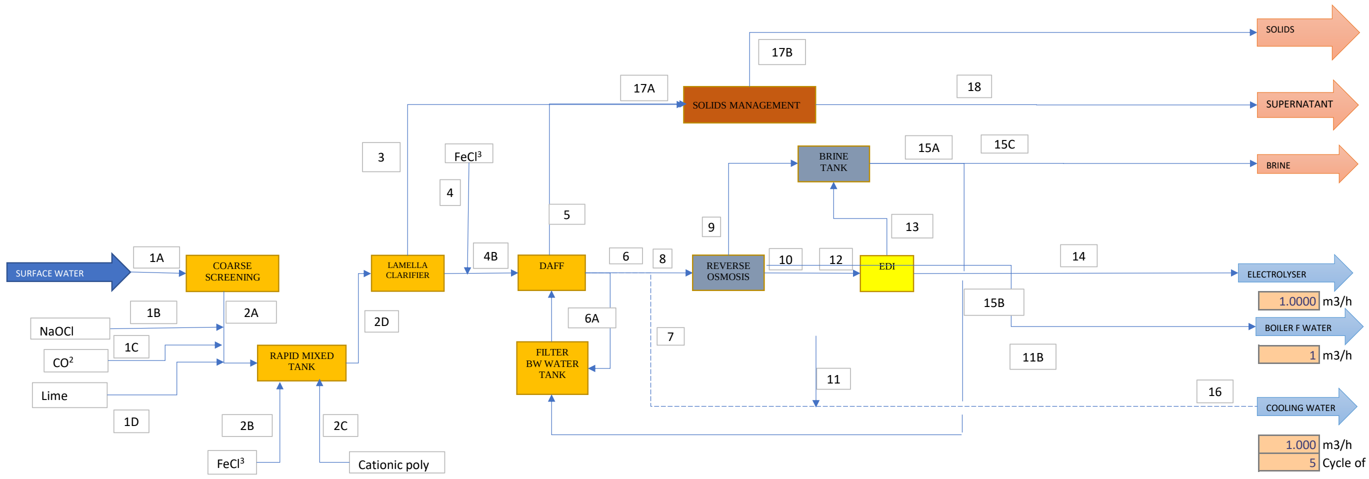


Figure B-5: Process Flow Diagram for High Salinity and Seawater Treatment Plant



Appendix C: Mass Balance Details

SURFACE WATER (TDS < 800 mg/L) MASS BALANCE



1.0000 m3/h
1 m3/h
1.000 m3/h
5 Cycle of concentration

L	L		
Raw water	ASTM Type II	CW	BF Water
1.61	1		
1.17		1	
1.45			1
2.62	1	1	
3.06	1		1
4.1	1	1	1

m3/h	MLD
41.66666667	1

Pre-treatment Technology	**% recovery**		INPUT
Coarse screening	99.5%		
conventional clarifier	97%		
High rate clarifer	97%		
DAF	92%	Adopted Cascade estimation	
Multimedia filter	93%	Adopted Cascade operational data based on good water quality	
DAFF or DAF & DMF	88%	Assumption with DAF upstream, backwash frequency will be less, about the same as membrane	
Membrane filtration	95%	Based on Pall (Recovery from AquaNet advance WTP is ~94%)	
Primary treatment technology			
RO	70%	For Brackish or low TDS water typically 60 - 75%	
EDR		Typically 85 - 94%	
Polishing technology			
Ion exchange		Assumed duty standby setup	
EDI	90%	Up to 95% according to Dupont EDI-310 module	

Pre-treatment Technology	Solids removal rate	Algae removal	**Dewatering Solid captured rate**	
conventional clarifier	90%	60%	Centrifuge	90%
High rate clarifer	95%	70%		
DAF	95%	90%		
Multimedia filter	98%	95%		
DAFF or DAF & DMF	97%	100%		
Membrane filtration	100.0%	100%		

RO treatment technology ionic rejection rate

TDS	98.5%	Calcium	99%	Silica	98%	Copper	99%	Sodium	97%
Cl	99%	Magnesium	99%	Sulphate	99.5%	Iron	99%	Manganese	99%

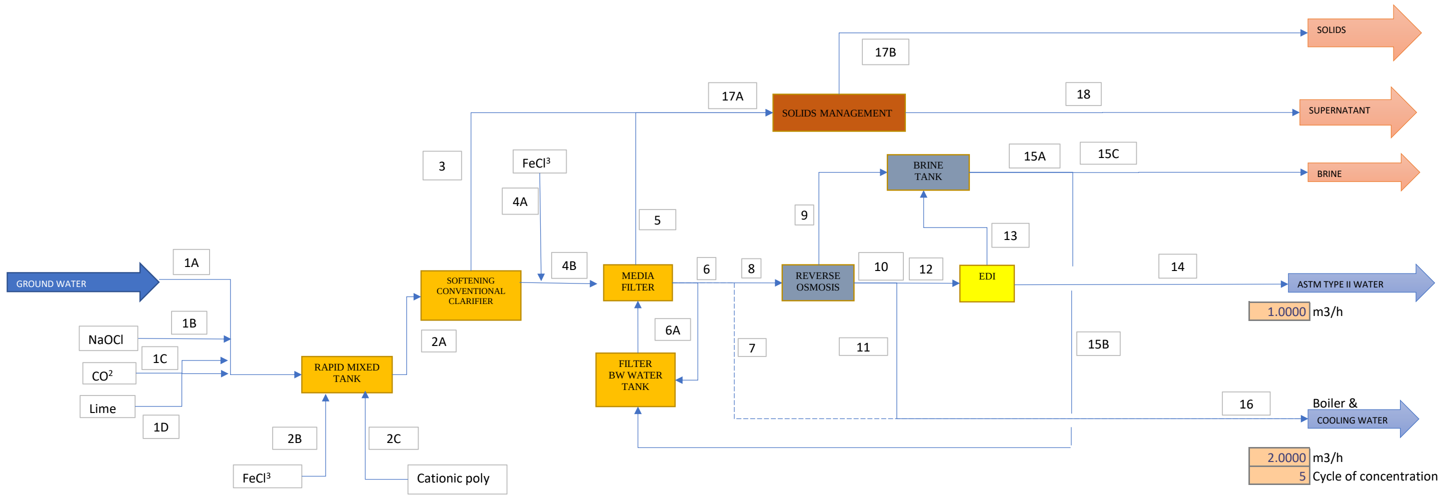
EDI polishing technology ionic rejection rate

TDS	98%	Calcium	98%	Silica	50%	Copper	99%	Sodium	99%
Cl	99%	Magnesium	99%	Sulphate	99%	Iron	99%	Manganese	99%

