Water Demand for Hydrogen Production

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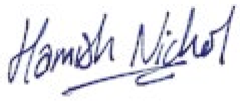
CS-NOW

Climate services for a net zero resilient world

Author(s)GR	Rhys Hart, Ricardo Jay Nyathi, Ricardo Shaifali Sood, Ricardo Maggie Adams, Ricardo Gwyn Rees, UKCEH Vicky Bell, UKCEH Helen Davies, UKCEH Ponnambalam Rameshwaran, UKCEH Majdi Mansour, BGS Marco Bianchi, BGS Setareh Nagheli, BGS Christopher Jackson, BGS
Peer reviewer(s)	Hamish Nichol, Ricardo & Gwyn Rees, UKCEH

Sign off



Sign off name	Gwyn Rees, UKCEH	Hamish Nichol, Ricardo
Sign off date	08 March 2024 v2.0	

About CS N0W

Commissioned by the UK Department for Energy Security and Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5.5 million research programme, that will use the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation ambitions.

CS-N0W aims to enhance the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It will contribute to evidence-based climate policy in the UK and internationally, and strengthen the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by **Ricardo** and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

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1. Executive Summary

The UK Department for Energy Security and Net Zero has commissioned Ricardo, the UK Centre for Ecology and Hydrology and the British Geological Survey as part of the CS-N0W consortium to establish the water demand of a future hydrogen economy and whether this can be accommodated given the current and future pressure on water resources within the UK.

This study has considered four raw water sources for use in the production of low-carbon hydrogen: potable water, groundwater, surface water and seawater. The use of water has been mapped for green hydrogen production via electrolysis and blue hydrogen production via steam methane reforming (SMR) coupled with carbon capture. Broadly, these fall into two categories, feedstock and cooling. Process water has the higher quality requirements. At a minimum electrolysis requires (equivalent to) ASTM Type II water. Boiler water requirements are outlined by ASME for use in SMR and are less stringent than electrolyser equivalents.

Water requirements have been established on a per kilogram of hydrogen basis for each hydrogen production technology considered with the assumptions of certain cooling technology requirements split and potential water resource split:

	Alkaline electrolysis	**PEM (Proton exchange membrane)**	**SOEC (Solid oxide electrolysis cell)**	**SMR w/CCUS (Steam methane reforming with carbon capture)**
Treated water demand (litres/kgH_2)	42.0	52.2	12.8	20.2

Further, the total water demand has been calculated for a range of hydrogen production scenarios in 2030 and 2035 and compared to overall nominal UK water availability and other industrial sectors. A snapshot of water requirements and demand for 2035 are detailed below:

	2035 surface water nominally available	**2035 ground water nominally available**	**2035 10 GW Hydrogen**	**2035 17 GW Hydrogen**
Fresh water (Mt/year)	68,030	18,200	34.9	58.5

Whilst the results indicate that, theoretically, overall, the UK possesses the necessary resources to meet the overall water requirements for hydrogen production, a multitude of variables can significantly influence water availability over time. A UK-scale approach will mask areas where there is no resource available or where it has very low reliability, or where there are environmental deficits and water rights are already being recovered to ensure sustainable use. It is therefore necessary to consider these figures as theoretical maximums. With real-world hydrogen production roll out, actual water availability will need to be considered at a regional and local level to ensure supply issues do not arise in the immediacy or in the future, and that any environmental impacts and the need to protect existing water rights are accounted for and properly mitigated.

Early engagement with environmental regulators on water needs for hydrogen projects is recommended.

2. Introduction

The impacts of climate change are increasingly being felt across the globe, hydrogen's potential as a clean energy vector is under growing scrutiny. While the extent of hydrogen uptake and the processes by which hydrogen is produced have both advantages and disadvantages, it is almost certain to play a role in the future energy system of the UK, with water being a key feedstock for any production facility.

Water is used not just in the production of hydrogen itself, but also for cooling. Water demand varies for a few key reasons: hydrogen production technologies have different process water requirements, they have different cooling duties, and different cooling technologies can be implemented to manage this heat.

Many of the studies and much of the modelling of hydrogen production to date is focussed on green hydrogen production and makes good account of electricity and energy use, but water demands have often been over simplified.

To establish the water demand for hydrogen production in the UK, the Department for Net Zero and Energy Security (DESNZ) asked the CS-N0W consortium to carry out a technical review of hydrogen production methods, cooling systems, water treatment requirements and the UK's hydrogen ambitions to develop water demand envelopes for 2030 and 2035. Information on surface water and groundwater availability has been provided by UK Centre for Ecology and Hydrology (UKCEH) and the British Geological Survey (BGS) and along with further context on these requirements.

3. Water Source Overview

This section summarises the different raw water sources considered for use in the production of low-carbon hydrogen, and details the treatment necessary to ensure they are fit for use and consumption in each process.

3.1 Introduction

For both blue and green[1] hydrogen production pathways, typically raw feedwater must undergo water treatment (including pre-treatment and water polishing). Pre-treatment and screening/filtering are first used to remove debris. More refined processes are then implemented to control for conductivity, hardness, total organic carbon (TOC), silica and gasses. This ensures the water meets cooling, boiler or electrolyser requirements. The byproduct of the treatment is a brine or sludge, depending on the source, which then must be disposed of appropriately.

Water used for process cooling requires the least intensive treatment, usually screening being sufficient. For this study boiler water treatment has been aligned requirements set out in ASME (ASME, 1994)[2], which is necessary to prevent long-term issues with the boiler or frequent maintenance. Water fed to any of the three electrolyser technologies is required to be at least ASTM (American Society for Testing and Materials) Type II (Atlas High Purity Solutions, 2019)[3] to prevent damage to the electrolyser and enable efficient electrolysis. While ASTM Type I is often preferred due to having finer conductivity specifications, Type II has been considered in this study.

[1] Green hydrogen denotes hydrogen produced from water electrolysis powered by renewables. Blue hydrogen denotes hydrogen produced by the steam reforming of natural gas with carbon capture.

[2] BS 2486:1997 (British Standards Institution, 1997) might also be used. Selection of standard has minimal impact on outputs of this work. A concise discussion of such standards is available (Cooper, 2022).

[3] Includes details of different water grades per ASTM and ISO

3.2 Water Treatment

Table 1 High-level summary of typical contamination levels for various raw water sources

Source	Particulate contamination	Dissolved organics	Mineral contamination	Total dissolved solids
Potable water	Low	Low	Low	Low
Surface water	High	High	Low	Low
Groundwater	Low	Low	Moderate-High	Low
Sea water	Low	Low	Low	Extreme

1. **Potable water treatment process**
   For use in a cooling system (single pass and evaporative cooling, see below), raw potable water requires no treatment. To meet standards for a boiler (ASME – American Society of Mechanical Engineers) the raw water passes through membrane filtration and thereafter is dechlorinated. After undergoing one pass through reverse osmosis the water can be fed to the boiler. For the water to be suitable for electrolysis a final step of electrodeionisation (EDI) or ion exchange, to reduce the content of ions is required.
2. **Surface water treatment process**
   For the use of single pass cooling, surface water must first undergo screening. A further pre-treatment removing suspended solids is required prior to feeding any water to evaporative cooling. One pass of reverse osmosis is needed to further treat the water to boiler quality. Finally, to treat the water to ASTM Type II (ASTM, 2017) quality (suitable for electrolysis), EDI or ion exchange is needed.
3. **Groundwater treatment process**
   Raw borehole water can be fed directly to a single pass cooling system. Thereafter, the water must undergo conventional pre-treatment or membrane filtration for evaporative cooling. A single pass of reverse osmosis is needed to increase the water quality for a steam boiler. Finally, EDI or Ion exchange is used to get the water to ASTM Type II quality.
4. **Sea water treatment process**
   Raw seawater must first be screened before it can be fed to a single pass heat exchanger. Membrane filtration will follow screening to treat the raw water to the quality required for evaporative cooling. A single pass of reverse osmosis is needed to ensure the water quality is adequate for boiler feed. A second pass of reverse osmosis followed by EDI/ion exchange are the final unit operations needed to get the raw water to ASTM Type II quality.

Water flows for each of these treatment steps are detailed in their respective raw water section.

3.3 Water Requirement for Cooling

Various cooling technologies might be used in hydrogen production depending on a number of factors such as the raw water available and plant location. Water used for process cooling system does not need to be of the same quality as is required for electrolysis, but some treatment is required depending on the water source and the cooling technology. The three cooling methods considered within this study are:

- Once-through water cooling (or single pass cooling): Single pass cooling takes place with the cooling fluid passing once through the system before being returned to the water course without any recirculation. Even small single pass cooling systems require large amounts of water. For this reason, this type of cooling has only been considered in the case of sea water. While it might be possible to use this technology along large rivers or where there is a plentiful supply of borehole water, the elevated return temperatures can have negative ecological impacts, so the assumption is it will mainly find use in future offshore or coastal green hydrogen facilities which will operate at multiple MW (or GW) scale.
- Evaporative cooling: This type of cooling employs the latent heat of vaporisation to absorb heat from the system. A small portion of water is lost through blowdown (non evaporative water losses), however the system requires much lower water flows than once-through cooling. As makeup water is added to compensate for the water lost, concentration of dissolved solids increases which can be detrimental to cooling performance, hence these systems require slightly more pre-treatment than once-through systems. Evaporative cooling has been considered for all water types within this study. The technology is applicable to hydrogen production systems from a few MW up to multiple MW (with a corresponding larger footprint).
- Air-cooling: Also called dry cooling systems as it requires no water for cooling. Ambient air is used to cool the working fluid instead of water. Given the focus of this study is on water use, this technology is not considered. This technology is most effective in cold and wet climates, however as plants increase in scale, the increased cooling load will likely prohibit widespread use of these systems.

3.4 Potable Water

Water Source Characteristics

Potable water ('tap water') is sourced from a retailer's distribution network, having been treated to drinking water standards. Potable water is characterised by having very low (as near as practical to zero) particulate and dissolved organic matter as it is removed during the treatment process by the retailer. The total dissolved solids (TDS) will be slightly variable but will generally be low to ensure the water is aesthetically acceptable. There will also be a residual disinfectant present, such as chlorine, to ensure the water is free of pathogens.

While circumstances vary by jurisdiction, there has been poor public reaction to hydrogen production facilities connecting to existing potable water supplies in some countries (Holder, 2023). This is generally because these supplies were designed to meet public (domestic) demand for water, and therefore and the use of these supplies for industrial purposes could place a strain on the system which needs to be managed. In the UK the Drinking Water Inspectorate provides independent reassurance that the UK tap water meets quality standards and there is international agreement on the standards required for drinking water and these have been documented by the World Health Organization, 2022. An indicative example for select parameters in potable water is shown in Table 2.