Parameter	Stream Unit	1A	1B	1C	1D	2A	2B	2C	2D	3	4A	4B	5	6	7	8	9
Flow	m3/hr	4.16088	0.000	0.03	0.09	4.28	0.00	0.03	4.140	0.12	0.00	4.016	0.55	4.02	1.0000	3.016	0.90
Flow	ML/d	0.10	0.000	0.00	0.00	0.10	0.000	0.00	0.10	0.00	0.000	0.10	0.01	0.10	0.024	0.07	0.02
pH		7.40				8.5	8.5		8.50								
NaOCl	mg/L		2.00														
	kg/d		0.20														
NaOCl prepared conc	%w/w		2%														
Lime	mg/L				30												
	kg/d				3.00												
Lime Sol Conc	g/L				1.40												
CO2	mg/L			10													
	kg/d			1.00													
CO2 prepared conc	%w/w			0.2%													
FeCl3	mg/L						10				10						
FeCl3 Sol Conc	%w/w						28.0%				28.0%						
Cationic polymer	mg/L							2									
	kL/d @ 40%							0.000423							7.00	8.00	9.00
Cat poly Soln Conc	%w/w							0.025%									
Turbidity	NTU	40							40.00			2.00	1.76	0.07	0.07	0.07	
TSS	mg/L	17.9				17.41			17.90	19722.88		0.92	6.45	0.23	0.23	0.23	0.03
	ton/d	0.00				0.00			0.00	0.06		0.00	0.00	0.00	0.00	0.00	0.00
	%DS								0.0%	2.0%							
TDS	mg/L	140				0.00			140.00			140.00	140.00	140.00	140.00	140.00	459.67
	ton/d	0.00				0.00			0.01			0.01	0.00	0.01	0.00	0.01	0.01
Conductivity	uS/cm2																
Calcium	mg/L	6.5				6.32			6.50			6.50		6.50	6.50	6.50	21.45
	ton/d	0.00				0.00			0.00			0.00		0.00	0.00	0.00	0.00
Magnesium	mg/L	11.5				11.19			11.50			11.50		11.50	11.50	11.50	37.95
	ton/d	0.00				0.00			0.00			0.00		0.00	0.00	0.00	0.00
Hardness	mg/L as CaCO3	63.52				15.79			16.23	0.00		16.23	0.00	16.23	16.23	16.23	53.56
Chloride	mg/L	26.63				25.91			26.63			26.63		26.63	26.63	26.63	87.88
	ton/d	0.00				0.00			0.00			0.00		0.00	0.001	0.00	0.00
Total silica	mg/L	4.3				4.18			4.30			4.30		4.30	4.30	4.30	14.05
	ton/d	0.00				0.00			0.00			0.00			0.0001	0.00	0.00
Sulphate	mg/L	19				18.48			19.00			19.00		19.00	19.00	19.00	62.38
	ton/d	0.00				0.00			0.00			0.00			0.00	0.00	0.00
Copper	mg/L	0.0022				0.00			0.00			0.00		0.00	0.00	0.00	0.01
	ton/d	0.00				0.00			0.00			0.00			0.0000	0.00	0.00
Iron	mg/L	0.6				0.58			0.60			0.001		0.00	0.00	0.00	0.00
	ton/d	0.00				0.00			0.00			0.00000			0.000	0.00	0.00
Sodium	mg/L	17.5				17.02			17.50			17.50		17.50	17.50	17.50	56.58
	ton/d	0.00				0.00			0.00			0.00			0.0004	0.00	0.00
Manganese	mg/L	0.1				0.10			0.10			0.000		0.00	0.00	0.00	0.00
	ton/d	0.00				0.00			0.00			0.00			0.0000	0.00	0.00
Agal cell count	cells/1ml	5800.00							5800.00			1740.00	1739.83	0.17	0.17		

Parameter	Stream Unit	10	11	11B	12	13	14	15A	15B	15C	16	17A	17B	18	ASTM TYPE II WATER	COOLING WATER	TARGETTED CW QUALITY
Flow	m3/hr	2.111	0.00	1	1.111	0.11	1.0000	1.016	0.554	0.462	1.000	0.68	0.01	0.67			
Flow	ML/d	0.05	0	0.024	0.03	0.00	0.02	0.02	0.01	0.01	0.02	0.02	0.000	0.02			
pH																	
NaOCl	mg/L																
	kg/d																
NaOCl prepared conc	%w/w																
Lime	mg/L																
	kg/d																
Lime Sol Conc	g/L																
CO2	mg/L																
	kg/d																
CO2 prepared conc	%w/w																
FeCl3	mg/L																
FeCl3 Sol Conc	%w/w																
Cationic polymer	mg/L																
	kL/d @ 40%	10.00	11.00														
Cat poly Soln Conc	%w/w																
Turbidity	NTU	0.00	0.00	0.00	0.00		0.00					1.76	1.58				
TSS	mg/L	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.03	0.23	3616.62	3254.96	366.63		25.00	5.00
	ton/d	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.05	0.01			
	%DS											0.36%	20%				
TDS	mg/L	3.00	0.00	3.00	3.00	29.40	0.07	412.61	412.61	412.61	140.00	114.37			0.46	1500.00	300.00
	ton/d	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00					
Conductivity	uS/cm2						0.14								1.000		
Calcium	mg/L	0.09	0.00	0.09	0.09	0.91	0.00	19.20	19.20	19.20	6.50	0.00					
	ton/d	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Magnesium	mg/L	0.16	0.00	0.16	0.16	1.63	0.00	33.98	33.98	33.98	11.50	0.00					
	ton/d	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Hardness	mg/L as CaCO3	0.23	0.00	0.23	0.23	2.27	0.01	47.95	47.95	47.95	16.23	0.00				500.00	100.00
Chloride	mg/L	0.38	0.00	0.38	0.38	3.77	0.0042	78.68	78.68	78.68	26.63	0.00			0.005	300.00	60.00
	ton/d	0.00	0.000	0.00	0.00	0.00	0.0000	0.00	0.00	0.00	0.001	0.00					
Total silica	mg/L	0.12	0.00	0.12	0.12	0.61	0.068	12.58	12.58	12.58	4.30	0.00			0.003	150.00	30.00
	ton/d	0.00	0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0001	0.00					
Sulphate	mg/L	0.41	0.00	0.41	0.41	4.01	0.01	56.00	56.00	56.00	19.00	0.00				250.00	50.00
	ton/d	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Copper	mg/L	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00				1.00	0.20
	ton/d	0.00	0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Iron	mg/L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.001	0.00				3.00	0.60
	ton/d	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Sodium	mg/L	0.75	0.00	0.75	0.75	7.43	0.008	51.21	51.21	51.21	17.50	0.00			0.005		
	ton/d	0.00	0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0004	0.00					
Manganese	mg/L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00				0.10	0.02
	ton/d	0.00	0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Agal cell count	cells/1ml																

GROUND WATER MASS BALANCE



1.0000 m3/h

2.0000 m3/h
5 Cycle of concentration

Pre-treatment Technology	% recovery		INPUT
Coarse screening	99.5%		
conventional clarifier	97%		
High rate clarifer	97%		
DAF	92%	Adopted Cascade estimation	
Multimedia filter	93%	Adopted Cascade operational data based on good water quality	
DAFF or DAF & DMF	88%	Assumption with DAF upstream, backwash frequency will be less,	
Membrane filtration	95%	Based on Pall design for Lang Lang project	
Primary treatment technology			
RO	70%	For Brackish or low TDS water typically 60 - 75%	
EDR		Typically 85 - 94%	
Polishing technology			
Ion exchange		Assumed duty standby setup	
EDI	90%	Up to 95% according to Dupont EDI-310 module	

Pre-treatment Technology	Solids removal rate	Algae removal	Dewatering Solid captured rate	
conventional clarifier	90%	60%	Centrifuge	90%
High rate clarifer	95%	70%		
DAF	95%	90%		
Multimedia filter	98%	95%		
DAFF or DAF & DMF	97%	100%		
Membrane filtration	100.0%	100%		

RO treatment technology ionic rejection rate

TDS	98.1%	Calcium	98.6%	Silica	97.7%	Copper	99.9%	Sodium	96.7%
Cl	99.0%	Magnesium	98.6%	Sulphate	99.5%	Iron	99.9%	Manganese	99.9%

EDI polishing technology ionic rejection rate

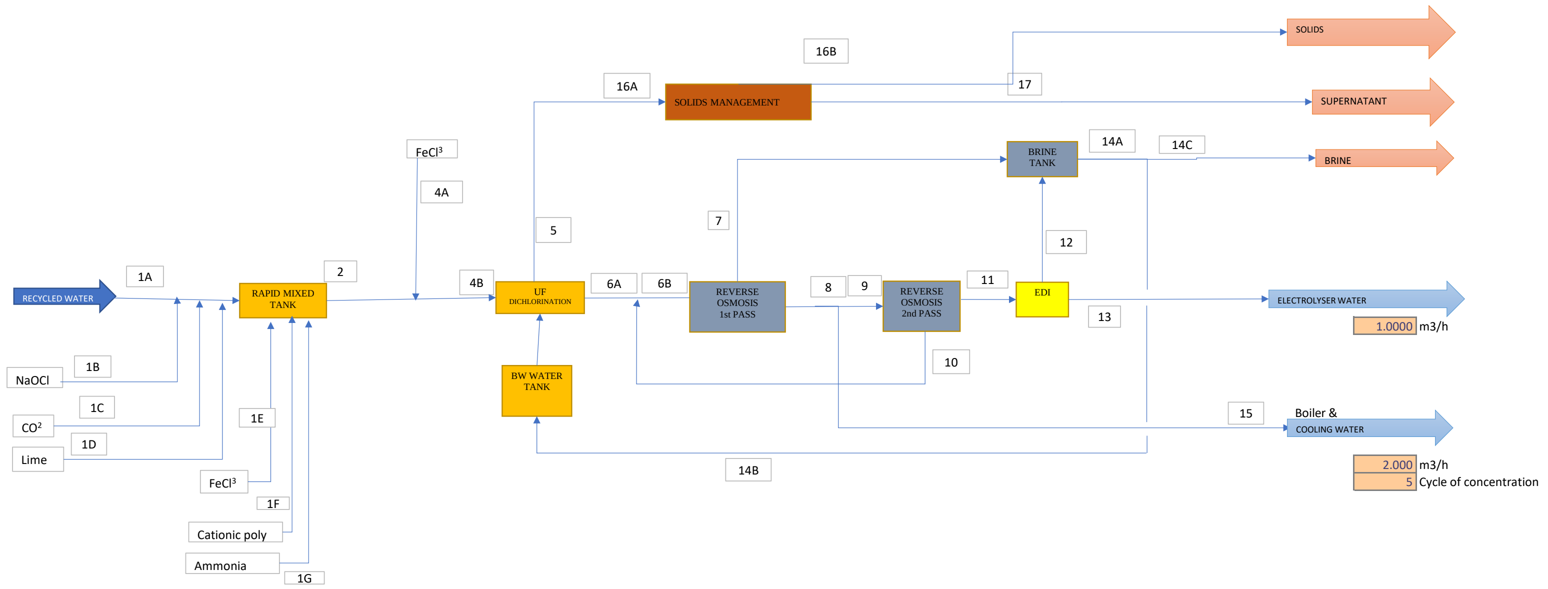
TDS	98%	Calcium	98%	Silica	50%	Copper	99%	Sodium	99%
Cl	99%	Magnesium	99%	Sulphate	99%	Iron	99%	Manganese	99%

Parameter	Stream Unit	1A	1B	1C	1D	2A	2B	2C	3	4A	4B
Flow	m3/hr	5.35167	0.000	0.03	0.11	5.32	0.00	0.04	0.16	0.00	5.2
Flow	ML/d	0.13	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.12
pH											
NaOCl	mg/L		2.00								
	kg/d		0.26								
NaOCl prepared conc	%w/w		2%								
Lime	mg/L				30						
	kg/d				3.85						
Lime Sol Conc	g/L				1.40						
CO2	mg/L			10							
	kg/d			1.28							
CO2 prepared conc	%w/w			0.2%							
FeCl3	mg/L						10			10	
FeCl3 Sol Conc	%w/w						28.0%			28.0%	
Cationic polymer	mg/L							2			
	kL/d @ 40%							0.00054			
Cat poly Soln Conc	%w/w							0.025%			
Turbidity	NTU	5.00				5.00					0.50
TSS	mg/L	7.5				7.50			6993.60		0.77
	ton/d	0.00				0.00			0.03		0.00
	%DS					0.00%			0.7%		
TDS	mg/L	425				425.00					425.00
	ton/d	0.05				0.05					0.05
Conductivity	uS/cm2										
Calcium	mg/L	21.3				21.30					3.31
	ton/d	0.00				0.00					0.00
Magnesium	mg/L	12.4				12.40					1.93
	ton/d	0.00				0.00					0.00
Hardness	mg/L as CaCO3	104.00				53.19					8.27
Chloride	mg/L	138				138.00					138.00
	ton/d	0.02				0.02					0.02
Total silica	mg/L	7				7.00					7.00
	ton/d	0.00				0.00					0.00
Sulphate	mg/L	59				59.00					59.00
	ton/d	0.01				0.01					0.01
Copper	mg/L	0.009				0.01					0.01
	ton/d	0.00				0.00					0.00
Iron	mg/L	0.021				0.02					0.000
	ton/d	0.00				0.00					0.000
Sodium	mg/L	102				102.00					102.00
	ton/d	0.01				0.01					0.01
Manganese	mg/L	0.015				0.02					0.0000
	ton/d	0.00				0.00					0.000