Table 2: Indicative potable water quality.

Parameter (*World Health Organization, 2022*)	**Min.**	**Mean**	**Max.**
Suspended solids (mg/L)[4]	0	0	< 1
Total dissolved solids (TDS) (mg/L)	100	250	600

Treatment Technology

While using potable water has a number of drawbacks, it does have the advantage that it is already very clean and minimal treatment is required. The water can be used without further treatment for cooling water, although using large volumes of cooling water from the potable network might require a network upgrade to accommodate higher flows.

Boiler feed water would need to be treated through a reverse osmosis (RO) system. Because the incoming water is low in contamination, this RO can operate at very high recovery in a single pass with low brine production (salt content of up to 200 mg/litre). To protect the RO membranes, it is prudent to include an ultra-filtration (UF) membrane (or equivalent) treatment step upstream of the RO. Additionally the water feed to the RO would need to be dechlorinated chemically prior to treatment.

To produce an ASME Type II quality water, the RO permeate would need to be deionised either by contact with an ion exchange (IEX) resin or using electrodeionisation (EDI). The selection of the process is dependent on the specific contaminant that needs to be removed. An example flowsheet for the use of potable water is shown below in Figure 1.

[4] Inferred from a turbidity limit of 0.5 NTU (Nephelometric turbidity unit).

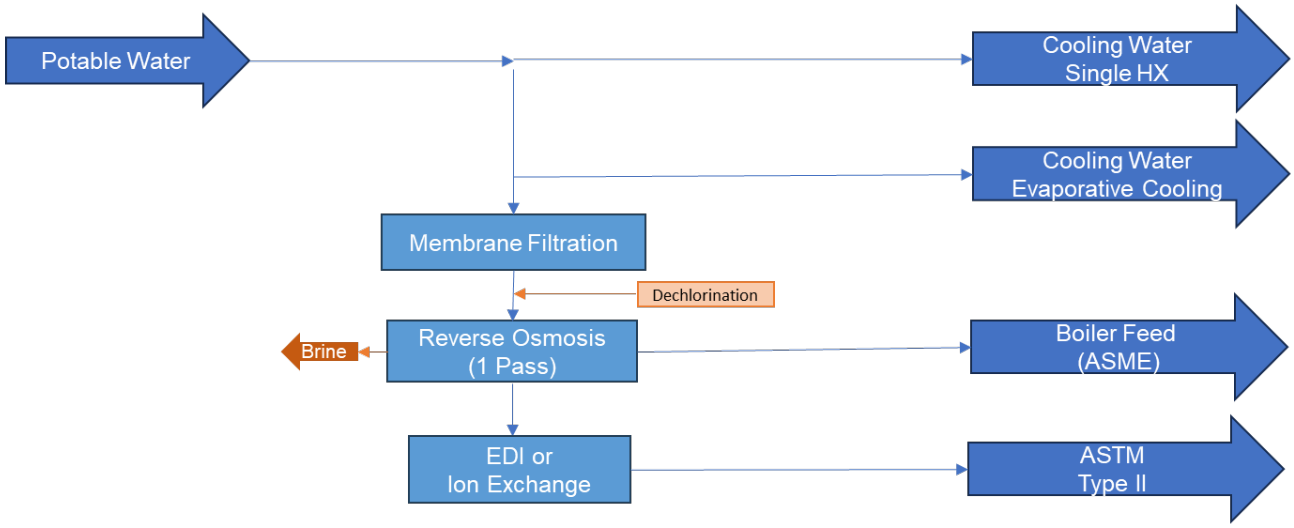

Figure 1: Example process flow diagram for the use of potable water in hydrogen production facilities.

Overview Mass Balance

In the case of potable water, the production of the mass balance can be considered consistent with the following basis:

- **Cooling Water (Single heat exchanger (HX)):** Used without further treatment. Overall, for 1 kg of cooling water (single HX), 1 kg of potable water is required.
- **Cooling Water (Evaporative Cooling):** Used without further treatment. Overall, for 1 kg of cooling water (evaporative cooling), 1 kg of potable water is required.
- **Boiler Feed (ASME):** Treatment through the UF membrane removes 100% of the suspended solids and operates at 95% water recovery. Treatment through the RO unit removes 98.5% of total dissolved solids (TDS) and operates at 70% water recovery. Overall, for 1.0 kg of boiler feed water (ASME), 1.5 kg of potable water is required.
- **ASTM Type II:** In addition to the UF and RO treatment, processing is required through the EDI unit which removes 98% of TDS and a water recovery of 90%. Overall, for 1.00 kg of ASTM Type II water, 1.67 kg of potable water is required.

3.5 Surface (River) Water

Water Source Characteristics

Surface water is sourced from a reservoir, river, dam or some other inland source. The quality of a surface water is highly influenced by the catchment which supplied the source. In the specific case of a river, this can vary along the length of the watercourse and as such it is difficult to make generalised predictions of quality, even within a single water body, let alone across the range of different surface water supplies. Water quality in surface water sources can be linked directly to extreme weather events with high rainfall, floods and bushfires presenting varied complications to predicting water quality.

Because of the nature of how rainfall runs over the catchment, surface waters can have high particulate contamination. If there is a large amount of decaying vegetable matter in the catchment, the water can also have a high amount of dissolved organic materials. Both TDS and mineral content is generally low, but again depends on the catchment.

Due to their continued exposure to sunlight, surface waters can be susceptible to algal blooms. This is particularly the case in reservoirs or slow flowing rivers when turbidity (the measure of particulate contamination) is low and nutrients are sufficiently high to sustain the growth of algal cells. In bodies that are prone to algal blooms, the treatment process needs to be tailored to remove algal cells. An indicative example for select parameters in surface water is shown in Table 3.

Table 3 Indicative surface water quality.

Parameter	Min.	Mean	Max.
Suspended solids (mg/L) (NSW Department of Planning and Environment, 2022)	0	40	275
TDS (mg/L)[5]	120	310	410

Treatment Technology

Due to the highly variable nature of surface waters, the treatment process employed must be sufficiently robust to cater for a wide-ranging set of scenarios. The first process step is some form of screening to remove material which could impact the downstream unit operations. The aperture of the screens will be driven by expected contaminants size. These could have different aperture sizes, ranging from bars to prevent clogging inlets down to small apertures with fine screens to avoid the entrainment of marine flora and fauna. Screened water should be suitable to supply some of the cooling water.

Any screened water not directed to cooling would need to be treated via a conventional treatment process. This would involve coagulating and flocculating the water with chemicals before removing the bulk of the particulate material through either sedimentation or flotation. The selection of sedimentation or flotation will depend on the prevailing characteristics of the material to be removed. Typically light, mostly dissolved material can be removed through flotation while heavier material can be removed through sedimentation. Both processes can generally be made to work by adjusting chemical dosing, but efficiency will be limited if the incorrect process is chosen. In rare instances, a

[5] Various references per pers. comms: Rees G to Hart R, 3 October 2023 (Rees, G).

sedimentation tank can be followed by a flotation process, but this would be specific to a supplier. After sedimentation or flotation, the water is filtered through a sand filter. This filtered water is suitable for high quality cooling water and should be of sufficient quality for a feed for an RO system.

The RO system can be a single pass as the TDS in the feed is very low. Similar to the case presented for potable water, RO permeate can be used for boiler feed water and ASTM Type II water can be further polished through an IEX or EDI process.

An example flowsheet for the use of surface water is shown below in Figure 2.

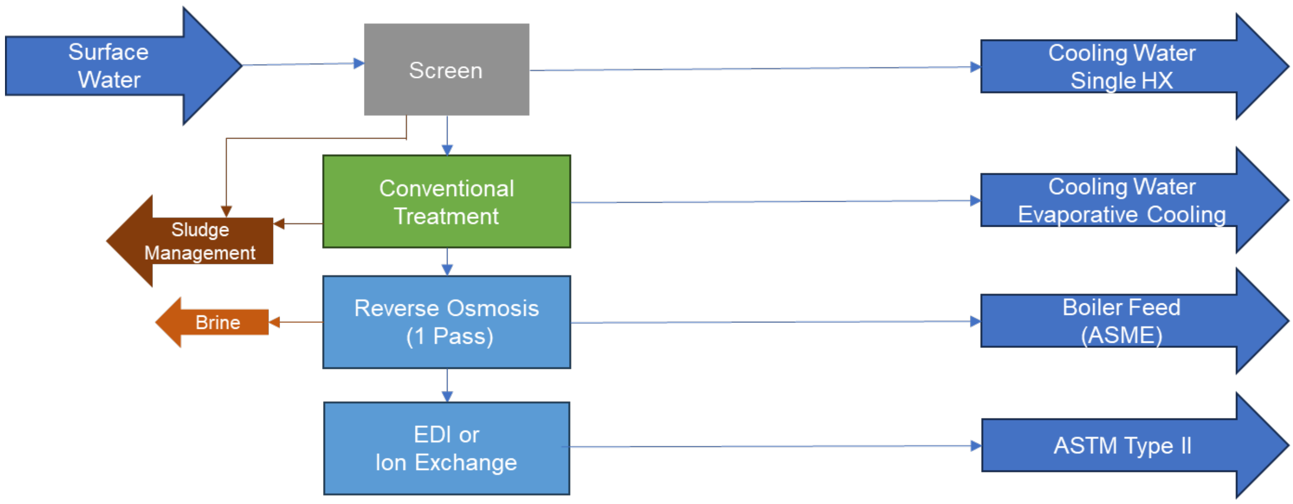

Figure 2: Example process flow diagram for the use of surface water in hydrogen production facilities.

Overview Mass Balance

In the case of surface water, the production of the mass balance can be considered consistent with the following basis:

- **Cooling Water (Single HX):** Treatment with just screening which does not remove any suspended solids or TDS and operates at 99.5% water recovery. Overall, for 1.000 kg of cooling water (single HX), 1.005 kg of surface water is required.
- **Cooling Water (Evaporative Cooling):** In additional to the screening, processing is required through conventional treatment which removes 100% of suspended solids and operates at 95% water recovery. Overall, for 1.00 kg of cooling water (evaporative cooling), 1.06 kg of surface water is required.
- **Boiler Feed (ASME):** In addition to screen and conventional treatment, processing is required through the RO unit which removes 98.5% of TDS and operates at 70% water recovery. Overall, for 1.00 kg of boiler feed water (ASME), 1.51 kg of surface water is required.
- **ASTM Type II:** In addition to the screen, conventional and RO treatment, processing is required through the EDI unit which removes 98% of TDS and a water recovery of 90%. Overall, for 1.00 kg of ASTM Type II water, 1.68 kg of surface water is required.

3.6 Groundwater

Water Source Characteristics

Groundwater is extracted from below ground aquifers. By its nature, ground water is highly variable and depends on local geological conditions, the structure of the aquifer, how it is recharged and the extraction methods. Although it is difficult to refer to any ground water as "typical" due to this variability, it is commonly low in solids and TDS. However, if the ground water is impacted by seawater or other saline sources, it can be high in TDS. It is not uncommon for ground water to have dissolved mineral contamination specific to the local aquifer and rock types it is in contact with. In the case of dissolved metals like iron and manganese, these can readily oxidised when the water is brought to the surface and can result in unsightly precipitates forming in the water.

Because of this variability in groundwater sources, depicting a typical groundwater quality is somewhat academic, however an indicative example for select parameters in groundwater water is shown in Table 4.

Table 4 Indicative groundwater quality.

Parameter	Min.	Mean	Max.
Suspended solids (mg/L)	N/A	N/A	N/A
TDS (mg/L) (Australian Government: Bureau of Meteorology, 2023)	170	N/A[6]	25,450

Treatment Technology

Groundwater is accessed by drilling a bore into the aquifers and pumping it to the surface. Screens are not required for the process as water at depth is generally free of gross solids. Raw untreated groundwater should be suitable for the use of cooling water single-pass processes. However, for other services it may require additional treatment depending on local conditions. The conditions of the ground water will dictate whether conventional treatment or UF is most efficient for an RO pre-treatment and for providing cooling water for evaporative cooling. Similar to the other water sources presented, RO and EDI (or IEX) will be required for further polishing treatment.

An example flowsheet for the use of groundwater is shown below in Figure 3.

[6] Data intended to show variability in measurements between bores and no attempt to find an average value has been undertaken.

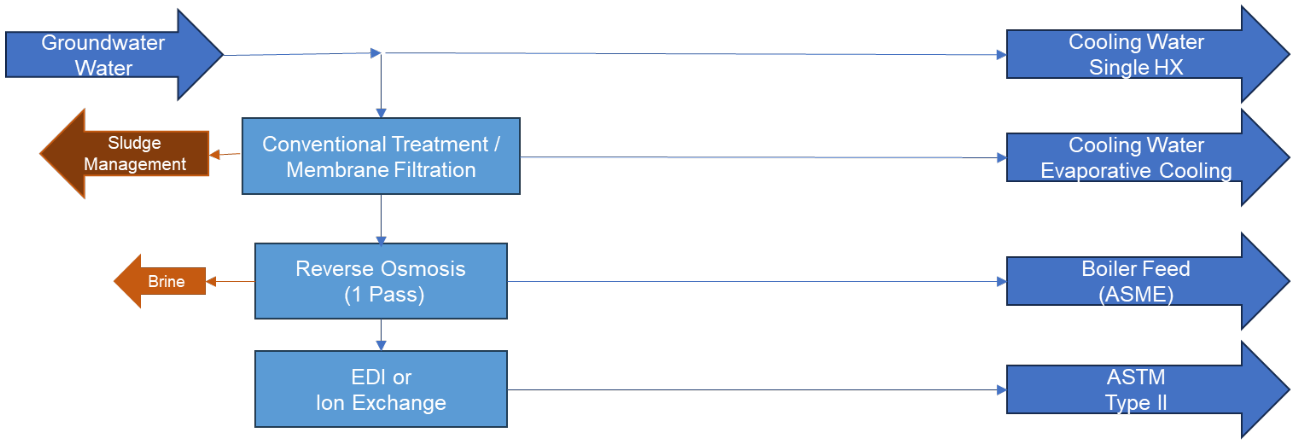

Figure 3: Example process flow diagram for the use of groundwater in hydrogen production facilities.

Overview Mass Balance

In the case of Ground water, the production of the mass balance can be considered consistent with the following basis:

- **Cooling Water (Single HX):** Treatment does not require screening or treatment and for 1 kg of cooling water (single HX), 1 kg of groundwater is required.
- **Cooling Water (Evaporative Cooling):** Treatment through conventional treatment which removes 100% of suspended solids and operates at 95% water recovery. Overall, for 1.00 kg of cooling water (evaporative cooling), 1.05 kg of groundwater is required.
- **Boiler Feed (ASME):** In addition to conventional treatment, processing is required through the RO unit which removes 98.5% of TDS and operates at 70% water recovery. Overall, for 1.00 kg of boiler feed water (ASME), 1.50 kg of groundwater is required.
- **ASTM Type II:** In addition to the conventional and RO treatment, processing is required through the EDI unit which removes 98% of TDS and a water recovery of 90%. Overall, for 1.00 kg of ASTM Type II water, 1.67 kg of groundwater is required.

3.7 Seawater

Water Source Characteristics

Seawater is sourced from the ocean, where it contains high level of dissolved solids consisting of sodium chloride ions. Its characteristics are generally consistent around the world with changes happening locally where bathymetry and flushing currents vary, and the degree of evaporation can impact the salinity. Shallow enclosed bays are particularly susceptible to higher salinity. For this reason, it is preferred to have seawater intakes located in a reasonable depth for consistency of feed water quality.

It may be possible to use seawater in cooling systems, especially in once-through systems, however it will require control of growing macro-organisms, such as molluscs, in the system as they can cause severe damage to the system by blocking pumps and reducing efficiency of the heat exchange.

To be able to use seawater for other applications, different treatments are required. The most common treatment is desalination through reverse osmosis, which is detailed further below. An indicative example for select parameters in seawater is shown in Table 5.

Table 5 Indicative seawater quality.

Parameter	Min.	Mean	Max.
Suspended solids (mg/L)[7]	< 1	5	<10
TDS (mg/L)[8]	34,400	34,500	35,000

Treatment Technology

The process required to treat seawater is shown below. The process begins with a screen to prevent molluscs and macro-contaminants from being entrained. Modern practice is to design screens with large apertures and low velocities. The low velocity allows marine creatures to swim around the screens without impact and prevent large foreign objects from being entrained. Any growth of macro-organisms within the intake tunnel are controlled via chlorine dosing or mechanical removal. Previous generation screening with exotic materials and fine apertures are no longer commonly used in the marine environment because of the degree of blinding which occurs.

Screened seawater may be suitable for use in a once-through heat exchanger without requiring additional treatment; aside from some chemical dosing to inhibit scale formation. Screened seawater is then treated through UF to remove suspended solids prior to RO treatment. The UF permeate can be used for evaporative cooling, provided the technology can handle the high TDS levels.

Due to extremely high TDS in the feed water, the RO treatment for seawater requires two passes of RO. The permeate of the first pass has the desired characteristics in TDS and suspended solids to be used as make-up water for a medium-pressure boiler feed according to the ASME standards. The permeate of the first pass is then treated again through a second pass with polishing in an EDI or IEX process to meet the ASTM Type II requirements.

An example flowsheet for the use of seawater is shown below in Figure 4.

[7] Ricardo sampling results, South Australia.
[8] Various references per pers. comms: Rees G to Hart R, 3 October 2023 (Rees, G).

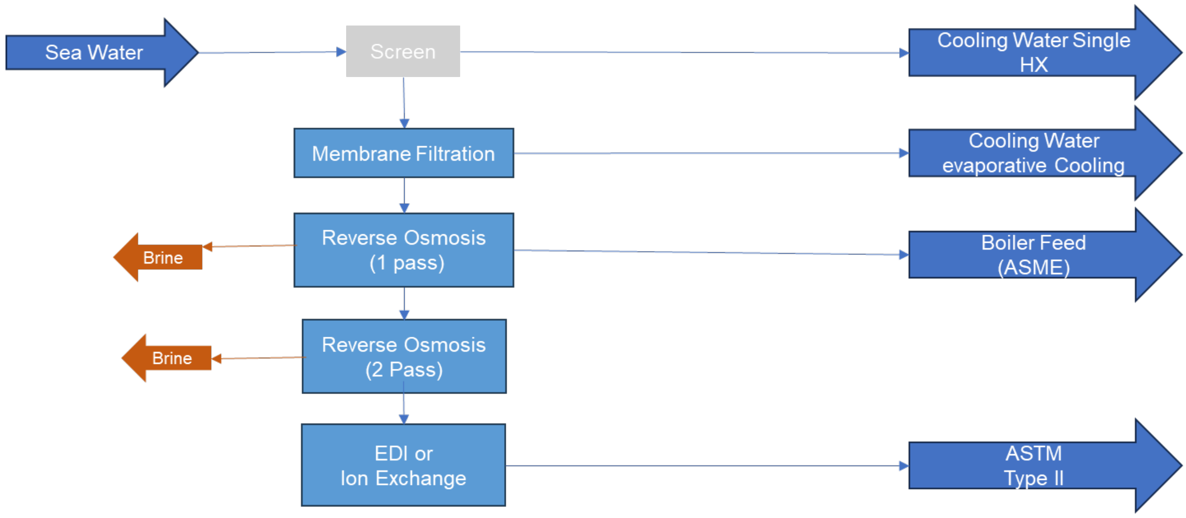

Figure 4: Example process flow diagram for the use of seawater in hydrogen production facilities.

Overview Mass Balance

In the case of seawater, the production of the mass balance can be considered consistent with the following basis:

- **Cooling Water (Single HX):** Treatment with just screening which does not remove any suspended solids or TDS and operate with at 99.5% water recovery. Overall, for 1.000 kg of cooling water (single HX), 1.005 kg of seawater is required.
- **Cooling Water (Evaporative Cooling):** Treatment through conventional treatment which removes 100% of suspended solids and operates at 95% water recovery. Overall, for 1.00kg of cooling water (evaporative cooling), 1.06 kg of seawater is required.
- **Boiler Feed (ASME):** In addition to conventional treatment, processing is required through a single pass RO unit which removes 98.5% of TDS and operates at 40% water recovery. Overall, for 1.00 kg of boiler feed water (ASME), 2.64 kg of seawater is required.
- **ASTM Type II:** In addition to the first pass RO treatment a second pass is required to be able to send it through the EDI unit, which removes 98.5% and 98.0% of TDS, respectively with a water recovery of 90% in each unit. Overall, for 1.00 kg of ASTM Type II water, 3.27 kg of seawater is required.

Table 6 summarises the raw water required to produce one kilogram of treated water at each specified grade.