Parameter	Stream Unit	5	6	7	8	9	10	11	12	13	14
Flow	m3/hr	0.36	4.44	0.00	4.44	1.33	3.11	2.00	1.11	0.11	1.00
Flow	ML/d	0.01	0.11	0.00	0.11	0.03	0.07	0.05	0.03	0.00	0.02
pH											
NaOCl	mg/L										
	kg/d										
NaOCl prepared conc	%w/w										
Lime	mg/L										
	kg/d										
Lime Sol Conc	g/L										
CO2	mg/L										
	kg/d										
CO2 prepared conc	%w/w										
FeCl3	mg/L										
FeCl3 Sol Conc	%w/w										
Cationic polymer	mg/L										
	kL/d @ 40%										
Cat poly Soln Conc	%w/w										
Turbidity	NTU	0.49	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.0000	0.000
TSS	mg/L	10.86	0.02	0.00	0.02	0.06	0.00	0.00	0.00	0.0000	0.000
	ton/d	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0000	0.000
	%DS										
TDS	mg/L	425.00	425.00	0.00	425.00	1389.75	11.54	11.54	11.536	113.05	0.256
	ton/d	0.00	0.05	0.000	0.05	0.04	0.00	0.001	0.000	0.00	0.00
Conductivity	uS/cm2										
Calcium	mg/L	3.31	3.310	0.000	3.310	10.92	0.05	0.047	0.047	0.46	0.0011
	ton/d	0.00	0.000	0.000	0.00	0.00	0.00	0.000	0.000	0.0000	0.0000
Magnesium	mg/L	1.93	1.927	0.000	1.927	6.33	0.04	0.039	0.039	0.38	0.000
	ton/d	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.0000	0.0000
Hardness	mg/L as CaCO3	8.27	8.27	0.00	8.27	27.28	0.12	0.12	0.12	1.16	0.003
Chloride	mg/L	138.00	138.000	138.000	138.000	455.40	1.97	1.9714	1.971	19.52	0.022
	ton/d	0.00	0.015	0.000	0.015	0.01	0.00	0.000	0.000	0.0001	0.0000
Total silica	mg/L	7.00	7.00	0.00	7.00	22.80	0.23	0.23	0.230	1.15	0.13
	ton/d	0.00	0.001	0.000	0.001	0.00	0.00	0.0000	0.000	0.0000	0.00
Sulphate	mg/L	59.00	59.00	0.00	59.00	195.68	0.42	0.42	0.421	4.16	0.007
	ton/d	0.00	0.006	0.000	0.006	0.01	0.00	0.0000	0.000	0.0000	0.00
Copper	mg/L	0.01	0.009	0.000	0.009	0.03	0.00	0.0000	0.000	0.00	0.00000
	ton/d	0.00	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0.0000	0.00000
Iron	mg/L	0.00	0.000	0.000	0.000	0.00	0.00	0.0000	0.000	0.00	0.00000
	ton/d	0.00	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0.0000	0.00
Sodium	mg/L	102.00	102.0	0.0	102.0	328.78	4.81	4.81	4.809	47.60	0.053
	ton/d	0.00	0.011	0.000	0.011	0.01	0.00	0.000	0.000	0.0001	0.000
Manganese	mg/L	0.00	0.000	0.000	0.000	0.00	0.00	0.00	0.000	0.00	0.00
	ton/d	0.00	0.000	0.000	0.000	0.00	0.00	0.00	0.000	0.00	0.00

Parameter	Stream Unit	15A	15B	15C	16	17A	17B	18		ASTM TYPE II	COOLING WATER	TARGETTED CW QUALITY
Flow	m3/hr	1.44	0.36	1.08	2.00	0.52	0.00	0.52				
Flow	ML/d	0.03	0.01	0.03	0.05	0.01	0.00	0.01				
pH												
NaOCl	mg/L											
	kg/d											
NaOCl prepared conc	%w/w											
Lime	mg/L											
	kg/d											
Lime Sol Conc	g/L											
CO2	mg/L											
	kg/d											
CO2 prepared conc	%w/w											
FeCl3	mg/L											
FeCl3 Sol Conc	%w/w											
Cationic polymer	mg/L											
	kL/d @ 40%											
Cat poly Soln Conc	%w/w											
Turbidity	NTU	0.01	0.01	0.01	0.000000	0.49	0.44	0.05				
TSS	mg/L	0.06	0.06	0.06	0.00	2155.56	1940.00	215.56			25.00	5.00
	ton/d	0.00	0.00	0.00	0.000000	0.03	0.02	0.00				
	%DS					0.22%	20%					
TDS	mg/L	1291.54	1291.54	1291.54	11.5	294.46				0.46	1500.00	300.00
	ton/d	0.04	0.04	0.04	0.00	0.00						
Conductivity	uS/cm2									1.000		
Calcium	mg/L	10.12	10.12	10.12	0.05							
	ton/d	0.00	0.00	0.00	0.00							
Magnesium	mg/L	5.88	5.88	5.88	0.04							
	ton/d	0.00	0.00	0.00	0.00							
Hardness	mg/L as CaCO3	25.27	25.27	25.27	0.12						500.00	100.00
Chloride	mg/L	421.87	421.87	421.87	1.97					0.005	300.00	60.00
	ton/d	0.01	0.01	0.01	0.000							
Total silica	mg/L	21.13	21.13	21.13	0.23					0.003	150.00	30.00
	ton/d	0.00	0.00	0.00	0.0000							
Sulphate	mg/L	180.95	180.95	180.95	0.42						250.00	50.00
	ton/d	0.01	0.01	0.01	0.00							
Copper	mg/L	0.03	0.03	0.03	0.000						1.00	0.20
	ton/d	0.00	0.00	0.00	0.0000							
Iron	mg/L	0.00	0.00	0.00	0.0000						3.00	0.60
	ton/d	0.00	0.00	0.00	0.0000							
Sodium	mg/L	307.15	307.15	307.15	4.81					0.005		
	ton/d	0.01	0.01	0.01	0.000							
Manganese	mg/L	0.00	0.00	0.00	0.0000						0.10	0.02
	ton/d	0.00	0.00	0.00	0.00							

RECYCLED WATER MASS BALANCE



m3/h	MLD
41.6666667	1

Pre-treatment Technology	% recovery		INPUT
Coarse screening	99.5%		
conventional clarifier	97%		
High rate clarifer	97%		
DAF	92%	Adopted Cascade estimation	
Multimedia filter	93%	Adopted Cascade operational data based on good water quality	
DAFF or DAF & DMF	88%	Assumption with DAF upstream, backwash frequency will be less, about the same as membrane	
Membrane filtration	95%	Based on Pall design for Lang Lang project	
UF	95%		