Table 6 Multipliers for water mass balance in hydrogen production[9]

	Feed Water Required Per Unit Production by Source (kg/kg)			
	Cooling Water (Evaporative Cooling)	Boiler Feed (ASME)	ASTM Type II (Electrolyser feed)	Cooling Water (Single HX)
Potable water	1.00	1.50	1.67	1.000
Surface water	1.06	1.51	1.68	1.005
Groundwater	1.05	1.50	1.67	1.000
Seawater	1.06	2.64	3.27	1.005

[9] Figures based on analysis by Ricardo

4. Hydrogen Production Overview

This section summarises the different hydrogen production technologies. It provides an overview of key technology parameters and assumptions used in the modelling of water required for each process.

4.1 Introduction

The production of low-carbon hydrogen at commercial scale is currently considered to have two viable long-term routes: electrolysis of water from renewable sources (green hydrogen) and steam reforming of natural gas with carbon capture, utilisation and storage (CCUS) (blue hydrogen).

The production of green hydrogen requires two primary feedstocks: renewable electricity and water. Electrolysis is a well-established technology with decades of use in industry. Its use for the production of hydrogen is not novel, however the forecast scale of deployment is. Alkaline, proton exchange membrane (PEM) and solid oxide electrolysis cell (SOEC) are the three electrolyser technologies commonly considered frontrunners. Alkaline and PEM are seeing deployment at scale today as mature technologies, while SOEC is still undergoing development but shows promise in terms of greater efficiency.

The most common hydrogen production method used today is steam methane reforming (SMR). With approximately 95% of all hydrogen produced today via SMR, it is every bit as technologically mature as any of the green hydrogen technologies. However, in reforming the natural gas, carbon dioxide is released to the atmosphere, so development is underway to include carbon capture, utilisation, and storage (CCUS) into the plants to reduce, but not entirely eliminate, the carbon dioxide emissions. While CCUS is operational across different process, mainly seeing use in enhanced oil recovery in upstream oil & gas. CCUS plants can be highly bespoke, with designs varying between technology suppliers and processes. The numbers provided herein are those available from literature and present a more general envelope than the relatively specific numbers available for green hydrogen produced via electrolysis.

4.2 Alkaline Electrolyser

For green hydrogen production, alkaline electrolysis is the most mature technology today. These electrolysers are a low-temperature, electrochemical water splitting technology. The water is split to produce the hydrogen and oxygen gas, and used to replenish the electrolyte solution. The electrolysers use a concentrated alkaline electrolyte solution also called lye.

The gas-liquid lye mixture from anodic and cathodic chambers of the electrolyser stack is separated in two gas separators downstream. Hydrogen and oxygen gas then exit from their respective separators, the gas is dried and then leaves the electrolyser for use. The electrolyte from the gas separators is collected in a small buffer tank. Additional water is added to lye tank to replenish the water consumed during electrolysis. The outlet stream from the buffer tank is pumped and cooled in a heat exchanger and is returned to the electrolyser stacks. The

As a minimum, alkaline electrolysers require ASTM Type II water as a feedstock. While ASTM Type I water is preferable, alkaline electrolysers are generally less sensitive to impurities compared to PEM electrolysers.

The tables below offer a summary of the technical characteristics of alkaline electrolysis as well as the water requirements based on various feed types.

Table 7 Technical data related to alkaline electrolysis

Parameter	**Efficiency (LHV)**	**Power efficiency**	**Load range**	**Start-up time**	**Ramp rate**
Unit	%	kWh/kgH_2	% of nominal load	min	%P_{rated}/sec
Alkaline	63-70	47.6-60.0	15-100	15-90	0.2-20.0

Table 8 Technical data related to alkaline electrolysis (continued)

Parameter	**Technology readiness level**	**Operating pressure**	**Operating temperature**	**Rare material requirement**	**Load flexibility (For direct wire to wind/solar)**
Unit	TRL	bara	°C	-	Rating
Alkaline	9	1-30	30-90	No need for noble metal catalysts	Less than PEM

The hydrogen produced with alkaline electrolysers requires significant post-production processing to separate hydrogen and oxygen. Water used in the electrolysis process is higher for alkaline electrolyser systems than for PEM systems, however, cooling water requirements are lower. If a once through (single pass) cooling system were employed for an alkaline electrolyser with water as the cooling medium, dependent upon heat exchanger design, a 10-15°C rise in water temperature would necessitate over 1200 litres of treated water per kilogram of hydrogen produced (ARUP, 2022). A similar cooling system used to cool a PEM electrolyser would require over 1800 litres of treated water per kilogram of hydrogen produced.

Generally, alkaline electrolysers require 11 litres[10] of process water per kilogram hydrogen for direct use in the electrolyser and 31 litres of water per kilogram of hydrogen (assuming a dry climate) for use in the evaporative cooling system (ARUP, 2022). For this study feedwater to the electrolyser has been assumed to be deionised water (ASTM Type II, minimum), while the cooling water is of a lower grade often simply undergoing coarse screening. Literature values for water use in green hydrogen production using alkaline electrolyser have been found in the *Water for Hydrogen* report produced by Arup in collaboration with the Australian Government and Australian Hydrogen Council as well as *Environmental Constraints in Industrial Clusters Humber Pathfinder Project* report by Environment Agency (EA). A comprehensive review of both papers found the methodology and assumptions used to be rigorous, and their ultimate findings of excellent quality. Table 9 below details the water consumption as reported in the *Water for Hydrogen* report.

Table 9 Water requirement for feed and cooling in green hydrogen production with alkaline electrolyser

Type of water	Electrolyser raw water requirement (l/kgH_2)	Evaporative cooling raw water requirement (l/kgH_2)	Total raw water requirement (l/kgH_2)
Potable water	18.37[11]	31.00	49.37
Surface water	18.48	32.86[12]	51.34
Groundwater	18.37	32.55	50.92
Seawater	34.10[13]	32.86[14]	66.96

[10] Throughout this study the density of water has been taken as 1,000 kg/m^3, hence 1 litre of water being equivalent to 1 kg of water.
[11] Potable water requirement of 20 l/kg is given in hydrogen supply chain evidence base - EA Environmental Constraints in Industrial Clusters Humber Pathfinder Project
[12] Freshwater requirement is 40 l/kg based on Discussion on Water Consumption in Hydrogen Production PA Consulting
[13] EA specifies total seawater requirement as 30 l/kg out of which 13 l in consumed in the production process and remaining is returned - EA Environmental Constraints in Industrial Clusters Humber Pathfinder Project
[14] Saline water requirement for cooling 60 l/kg and only 20 litre is consumed rest is returned as wastewater- Response from Uniper Hydrogen UK Limited to the EA questionnaire EA report

4.3 PEM

The use of PEM electrolysers began in the 1960s and they are now one of only two commercially available electrolysis technologies (TRL 9) for hydrogen production, holding the second highest global installed electrolyser capacity. PEM electrolysers use a solid polymer (plastic) as the electrolyte. Water reacts at the anode and hydrogen ions selectively move across the polymer to the cathode. PEM electrolysis is ideal for flexible operation which works well with intermittent renewables. The tables below (10 and 11) offer a summary of the technical characteristics of PEM electrolysis as well as the water requirements based on various raw water types.

Table 10 Technical data related to PEM electrolysis

Parameter	Efficiency (LHV)	Power efficiency	Load range	Start-up time	Ramp rate
Unit	%	kWh/kg H_2	$\%P_{rated}$	minutes	$\%P_{rated}$/sec
PEM	56-63	50.4-59.5	10-100	<5-30	<=15

Table 11 Technical data related to PEM electrolysis (continued)

Parameter	Technology readiness level	Operating pressure	Operating temperature	Rare material requirement	Load flexibility (For direct wire to wind/solar)
Unit	TRL	bara	°C	-	Rating
PEM	9	<70	50-80	Platinum, iridium,	Excellent

As with alkaline electrolysers it has been assumed that PEM electrolysers require feedwater at ASTM Type II quality at a minimum. The electrolysis process consumes 9.2 litres of water per kilogram of hydrogen produced. For evaporative cooling approximately 43 litres of water are consumed per kilogram of hydrogen. Table 12 details the water consumed per kilogram of hydrogen in PEM electrolysis for a variety of water sources, again using the *Water for Hydrogen* report as a basis.

Table 12 Water requirement for feed and cooling in green hydrogen production with PEM electrolyser

Type of water	Electrolyser raw water requirement (l/kgH_2)	Evaporative cooling raw water requirement (l/kgH_2)	Total raw water requirement (l/kgH_2)
Potable water	15.36	43.0	58.4
Surface water	15.46	45.6	61.0
Groundwater	15.36	45.2	60.5
Seawater	28.52	45.6	74.1

4.4 SOEC

SOEC differs from alkaline and PEM electrolysis in that it requires higher operating temperatures, however, it is expected that in future this will enable better efficiencies. Solid oxide electrolysers make use of ceramic as an electrolyte which at elevated temperatures can selectively conduct oxygen from the cathode to the anode. To achieve elevated temperatures, water is fed to the system as steam. Steam can either be produced specifically for the process, however it is more cost effective and overall efficient to use waste heat or low-grade steam from other sources. There are no other water requirements for the technology outside of steam production. It can be assumed that to produce one kilogram of hydrogen, approximately 12.8 litres of water are required for the SOEC process (Sunfire GmbH, 2023). Of the 12.8 litres, 9.0 litres is used in electrolysis, with the 3.8 litre uplift a simple surplus which is not consumed and can be reused.

The following tables (13 and 14) detail the technical aspects of SOEC.

Table 13 Technical data related to SOEC electrolysis

Parameter	Efficiency (LHV)	Power efficiency	Load range	Start-up time	Ramp Time (hot idle)
Unit	%	kWh/kg H_2	% of nominal load	minutes	minutes
SOEC	74-84	52.9-49.0	20-100	>60	<10

* Data taken from a confidential Ricardo report that analysed a large set of open-source data relating to SOEC

Table 14 Technical data related to SOEC electrolysis (continued)

Parameter	Technology readiness level	Operating pressure	Operating temperature	Rare material requirement	Load flexibility (For direct wire to wind/solar)
Unit	TRL	bara	°C	-	Rating
SOEC	7	1	600-1000	Zirconium, samarium, lanthanum & cerium	Not ideal (*but depends on application*)

* Data taken from a confidential Ricardo report that analysed a large set of open-source data relating to SOEC

As the SOEC system operates at high temperatures, no cooling duty is required. Table 15 details the required raw water quantities to produce 12.8 litres of water per kilogram of hydrogen of Type II ASTM water for use within the electrolyser.

Table 15 Water requirement for feed and cooling in green hydrogen production with SOEC electrolyser

Type of water	Electrolyser raw water requirement (l/kgH_2)	Evaporative cooling raw water requirement (l/kgH_2)	Total raw water requirement (l/kgH_2)
Potable water	21.4	N/A	21.4
Surface water	21.5	N/A	21.5
Groundwater	21.4	N/A	21.4
Seawater	39.7	N/A	39.7

4.5 SMR with CCUS

SMR plants are usually co-located with significant hydrogen users ('offtakers') and have been the main pathway for hydrogen production for decades. CCUS systems are not as well established technologically. While several CCUS technologies exist at TRL 9 and follow similar key principles, the plants themselves are often highly bespoke. Consequently, it is simpler to consider the water requirement for SMR and carbon capture in blue hydrogen production independent of one another.

In the SMR process, feedstock water is used for steam reforming of natural gas and water gas shift (WGS) reaction. Feed water might be used to produce steam or be returned as a waste stream as part of boiler blowdown. Additionally, water used to produce steam must undergo deaeration to remove oxygen. While water used for steam generation must be purified, it does not require deionization. Water used for boiler blowdown and deaeration account for an uplift of approximately 15% of total water consumption in steam generation. The energy required for the steam generation is provided by the heat generated by the WGS reaction (exothermic) and by the combustion of additional natural gas in the steam reformer furnace.

The carbon capture process requires cooling for the sorbent condenser (monoethanolamine (MEA) is taken as a basis) and for CO_2 compression. The sorbent condenser has the highest cooling requirement in the process. Using MEA, the solvent absorbs CO_2 in an exothermic reaction. The regenerated lean MEA is cooled in the MEA to MEA heat exchanger and then further reduced in temperature in the MEA cooler. Note that low temperature and high pressure favour the absorption of CO2 in MEA. The system cooling is provided by cooling water exchanging heat with the process streams at the condenser and the MEA cooler.

Table 16 Technical data related to SMR with CCS

Parameter	Plant Efficiency (HHV)	Carbon Capture Rate	Carbon Emissions after Capture	Carbon capture technology	Catalysts
Unit	%	%	$kgCO_2/kgH_2$	Process	Materials
SMR with CCS (2020)	73.8	50-90	3.0[15]	MEA or MDEA (activated methyl diethanolamine)	Typically, nickel, but also platinum group metals

[15] This is higher than the UK Low Carbon Standard of 2.4 $kgCO_2$ kgH_2

The Environmental Agency (EA) indicates a requirement of 4.7 litres of raw water per kilogram hydrogen for production and 5.5 litres of raw water per kilogram hydrogen for cooling in the SMR process, however the method of cooling is not specified[16]. A report from the EA provides annual water consumption for a 720 MW blue hydrogen plant in the UK detailed in Table 17 .

Table 17 Annual consumptive water requirement for feed and cooling in blue hydrogen production in UK

Process	Water type (as specified by report)	Annual consumption (Mm^3/year)	Corresponding water requirement (l/kgH_2)
Production	Demineralised water	1.53	8.9
Production	Non-potable water	2.10	12.2
Production	Sea water	2.10	12.2
Cooling	Raw water	1.53	8.9

The *Water for Hydrogen* reports a combined water consumption for SMR and carbon capture. It has similar raw water requirement for wet and dry zones for different water types. In the process, water losses account for additional 15% water consumption compared to stoichiometric water demand of 4.5 litres of feedstock water per kg hydrogen. Additional treated water for intermittent blowdown of the steam cycle water and utilised as feedstock water for the deaerator is 0.6 litres per kilogram of hydrogen.

As per the report, total specific cooling requirement in the carbon capture and compression is 34.4 MJ/kg which is equivalent to 202 litres of water per kilogram of hydrogen[17]. Cooling water consumption using evaporative water cooling is 15 litres of water per kilogram of hydrogen in a wet zone. For once through cooling system using sea water the requirement is 1,170 litres of water per kilogram of hydrogen[18].

[16] Beyond steam production, additional water is required for blowdown and deaeration
[17] Specific cooling requirement is 34.4 MJ per kilogram of hydrogen produced, considering allowed temperature increase of 40°C and specific heat of water is 4.2 J/g°C. This requirement will increase if small increase in temperature is allowed. This happens in the case where seawater is used for cooling.
[18] Based on EA Environmental Constraints in Industrial Clusters Humber Pathfinder Project report

Table 18 Water requirement for feed and cooling in blue hydrogen production

Types of water	Process water requirement for SMR (l/kgH_2)	Evaporative cooling requirement for carbon capture (l/kgH_2)	Blue hydrogen plant total raw water requirements (l/kgH_2)
Potable water	7.80[19]	15.00	22.80
Surface water	7.85 (ARUP, 2022)[20]	15.90	23.75
Groundwater	7.80 (ARUP, 2022)[21]	15.75	23.55
Seawater	13.05 (ARUP, 2022)[22]	15.90[23]	28.95

The report published by EA, the findings of which are summarised in Table 17 , indicates the total water consumption of a blue hydrogen plant but does not provide the water requirement for SMR and carbon capture process independently. The report published by the Australian Government, the Australian Hydrogen Council and Arup contains the standalone usage of water in the two processes, considering water used for the hydrogen production process and cooling needs. The latter is more suitable for estimating the water demand for blue hydrogen plant and has subsequently been used in our calculations.

[19] EA reports a higher value of 8 l for demineralised water and 11 l for potable water per kg hydrogen.
[20] Arup reports surface water requirement of 8.6 l/kgH_2 for process water
[21] Arup reports ground water requirement of 9.9 l/kgH_2 for process water
[22] Arup reports ground water requirement of 14.3 l/kgH_2 for process water. Another source has seawater requirement for reforming at 25 l/kgH_2 from which 11 litres is used and the rest is returned (EA)
[23] Based on responses from Uniper Hydrogen UK Limited sea water consumption for cooling in blue hydrogen production process is 20 l/kgH_2 - EA report

5. Determination of Water Requirements

This section details the methodology and key assumptions applied in determining the water consumed for hydrogen production in the UK in 2030 and 2035.

5.1 Modelled Scenarios

Hydrogen water requirements are calculated assuming a mix of hydrogen ambitions for 2030 and 2035, as agreed with DESNZ. Six baseline scenarios have been modelled:

Table 19 Modelled Hydrogen Production Scenarios

Scenario	1	2	3	4	5	6
Year	2030	2030	2035	2035	2035	2035
Green H_2 Capacity (GW)	5.0	8.0	5.0	8.0	8.5	13.6
Blue H_2 Capacity (GW)	5.0	2.0	5.0	2.0	8.5	3.4
Total H_2 Capacity (GW)	10	10	10	10	17	17

Scenarios 1, 2, 4 and 6 assume early adoption and build out of hydrogen capacity, with use cases including industrial heat and potentially heating for homes. Scenarios 3 and 4 represent a steadier build out through 2035 where use cases are more limited.

5.2 Load Factors and Process Efficiencies

The production of hydrogen is constrained by process efficiencies and load factor[24], both of which are inherently linked to their respective technology.

The production of green hydrogen is dependent upon renewable generation (wind and solar), meaning lower load factors apply. Process efficiency varies by electrolyser technology with improvements expected over time. These efficiencies have been taken from the *BEIS 2021 Hydrogen Production Costs* report (Department for Business, Energy & Industrial Strategy, 2021) annex. A breakdown is given in the table below. For this study a load factor of 0.5 has been used.

[24] Load factor is the ratio of electricity/hydrogen generated in a given time of period to the product of maximum (or rated) load and number of hours of operation

Table 20 Hydrogen Production System Efficiencies

Total Process Efficiency	Alkaline (kWh_e /kWh_{H2})	PEM (kWh_e /kWh_{H2})	SOEC* (kWh /kWh_{H2})	Alkaline (%)	PEM (%)	SOEC (%)
2030	1.25	1.27	1.32	79.9	78.7	75.5
2035	1.24	1.25	1.24	80.6	79.9	81.0

**SOEC has both an electrical and thermal component*

Blue hydrogen is typically assumed to have a high load factor as SMR processes run continuously, with downtime predominantly for scheduled plant maintenance. Process efficiency is a measure of energy content of hydrogen produced against the energy consumed in the production of the hydrogen. This is a thermal efficiency measured by the natural gas consumed in the process and boiler operation. A load factor of 0.95 has been applied. The BEIS 2021 Hydrogen Production Costs report has been used for process efficiency, taken as fixed for 2030 and 2035 at 1.355 kWh input / kWh hydrogen produced (η = 73.8%).

5.3 Hydrogen Technology Split

For simplicity, the three electrolyser types outlined previously are assumed to take 100% of market share in 2030 and 2035, although it is acknowledged other types of electrolyser might emerge in the next decade. For 2030 a technology split of 75:25 has been assumed for alkaline:PEM. As SOEC are still undergoing development, their contribution is expected to increase through 2030 but remain marginal overall. By 2035 a technology spit of 60:30:10 has been assumed for alkaline:PEM:SOEC, roughly aligning with those predicted in the most recent 2023 Global Hydrogen Review from the IEA (IEA, 2023).