Primary treatment technology	1st pass	2nd pass	Overall	
RO	42%	90%	38%	For double pass RO with high saline to seawater quality
EDR		Typically 85 - 94%		
Polishing technology				
Ion exchange		Assumed duty standby setup		
EDI	90%	Up to 95% according to Dupont EDI-310 module		

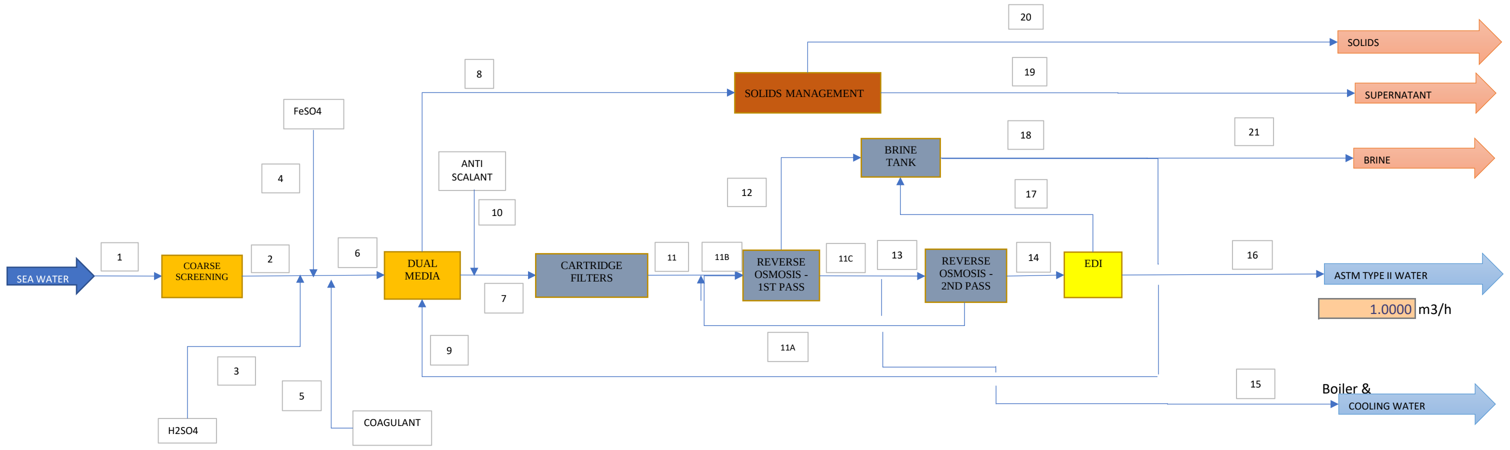
Pre-treatment Technology	Solids removal rate	Algae removal	Dewatering Solid captured rate	
conventional clarifier	90%	60%	Centrifuge	90%
High rate clarifer	95%	70%		
DAF	95%	90%		
Multimedia filter	98%	95%		
DAFF or DAF & DMF	97%	100%		
Membrane filtration	100.0%	100%		

RO treatment technology ionic rejection rate									
TDS	98.5%	Calcium	99%	Silica	98%	Copper	99%	Sodium	97%
Cl	99%	Magnesium	99%	Sulphate	99.5%	Iron	99%	Manganese	99%

EDI polishing technology ionic rejection rate									
TDS	98%	Calcium	98%	Silica	50%	Copper	99%	Sodium	99%
Cl	99%	Magnesium	99%	Sulphate	99%	Iron	99%	Manganese	99%

Parameter	Stream Unit	1A	1B	1C	1D	1E	1F	1G	2	3 (not used)	4A	4B	5	6A	6B	7	8	9	10	11	12	13	14A	14B	14C	15	16A	16B	17	ASTM TYPE II WATER	COOLING WATER	TARGETTED CW QUALITY
Flow	m3/hr	8.01682	0.000	0.05	0.17	0.00	0.05	0.00	7.98	0.00	0.00	7.98	0.40	7.58	7.70	4.47	3.23	1.23	0.12	1.11	0.11	1.00	4.58	0.40	4.18	2.00	0.40	0.000	0.40			
Flow	ML/d	0.19	0.000	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.19	0.01	0.18	0.18	0.11	0.08	0.03	0.00	0.03	0.00	0.02	0.11	0.01	0.10	0.05	0.01	0.000	0.01			
pH		7.40																														
NaOCl	mg/L		2.00																													
	kg/d		0.38																													
NaOCl prepared conc	%w/w		2%																													
Lime	mg/L				30																											
	kg/d				5.77																											
Lime Sol Conc	g/L				1.40																											
CO2	mg/L			10																												
	kg/d			1.92																												
CO2 prepared conc	%w/w			0.2%																												
FeCl3	mg/L					10					10																					
FeCl3 Sol Conc	%w/w					28.0%					28.0%																					
Cationic polymer	mg/L						2																									
	kL/d @ 40%						0.00																									
Cat poly Soln Conc	%w/w						0.025%																									
Ammonia	mg/L							2																								
Ammonia Soln Conc	%w/w							20.0%																								
Turbidity	NTU	0.80							0.80			0.80	0.76	0.04	0.04	0.0168	0.0232	0.02	0.02	0.0023	0.00	0.00	0.02	0.02	0.00	0.02	0.76	0.68				
TSS	mg/L	3.90							3.90			0.20	3.71	0.14	0.14	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.09	0.08	0.01		25.00	5.00
	ton/d	0.00							0.00			0.00	0.00	0.00	0.00	0.0000	0.0000			0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
	%DS								0.0%																		0.00%	20%				
TDS	mg/L	425							425.00			425.00	425.00	425.00	425.00	710.20	14.94	14.94	14.94	0.25	8.70	0.006	693.17	693.17	693.17	14.94	10.20			0.46	1500.00	300.00
	ton/d	0.08							0.08			0.08	0.00	0.08	0.08	0.0761	0.0012	0.0004	0.0000	0.0000	0.0000	0.00	0.08	0.0066	0.07	0.00	0.00					
Conductivity	uS/cm2																													1.000		
Calcium	mg/L	21.3							21.30			21.30	21.30	21.30	21.30	35.77	0.50	0.50	0.50	0.01	0.29	0.00	34.91	34.91	34.91	0.50	0.51					
	ton/d	0.00							0.00			0.00	0.00	0.00	0.00	0.0038	0.0000	0.0000	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00					
Magnesium	mg/L	12.4							12.40			12.40	12.40	12.40	12.40	20.83	0.29	0.29	0.29	0.00	0.08	0.00	20.32	20.32	20.32	0.29	0.30					
	ton/d	0.00							0.00			0.00	0.00	0.00	0.00	0.0022	0.0000	0.0000	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00					
Hardness	mg/L as CaCO3	104.15							53.19			53.19	53.19	53.19	53.19	89.33	1.25	1.25	1.25	0.03	0.73	0.001	87.18	87.18	87.18	1.25	1.28				500.00	100.00
Chloride	mg/L	137.54							137.54			137.54	137.54	137.54	137.54	231.00	3.22	3.22	3.22	0.04	0.94	0.0004	225.42	225.42	225.42	3.22	3.30			0.005	300.00	60.00
	ton/d	0.03							0.03			0.03	0.00	0.03	0.03	0.0248	0.0003	0.0001	0.0000	0.0000	0.0000	0.00	0.02	0.00	0.02	0.00	0.00					
Total silica	mg/L	7.1							7.10			7.10	7.10	7.10	7.10	0.62	0.02	0.02	0.02	0.00	0.25	0.0002	0.61	0.61	0.61	0.02	0.17			0.003	150.00	30.00
	ton/d	0.00							0.00			0.00	0.00	0.00	0.00	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00					
Sulphate	mg/L	59							59.00			59.00	59.00	59.00	59.00	5.24	0.04	0.04	0.04	0.00	0.01	0.00	5.11	5.11	5.11	0.04	1.42				250.00	50.00
	ton/d	0.01							0.01			0.01	0.00	0.00	0.00	0.0006	0.0000	0.0000	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00					
Copper	mg/L	0.009							0.01			0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				1.00	0.20
	ton/d	0.00							0.00			0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00					
Iron	mg/L	0.021							0.02			0.00	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				3.00	0.60
	ton/d	0.00							0.00			0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00					
Sodium	mg/L	102							102.00			102.00	102.00	102.00	102.00	8.83	0.38	0.38	0.38	0.00	0.11	0.0047	8.62	8.62	8.62	0.38	2.45			0.005		
	ton/d	0.02							0.02			0.02	0.00	0.00	0.00	0.0009	0.0000	0.0000	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00					
Manganese	mg/L	0.015							0.02			0.000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				0.10	0.02
	ton/d	0.00							0.00			0.00	0.0000	0.0000	0.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00	0.00	0.00	0.00	0.00	0.00					
Agal cell count	cells/1ml	0.00																														

BRACKISH MASS BALANCE



2.000 m3/h

5 Cycle of concentration

m3/h	MLD
41.66667	1

INPUT

Pre-treatment Technology	% recovery	
Coarse screening	99.5%	
Multimedia filter	93%	Adopted Victorian Desal

Primary treatment technology	1st pass	2nd pass	Overall	
RO	45%	90%	41%	For double pass RO with high saline to seawater quality

Polishing technology		
EDI	90%	Up to 95% according to Dupont EDI-310 module

Pre-treatment Technology	**Solids removal rate**	**Algae removal**	**Dewatering Solid captured rate**
Multimedia filter	98%	95%	90%
Cartridge filter (5 micron)	99%	99%	

RO treatment technology ionic rejection rate - 1st Pass

TDS	99.5%	Calcium	99.9%	Silica	99.9%	Copper	99.9%	Sodium	99.5%
Cl	99.5%	Magnesium	99.9%	Sulphate	99.95%	Iron	99.9%	Manganese	99.9%

RO treatment technology ionic rejection rate - 2nd Pass

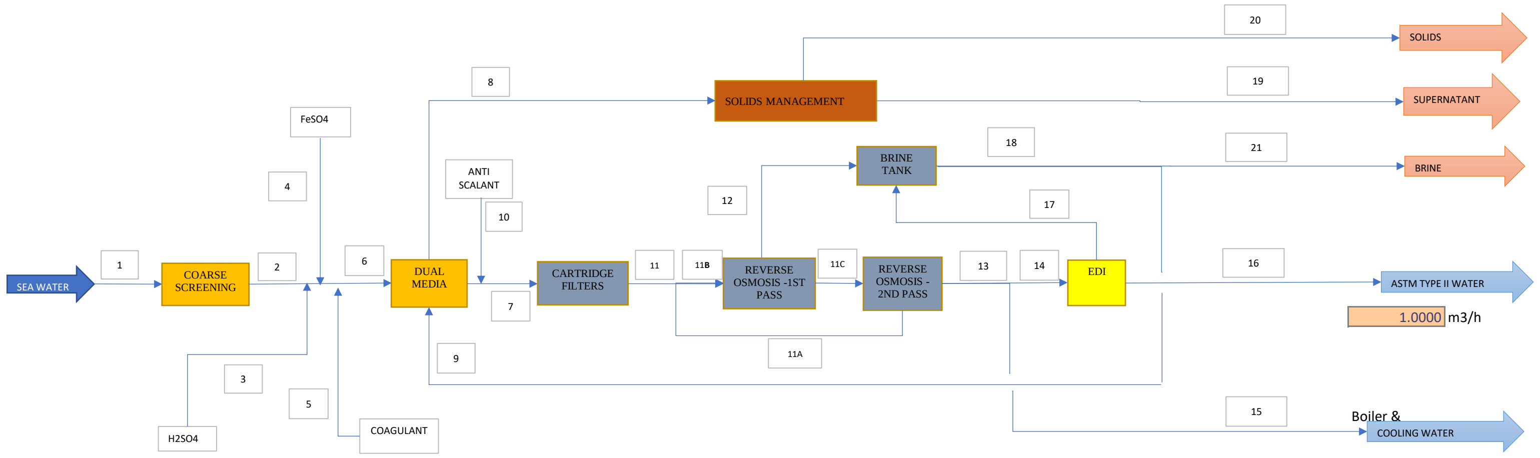
TDS	98%	Calcium	98%	Silica	98%	Copper	98%	Sodium	99%
Cl	99%	Magnesium	99.4%	Sulphate	99.3%	Iron	98%	Manganese	98%

EDI polishing technology ionic rejection rate

TDS	98%	Calcium	98%	Silica	50%	Copper	99%	Sodium	99%
Cl	99%	Magnesium	99%	Sulphate	99%	Iron	99%	Manganese	99%