Table 21 Green Hydrogen Technology Split

Scenario	1	2	3	4	5	6
Alkaline Capacity (GW)	3.75	6.00	3.00	4.80	5.10	8.04
PEM Capacity (GW)	1.25	2.00	1.50	2.40	2.55	4.02
SOEC Capacity (GW)	0.00	0.00	0.50	0.80	0.85	1.34
Total Green H_2 Capacity (GW)	5.0	8.0	5.0	8.0	8.5	13.4

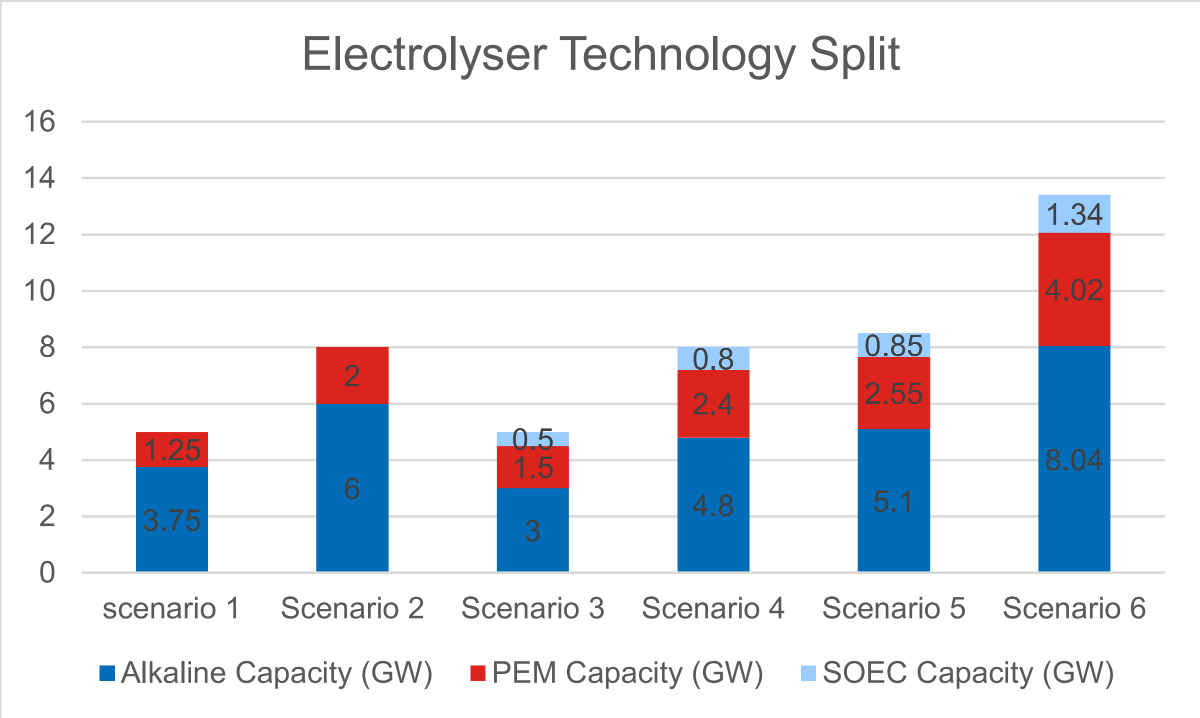

Figure 5 Electrolyser technology split by scenario

5.4 Cooling Technologies

While multiple cooling technologies might be considered for hydrogen production, three most common have been considered within the scope of this report: evaporative cooling, air cooling and once through cooling.

Air cooling limits water abstraction to the water consumed directly in producing the hydrogen. As cooling is via sensible heat, usually in dry cooling towers, the footprint of the cooling plant is larger than that of evaporative and once-through cooling systems, and typically more expensive. This technology works best in colder climates and at lower production scales. Its use in high-capacity plants is questionable.

Evaporative cooling also uses cooling towers, however as heat transfer to the environment is driven by latent heat, sizing will be smaller than for a dry cooling tower of equal duty. Again, the technology works best in dry and cold climates, but this technology will be a better fit for mid to large scale plants. The water which evaporates to cool the process is abstracted.

Once-through cooling uses more traditional heat exchangers to remove heat from a process. As cooling is via sensible heat, water flows are orders of magnitude higher than for evaporative cooling, however all water can be returned to the water course albeit at a higher temperature. This technology is widely applied in the process industries, and it is expected to be a good fit for many of the mid and large-scale hydrogen production plants, but the water flows required are likely to limit it to use of surface water and seawater.

Choice of cooling technology will depend on several factors, including plant size, available water flows, environmental restrictions, low-carbon production technology and specifics of plant-design. There is no simple selection process such as plant capacity on which to base this selection, and like the rest of the process will, for early projects, likely be somewhat bespoke.

5.5 Raw Water Sources

Four raw water sources have been considered for each of the hydrogen production methods: potable, surface water, groundwater, and seawater. While the number of projects expected to draw from each of these is currently poorly defined, a representative split has been applied to understand the impact that hydrogen production might have on each source.

Table 22 Modelled Raw Water Split

	Hydrogen generation utilising potable water (%)	Hydrogen generation utilising surface water (%)	Hydrogen generation utilising groundwater (%)	Hydrogen generation utilising seawater (%)
2030	30	35	30	5
2035	15	35	30	20

A relatively even split is anticipated for 2030 as projects utilise water sources that are most readily available. As the use of seawater generally entails higher capital investment, this is eschewed. By 2035 however, a more developed technology landscape is expected to bring down hydrogen production costs, and this coupled with a better awareness of water resource management will see projects shift towards the use of seawater as a feedstock and cooling medium. It should be noted the numbers selected here are arbitrary as their purpose is simply to illustrate a potential demand scenario.

6. National Water Requirements for Hydrogen

This section considers the UK's hydrogen ambitions for 2030 and 2035, along with a forecast split of blue and green hydrogen technologies across each country. This is used to determine total water demand in each region for these years.

6.1 Findings

Figure 6 through Figure 9 provide a breakdown of the water demands for each hydrogen production scenario detailed in Table 19. A more detailed breakdown of these figures can be found in Table 23.