Parameter	Stream Unit	1	2	3	4	5	6	7	8	9	10	11	11A	11B	11C	12	13	14	15	16	17	18	19	20	21	ASTM TYPE II WATER	COOLING WATER	TARGETTED CW QUALITY
Flow	m3/hr	7.0645	7.064	0.046			7.11	7.06	0.53	0.53		7.1	0.12	7.19	3.23	3.95	1.23	1.11	2.00	1.00	0.11	4.06	0.53	0.01	3.53			
Flow	ML/d	0.17	0.17	0.001	0.00	0.00	0.17	0.17	0.01	0.01	0.00	0.17	0.00	0.17	0.08	0.09	0.03	0.03	0.05	0.02	0.00	0.10	0.01	0.00	0.08			
pH																												
H2SO4	mg/L			15.00																								
	kg/d			2.54																								
H2SO4 prepared conc	%w/w			98.0%																								
Lime	mg/L																											
	kg/d																											
Lime Sol Conc	g/L																											
CO2	mg/L																											
	kg/d																											
CO2 prepared conc	%w/w																											
FeCl3	mg/L				5																							
FeCl3 Sol Conc	%w/w				28.0%																							
Cationic polymer	mg/L																											
	kL/d @ 40%																											
Cat poly Soln Conc	%w/w																											
Turbidity	NTU	165.00	165.00				165.00	3.30	161.70			0.0330	0.0163	0.03	0.0182	0.0149	0.0182	0.0018	0.0182	0.0018	0.0000	0.0149	16.170	145.53	0.0149			
TSS	mg/L	247.50	247.5				245.9096	4.95	3222.45			0.0495	0.0245	0.05	0.0272	0.0223	0.0272	0.0027	0.027	0.0027	0.0000	0.0223	322.245	2900.21	0.0223		25.00	5.00
	ton/d	0.04	0.04				0.04	0.00	0.041			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.004	0.04	0.0000			
	%DS																							20%	0.00			
TDS	mg/L	2250.00	2250				2235.54	2250	2235.54	3891.56		2250.00	23.14	2250.00	24.57	2225.43	24.57	1.43	24.57	0.03	14.02	3891.56			3891.56	0.46	1500.00	300.00
	ton/d	0.38	0.38				0.38	0.38	0.38	0.05		0.38	0.00	0.38	0.00	0.38	0.00	0.00	0.00	0.00	0.00	0.38			0.38			
Conductivity	uS/cm2																			0.07					0.00	1.000		
Calcium	mg/L	80.00	80				80.00	80		138.88		80.00	0.20	80.00	0.21	79.79	0.21	0.01	0.21	0.00	0.11	138.88			138.88			
	ton/d	0.01	0.01				0.01	0.01		0.00		0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01			0.01			
Magnesium	mg/L	160.00	160				160.00	160		277.74		160.00	0.45	160.00	0.45	159.55	0.45	0.01	0.45	0.00	0.08	277.74			277.74			
	ton/d	0.03	0.03				0.03	0.03		0.00		0.03	0.00	0.03	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.03			0.03			
Hardness	mg/L as CaCO3	199.76	199.76				199.76	199.76	0.00	346.80		199.76	0.50	199.76	0.52	199.24	0.52	0.03	0.52	0.001	0.27	346.80					500.00	100.00
Chloride	mg/L	1800.00	1800				1800.00	1800		3113.10		1800.00	19.08	1800.00	19.66	1780.34	19.66	0.57	19.66	0.006	5.67	3113.10			3113.10	0.005	300.00	60.00
	ton/d	0.31	0.31				0.31	0.31		0.04		0.31	0.00	0.31	0.00	0.30	0.00	0.0000	0.00	0.00	0.00	0.30			0.30			
Total silica	mg/L	23.00	23				23.00	0.46		0.80		0.46	0.00	0.46	0.0010	0.46	0.00	0.0001	0.001	0.0000	0.00	0.80			0.80	0.003	150.00	30.00
	ton/d	0.00	0.00				0.00	0.00		0.00		0.00	0.00	0.00	0.000	0.00	0.00	0.0000	0.00	0.00	0.00	0.00			0.00			
Sulphate	mg/L	320.00	320				320.00	320		555.47		320.00	0.90	320.00	0.91	319.09	0.91	0.0071	0.91	0.00	0.07	555.47			555.47		250.00	50.00
	ton/d	0.05	0.05				0.05	0.05		0.01		0.05	0.00	0.05	0.00	0.05	0.00	0.0000	0.00	0.00	0.00	0.05			0.05			
Copper	mg/L	0.01	0.01				0.01	0.01		0.02		0.01	0.00	0.01	0.0000	0.01	0.00	0.00000	0.00	0.0000	0.00	0.02			0.02		1.00	0.20
	ton/d	0.00	0.00				0.00	0.00		0.00		0.00	0.00	0.00	1.69547E-09	0.00	0.00	0.00000	0.00	0.00	0.00	0.00			0.00			
Iron	mg/L	7.00	7				7.00	7		12.15		7.00	0.01	7.00	0.0153	6.98	0.02	0.00089	0.02	0.0000	0.01	12.15			12.15		3.00	0.60
	ton/d	0.00	0.00				0.00	0.00		0.00		0.00	0.00	0.00	1.18683E-06	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.00			
Sodium	mg/L	880.00	880				880.00	880		1521.96		880.00	9.33	880.00	9.610	870.39	9.61	0.280	9.61	0.0031	2.77	1521.96			1521.96	0.005		
	ton/d	0.15	0.15				0.15	0.15		0.02		0.15	0.00	0.15	0.001	0.15	0.00	0.000	0.00	0.00	0.00	0.15			0.15			
Manganese	mg/L	0.14	0.14				0.14	0.14		0.24		0.14	0.00	0.14	0.0003	0.14	0.00	0.00002	0.000	0.00	0.00	0.24			0.24		0.10	0.02
	ton/d	0.00	0.00				0.00	0.00		0.00		0.00	0.00	0.00	2.37366E-08	0.00	0.00	0.00000	0.00	0.00	0.00	0.00			0.00			
Agal cell count	cells/1ml	0.00					0.00	0																				

HIGH SALINITY AND SEAWATER MASS BALANCE



1.0000 m3/h

2.0 m3/h
5 Cycle of concentration

m3/h	MLD
41.66667	1

	INPUT							
Pre-treatment Technology	% recovery							
Coarse screening	99.5%							
Multimedia filter	93%	Adopted Victorian Desal						
Primary treatment technology	1st pass	2nd pass	Overall					
RO	45%	90%	41%	For double pass RO with high saline to seawater quality				
Polishing technology								
EDI	90%	Up to 95% according to Dupont EDI-310 module						
Pre-treatment Technology	**Solids removal rate**		**Algae removal**		**Dewatering Solid captured rate**			
Multimedia filter	98%		95%		90%			
Cartridge filter (5 micron)	99%		99%					

RO treatment technology ionic rejection rate - 1st Pass

TDS	99.5%	Calcium	99.9%	Silica	99.9%	Copper	99.9%	Sodium	99.5%
Cl	99.5%	Magnesium	99.9%	Sulphate	99.95%	Iron	99.9%	Manganese	99.9%

RO treatment technology ionic rejection rate - 2nd Pass

TDS	98%	Calcium	98%	Silica	98%	Copper	98%	Sodium	99%
Cl	99%	Magnesium	99.4%	Sulphate	99.3%	Iron	98%	Manganese	98%