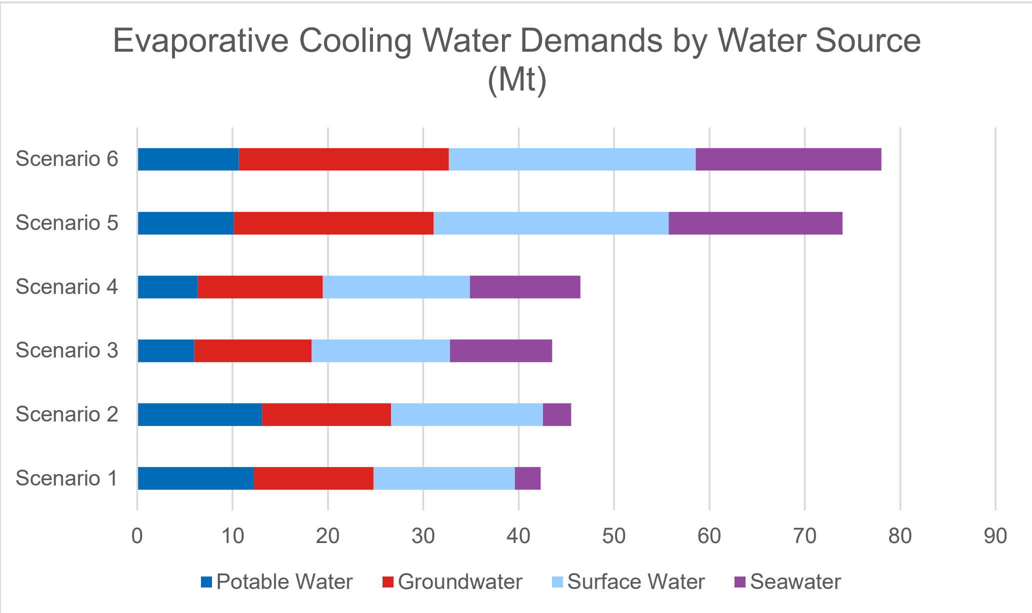

Figure 6 Evaporative cooling water demands by water source

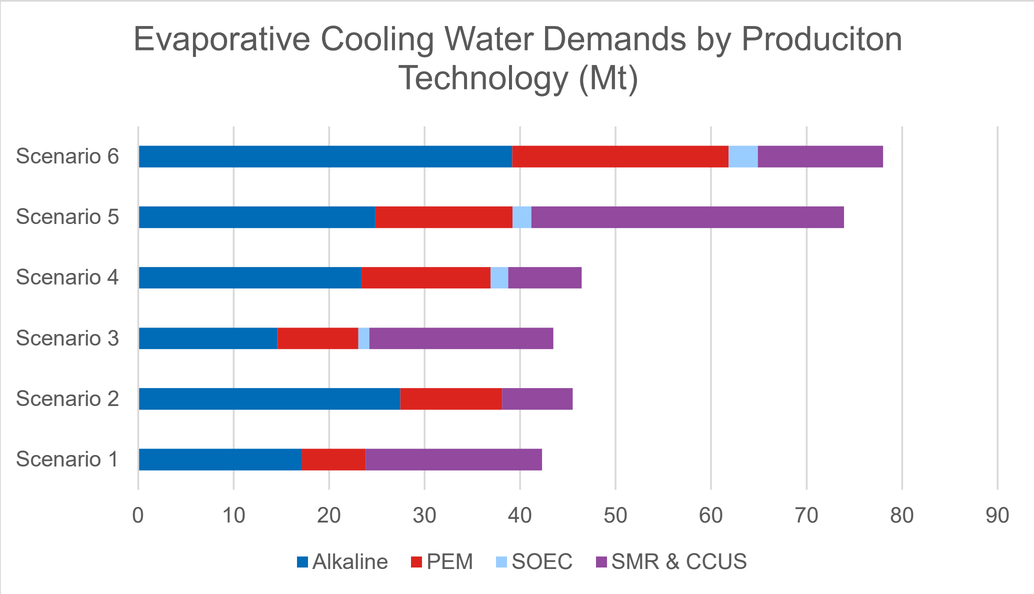

Figure 7 Evaporative cooling water demands by hydrogen production technology

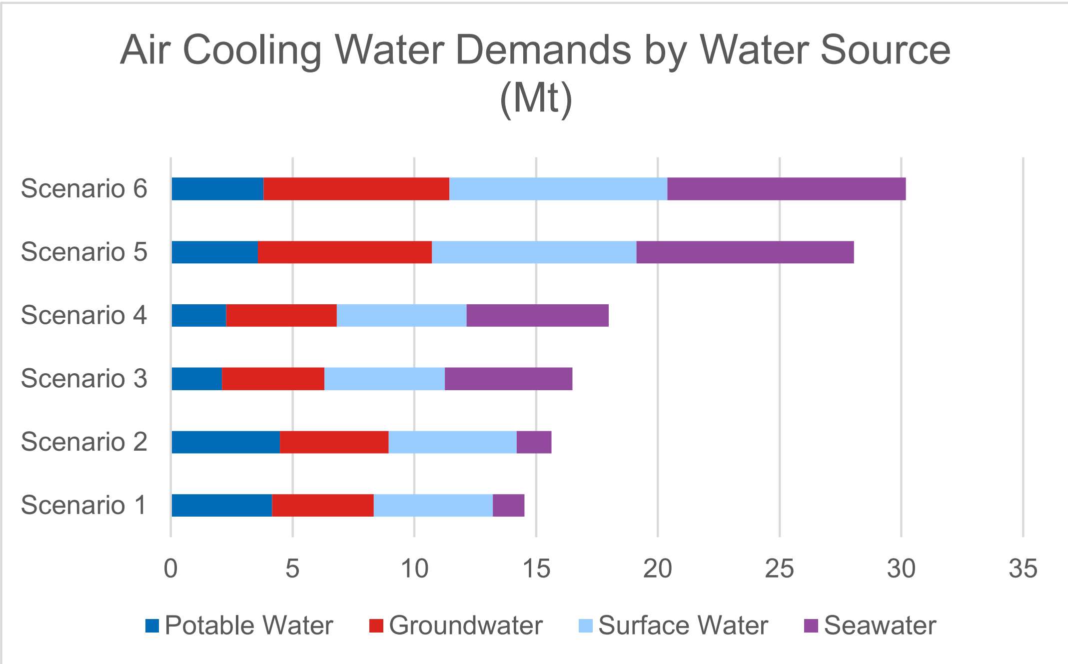

Figure 8 Air cooling water demands by water source

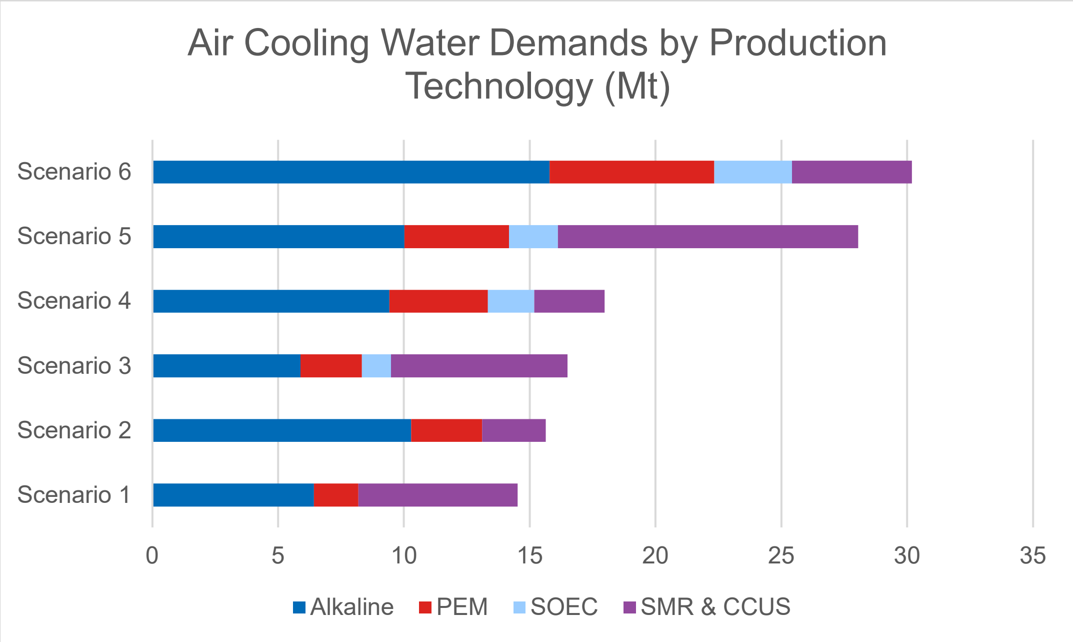

Figure 9 Air cooling water demands by hydrogen production technology

Table 23 Raw water demands for hydrogen production within the UK

Scenario	1	2	3	4	5	6
Evaporative cooling total water consumed (Mt)	42.3	45.5	43.5	46.5	73.9	78.0
Evaporative cooling fresh water consumed (Mt)	39.6	42.5	32.8	34.9	55.7	58.5
Evaporative cooling seawater consumed (Mt)	2.7	3.0	10.7	11.6	18.2	19.5
Air cooling total water consumed (Mt)	14.5	15.6	16.5	17.9	28.1	30.2
Air cooling fresh water consumed (Mt)	13.2	14.2	11.3	12.2	19.1	20.4
Air cooling seawater consumed (Mt)	1.3	1.4	5.2	5.7	9.0	9.8

By these estimates the highest quantity of water abstraction occurs under scenario 6 and for evaporative cooling, in which 78 million tonnes of water would be required, 58.5 Mt from freshwater sources (potable water, groundwater and surface water) and 19.5 Mt from seawater.

Comparatively, the UK water industry treats approximately 5,600 million tonnes of water per year (Water UK, 2023). Table 24 details the nominal annual available surface water and groundwater resources predicted for each nation within the UK in 2030 and 2035. It should be noted surface water estimates are inclusive of groundwater. The predicted demand of 78 Mt per year for scenario 6 (evaporative cooling) in 2035 represents 0.4% of total annual groundwater predicted to be available on the British mainland in 2035 and 0.1% of total annual useable surface water on the mainland in 2035.

Water availability is subject to seasonal fluctuations, with lowest availability in summer months. The lowest reported quantity of groundwater is seen in Wales in 2035 at 100 Mt.

Table 24 Nominal available surface water and groundwater resources within the UK

	Observed total river flow (NRFA data) (Mt*)	Nominal useable surface water 2030 (Mt)	Nominal useable water 2035 (Mt)	Estimated useable groundwater 2021 – 2030 (Mt)	Estimated useable groundwater 2026 – 2035 (Mt)
GB mainland	157,660	69,680	68,030	18,800	18,200
England	55,950	22,250	22,760	6,100	59,00
Wales	21,420	9,880	9,900	2,600	2,600
Scotland	82,260	36,530	35,350	10,200	9,700
N Ireland	9,630	5,620	5,480	*Not Available*	*Not Available*

*all flows were provided in km^3 however, for sake of comparison they are presented here on a mass basis, where the density of water has been taken as 1000 kg/m^3.

A large proportion of low-carbon hydrogen projects are focussed in Scotland. During the summer months, Scotland is expected to have 9,900 Mt of surface water nominally available, of which 200 Mt would be groundwater. Even with expanding water demand from other industries, the use of water in hydrogen is marginal when compared to existing demand.

More detailed information on nominal water availability and potential ecological impacts can be found in later chapters of this report produced by UKCEH and BGS.

Table 25 details the estimated water consumption of other industrial sectors. The chemicals usage might also be inclusive of existing hydrogen production from SMR ('grey hydrogen'), for which the UK currently produces approximately 700,000 tonnes of per year and will ultimately be displaced in the long-term by low-carbon production paths ('green' and 'blue' primarily). While water use of low-carbon hydrogen production is obviously significant, it is relatively low at the planned scale.

The exact amount of water requirement for cooling in power generation was not publicly available, though sources did find this it is the largest licensed water abstractor. Five percent of the freshwater abstracted by the sector is used for thermal generation and ninety-five percent for hydropower (Environment Agency, 2015). However, the majority of this water is returned to the environment.

Table 25 Water consumption by industrial sector in 2007 (Ajiero & Campbell, 2018)

Sector	Annual water use (Mt)
Food and drink processing	307
Chemicals	273
Electronics	241
Paper and board	155
Plastic and rubber	83
Textiles and leather	63

While water is abstracted in the production of hydrogen, the end use of hydrogen may reintroduce this water to the water cycle – burning hydrogen or its use in fuel cells will result in a balance of water being produced. Not all water will be returned in this way as some hydrogen might be used as chemical feedstock or exported.

Whilst the water demand for hydrogen production ranks low compared with other sectors, consideration must be given to the water system both as a whole and at a more local level, particularly in areas where water stress is a current or growing concern. Existing procedures, such as water abstraction licences, should be sufficient to manage water demand for hydrogen going forward. Where hydrogen projects are proposed as part of an integrated industrial cluster, in-combination impacts from water use should be taken into account and cluster-based infrastructure solutions explored.

7. Further Considerations

While the focus of this report has been the water consumption of various hydrogen production technologies, several relevant findings and avenues recommended for further investigation were identified through the literature review and subsequent analysis.

First, it is important to consider the practicalities of the findings. While the total water consumed by a full hydrogen economy appears relatively small, issues are still being encountered where water consumption for projects is not being considered until late in design, despite water being one of two key process feedstocks. Water abstraction and use in the process industries is not a new concept. There are well-developed procedures for project developers to interface with relevant bodies. These should be considered early in the project lifecycle. Further, water companies and regulators should be engaged not just at a project level but also to consider whether the existing standards and methodologies fit hydrogen, or if they need review.

There are also opportunities to be had. Desalination plants could present an opportunity for investment by multiple parties, oversized to serve several offtakers, such as, a source of clean drinking water, as well as feedstock for hydrogen electrolysis. As always, the wider context must be considered – a green hydrogen plant powered by solar will likely see highest water demand on sunny days, which is also when demand for drinking water is liable to be highest. Similarly, it is hoped SOEC will be integrated within industrial clusters to make use of ‘waste’ heat, however opportunity costs must be considered not just from an economic perspective but from a wider decarbonisation perspective.

Finally, the shortcomings of this report must also be accounted for. While water abstraction has been reported for the production of hydrogen, no consideration is given to onward use of that hydrogen. Water demand will be increased if the hydrogen is to be compressed or transported and will be even higher if hydrogen is used in a secondary process, such as the production of chemicals. It is essential that an entire lifecycle analysis be performed to understand full water requirements.

8. Conclusions

The aim of this study was to determine the water requirements for low-carbon hydrogen production in the UK and assess whether this could be theoretically accommodated at a national level.

Water treatment requirements have been identified for four raw water sources and four hydrogen production routes. Electrolysis has the highest water purity requirements, followed by boiler water, then cooling water. Seawater requires the highest level of processing, generally followed by surface water, groundwater and potable water.

Generic process flows have been produced for each treatment route and raw water source, as well as for each low-carbon production technology. While overall water requirements are expected to be fairly consistent within each technology group, process design will be unique to each manufacturer and technology provider. The figures in this report will be useful in approximating overall water consumption, as well as potentially providing suitable estimates very early in project lifecycles but are in no way a replacement for detailed engineering design.

Total annual water demand might range from roughly 30 Mt to 60 Mt by 2035, depending on hydrogen production ambitions. As real-world hydrogen production unfolds, it becomes imperative to assess actual water availability rather than the nominal water availability identified in this report. This will involve considering environmental needs and the legal requirement to protect existing water rights at both regional and local levels to ensure supply issues do not arise and any environmental impacts are accounted for and properly mitigated.

Existing water management systems should generally be sufficient to ensure abstraction and water use is appropriately controlled. It is recommended that these be reviewed with input from appropriate stakeholders such as the Environment Agency and water utility providers to confirm they remain fit for purpose.

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10. Annex 1: Estimation of Nominal Surface Water Availability

10.1 Deriving regional estimates of usable river water

For the purposes of this study, it is assumed that, of the various types of surface-freshwaters, rivers are most likely to be the primary sources of freshwater for the abstraction of hydrogen. The UK benefits from a relatively dense and well-established network of river gauging stations, which enables reasonably accurate estimates of contemporary and historic water availability at a range of scales, from a single catchment through to regional- and national-level.