EDI polishing technology ionic rejection rate

TDS	98%	Calcium	98%	Silica	50%	Copper	99%	Sodium	99%
Cl	99%	Magnesium	99%	Sulphate	99%	Iron	99%	Manganese	99%

Parameter	Stream Unit	1	2	3	4	5	6	7	8	9	10	11	11A	11B	11C	12	13	14	15	16	17	18	19	20	21
Flow	m3/hr	7.7204	7.682	0.050			7.73	7.68	0.58	0.58		7.7	0.35	8.03	3.456790123	4.57	3.11	1.11	2.00	1.00	0.11	4.68	0.58	0.00	4.10
Flow	ML/d	0.19	0.18	0.001	0.00	0.00	0.19	0.18	0.01	0.01	0.00	0.18	0.01	0.19	0.08	0.11	0.07	0.03	0.05	0.02	0.00	0.11	0.01	0.000	0.10
pH																									
H2SO4	mg/L			15.00																					
	kg/d			2.78																					
H2SO4 prepared conc	%w/w			98.0%																					
Lime	mg/L																								
	kg/d																								
Lime Sol Conc	g/L																								
CO2	mg/L																								
	kg/d																								
CO2 prepared conc	%w/w																								
FeCl3	mg/L				5																				
FeCl3 Sol Conc	%w/w				28.0%																				
Cationic polymer	mg/L																								
	kL/d @ 40%																								
Cat poly Soln Conc	%w/w																								
Turbidity	NTU	2.00	2.00				2.00	0.04	1.86			0.0004	0.0002	0.0004	0.0002	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.186	1.67	0.0002
TSS	mg/L	3.50	3.52				3.49463236	0.070352	45.80			0.0007	0.0008	0.0007	0.0009	0.0003	0.0001	0.0001	0.0001	0.0000	0.0001	0.0004	4.580	41.22	0.0004
	ton/d	0.00	0.00				0.00	0.00	0.001			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.000	0.00	0.0000
	%DS																							20%	0.00
TDS	mg/L	39500.00	39698.49				39439.42	39698.49	39439.42	65132.47		39698.49	39698.49	39698.49		66713.48	9.80	9.80	9.80	0.22	96.06	65132.47			65132.47
	ton/d	7.32	7.32				7.32	7.32	7.32	0.90		7.32	7.32	7.32		7.32	0.00	0.00	0.00	0.00	0.00	7.32			7.32
Conductivity	uS/cm2																		21.18	0.47					0.00
Calcium	mg/L	475.00	477.39				475.00	477.3869		783.28		477.39	477.39	477.39		802.31	0.03	0.03	0.03	0.00	0.25	783.28			783.28
	ton/d	0.09	0.09				0.09	0.09		0.01		0.09	0.09	0.09		0.09	0.00	0.00	0.00	0.00	0.00	0.09			0.09
Magnesium	mg/L	1500.00	1507.54				1500.00	1507.538		2473.53		1507.54	1507.54	1507.54		2533.66	0.03	0.03	0.03	0.00	0.29	2473.53			2473.53
	ton/d	0.28	0.28				0.28	0.28		0.03		0.28	0.28	0.28		0.28	0.00	0.00	0.00	0.00	0.00	0.28			0.28
Hardness	mg/L as CaCO3	1186.08	1192.04				1186.08	1192.04		1955.85		1192.04	1192.04	1192.04		2003.38	0.06	0.06	0.06	0.001	0.62	1955.85			
Chloride	mg/L	22000.00	22110.55				22000.00	22110.55		36277.50		22110.55	22110.55	22110.55		37158.73	2.73	2.73	2.73	0.030	27.02	36277.50			36277.50
	ton/d	4.08	4.08				4.08	4.08		0.50		4.08	4.08	4.08		4.08	0.00	0.00	0.00	0.00	0.00	4.08			4.08
Total silica	mg/L	2.50	2.51				2.50	0.05		0.08		0.05	0.05	0.05		0.08	0.00	0.00	0.0000	0.0000	0.00	0.08			0.08
	ton/d	0.00	0.00				0.00	0.00		0.00		0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.00
Sulphate	mg/L	3100.00	3115.58				3100.00	3115.58		5111.98		3115.58	3115.58	3115.58		5236.25	0.03	0.03	0.03	0.00	0.27	5111.98			5111.98
	ton/d	0.57	0.57				0.57	0.57		0.07		0.57	0.57	0.57		0.57	0.00	0.00	0.00	0.00	0.00	0.57			0.57
Copper	mg/L	0.002	0.00				0.00	0.00201		0.00		0.00	0.00	0.00		0.00	0.00	0.00	0.0000	0.00	0.00	0.00			0.00
	ton/d	0.00	0.00				0.00	0.00		0.00		0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.00
Iron	mg/L	0.03	0.03				0.03	0.030151		0.05		0.03	0.03	0.03		0.05	0.00	0.00	0.0000	0.000	0.00	0.05			0.05
	ton/d	0.00	0.00				0.00	0.00		0.00		0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.00
Sodium	mg/L	12300.00	12361.81				12300.00	12361.81		20282.42		12361.81	12361.81	12361.81		20775.11	1.53	1.53	1.53	0.017	15.11	20282.42			20282.42
	ton/d	2.28	2.28				2.28	2.28		0.28		2.28	2.28	2.28		2.28	0.00	0.00	0.00	0.00	0.00	2.28			2.28
Manganese	mg/L	0.01	0.01				0.01	0.00603		0.01		0.01	0.01	0.01		0.01	0.00	0.00	0.0000	0.00	0.00	0.01			0.01
	ton/d	0.00	0.00				0.00	0.00		0.00		0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.00
Agal cell count	cells/1ml	250.00					250.00	5																	

Parameter	Stream Unit	ASTM TYPE II WATER	COOLING WATER	TARGETTED CW QUALITY
TSS	mg/L		25.00	5.00
	ton/d			
	%DS			
TDS	mg/L	0.46	1500.00	300.00
	ton/d			
Conductivity	uS/cm2	1.000		
Calcium	mg/L			
	ton/d			
Magnesium	mg/L			
	ton/d			
Hardness	mg/L as CaCO3		500.00	100.00
Chloride	mg/L	0.005	300.00	60.00
	ton/d			
Total silica	mg/L	0.003	150.00	30.00
	ton/d			
Sulphate	mg/L		250.00	50.00
	ton/d			
Copper	mg/L		1.00	0.20
	ton/d			
Iron	mg/L		3.00	0.60
	ton/d			
Sodium	mg/L	0.005		
	ton/d			
Manganese	mg/L		0.10	0.02
	ton/d			
Agal cell count	cells/1ml			

SUPPLEMENTAL CALCULATIONS