Much of the UK's gauged (observed) river flow data is held by the UKCEH's National River Flow Archive (NRFA). NRFA catchments drain over 70% of the UK's land area. Five mainland "regions" were defined and delineated: England, Northern Ireland, Scotland, Wales and Great Britain. By combining the observed daily flows from the downstream-most gauged catchment areas with an adjustment for ungauged areas, a daily time series of the outflows for each region was derived. The approach is described fully in Marsh et al. (2015).

Having derived a daily time series, the (out-flows can be ranked in such a way as to describe the proportion of time a given flow is exceeded and produce a regional "flow duration curve" (FDC). FDCs are commonly used in operational hydrology as a means of characterising the hydrological regime of a catchment or region (Gustard et al, 2004), for example, for licensing river water abstractions, discharge consents and hydropower design*, inter alia*.

As with any scheme that involves the abstraction of water from rivers, it is neither possible nor desirable to abstract all of the water all of the time. During periods of high-flow, a certain proportion of the flow will by-pass a scheme either due to limitations of capacity or for scheme-safety or resilience reasons. In run-of-river hydropower design, this upper flow usually is set as the river's mean flow value (Q_{mean}), typically this is the flow that is exceeded 30% of the time (Q30). At the low-flow end of the flow regime, there is a requirement to maintain a minimum river flow, to protect the instream river ecology (environmental flow) and the requirements of downstream users. This flow value is often referred to as the "hands-off flow" or "residual flow" ($Q_{residual}$). These two flow levels (Q_{mean} and $Q_{residual}$) map onto a FDC, as shown in Figure 10. The difference between these two values is known as the "rated flow" (Q_{rated}). In hydropower design, the minimum operating flow for turbines (Q_{min}) usually is a function of Q_{rated}. The area under the FDC that is bounded by the flow values Q_{mean}, Q_{min} and $Q_{residual}$ (i.e. the shaded area) represents the volume of "useable water" that is nominally available.

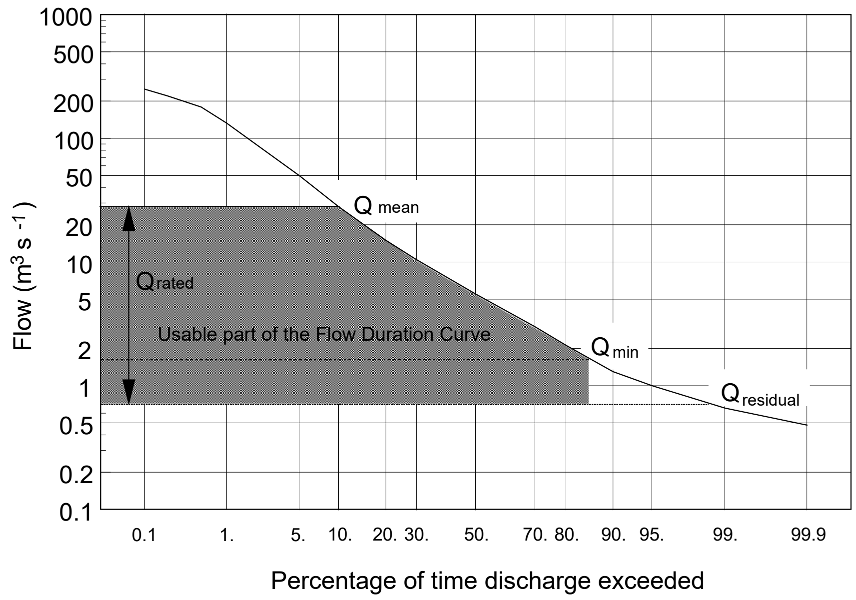


Figure 10 Deriving estimates of usable river water from the flow duration curve (after ESHA, 1994).

10.2 Method: nominal surface water availability

The approach outlined above provides the basis for estimating the volume of "nominally usable water" in each region, applying the respective regional FDC and defining Q_{mean} as the flow that is exceeded 30% of the time (Q30) and $Q_{residual}$ as the flow that is exceeded 90% of the time (Q90). Q90 was chosen as a more conservative environmental flow measure than the Q95 value that is traditionally used (see Section 2); being at the low end of the flow regime, the choice of Q90 over Q95 is unlikely to have a significant impact on the regional gross estimates of usable water that are presented later. As there are no turbines to consider in this type of application (abstraction for hydrogen generation), Q_{min} and $Q_{residual}$ are taken as being equal.

Annual, Winter (October to March) and Summer (April – September) FDCs were defined for each region for a baseline and two future periods. These 10-year periods were defined as follows:

- **Baseline period**: 2012-2021 (ending 2021).
- **Future period**: 2021-2030 (ending 2030).

- **Future period**: 2026-2035 (ending 2035).

Estimates of annual and seasonal (winter- and summer-half years) total volumes (km^3) of rated flow are provided for 5 UK regions:

- **Mainland Great Britain (GB)** – includes England, Wales and Scotland
- **England (E)**
- **Scotland (S)**
- **Northern Ireland (NI)** and
- **Wales (W)**

Estimates of total and nominally useable water (km^3) for the baseline period for each UK region are based on NRFA observation-derived river flow data (Marsh et al., 2015). For the two 10-year future periods ending 2030 and 2035, observations of river flows are not yet available to estimate future useable water. Instead, G2G hydrological model-derived natural flow estimates driven by UKCP18 regional climate model data (CS-N0W Hydrological modelling report: Bell et al., 2023) were used to derive the % change in mean annual river flows across 12 UKCP18 RCM ensemble members. The ensemble median % change was then used to estimate the change in nominally useable flows between the 10-year baseline and two future periods (2030 and 2035). The G2G-derived % flow changes between baseline and future were then applied to the observation-derived baseline estimates of useable flows to derive 2030 and 2035 estimates of useable water, consistent with the observation-derived baseline estimate.

For example, the volume useable surface-water for 2030 is derived as follows:

Useable surface-water for 2030 is:

Useable surface-water for 2021 × (100 + % change factor) / 100

Thus, for Mainland GB useable annual surface-water for 2030 is:

$$71.54 \times (100 - 2.6) / 100 = 69.68 \text{ km}^3$$

Unfortunately, the CS-N0W report (Bell et al., 2023) and associated G2G output datasets from which the % change factors were derived do not provide the natural flow data for Northern Ireland from which NI change factors can be derived. Instead, a study undertaken by Kay et al. (2021) of projected future changes in G2G-estimated river flows across Northern Ireland formed the basis for the % change factors used here for NI. Kay et al. (2021) indicate that for NI, future flow changes are "*similar to the flow changes simulated for north-west England*", so for consistency with the flow changes derived for other UK regions in this study, % changes in useable water for NI are derived from the NW England values already available in the CS-N0W G2G output dataset.

10.3 Results and discussion of uncertainty

Contemporary and near-future estimates of useable water for hydrogen production

The volumes of usable surface-water on an average annual and seasonal basis are summarised in Table 26, and Figure 11 provides a graphical summary of the baseline and future useable surface-water estimates in Table 26. The baseline and projected-future useable water volumes are plotted on the same scale, and the bar-charts highlight the relative sizes of useable water nominally available for each UK region. As expected, Mainland GB nominally useable water estimates dominate, with Scottish estimates being the second largest. Northern Ireland has the smallest nominally useable water available, in line with its relative area. For each UK region, nominal useable water estimates are plotted in order of time-period (baseline, 2030, 2035), then in order of season. Future estimates of nominal useable water are generally lower than baseline estimates, with 2035 values typically lower than for 2030. Winter useable surface-water is ~70-75% of the annual total, with summer providing the remaining ~25-30% of the UK's annual useable surface-water.

The estimated annual volume of freshwater useable for the abstraction of hydrogen in Mainland GB is currently 71.54 km^3. This value is likely to reduce by 2.6% to 69.68 km^3 by 2030 and reduce again by 4.91% to 68.03 km^3 by 2035. Figure 13 provides a visual summary of the % changes in useable freshwater for each UK region and season between 2021, 2030 and 2035. Note that change values for these 3 years have been connected linearly for clarity, but if the changes were calculated for each intervening year there would be much greater variation. Generally the G2G/UKCP18-derived % change projections indicate a *decrease* in useable water from baseline (2021) to near-future (2030 and 2035), particularly for Annual and Summer totals (Figure 13a,b). However, Figure 13(c) highlights that Winter useable water for Northern Ireland and Scotland may well *increase* by 2030, before dropping back to pre-2021 values by 2035. These results should be considered highly uncertain as they are based on median G2G/RCM-projections of change for just two ten-year periods (ending in 2030 and 2035), and a more-robust result should consider the full ensemble of G2G/RCM-projections of change, rather than the median change, and derive changes for more than two ten-year periods.

Table 26 Volumes of nominal usable surface-water on an average annual and seasonal basis for UK regions for a baseline period (ending 2021), and two future periods (ending 2030 and 2035)

	Observed total river flow (NRFA data)	Nominal useable surface-water for 2021 (derived from NRFA data)	Estimated % change in useable water from 2021 - 2030 (derived from G2G output)	Nominal useable surface-water for 2030	Estimated % change in Useable water from 2021 - 2035 (derived from G2G output)	Nominal useable surface-water for 2035
Units	km^3	km^3	%	km^3	%	km^3
			Annual			
GB mainland	157.66	71.54	-2.60	69.68	-4.91	68.03
England	55.95	23.83	-6.62	22.25	-4.46	22.76
Wales	21.42	10.28	-3.87	9.88	-3.67	9.90
Scotland	82.26	37.15	-1.68	36.53	-4.84	35.35
N Ireland	9.63	5.74	-2.05	5.62	-4.47	5.48
			Winter			
GB mainland	112.96	52.17	-0.02	52.16	-2.05	51.10
England	39.87	17.18	-2.53	16.74	-2.90	16.68
Wales	16.06	7.46	-0.32	7.44	-0.40	7.43
Scotland	57.73	26.12	0.66	26.30	-1.10	25.84
N Ireland	7.23	4.31	2.84	4.43	-1.27	4.25
			Summer			

GB mainland	44.70	19.37	-7.24	17.97	-9.34	17.56
England	16.08	6.65	-8.85	6.06	-5.88	6.26
Wales	5.36	2.82	-3.22	2.72	-6.55	2.63
Scotland	24.53	11.03	-7.32	10.22	-9.87	9.94
N Ireland	2.40	1.43	-3.94	1.38	-7.35	1.33

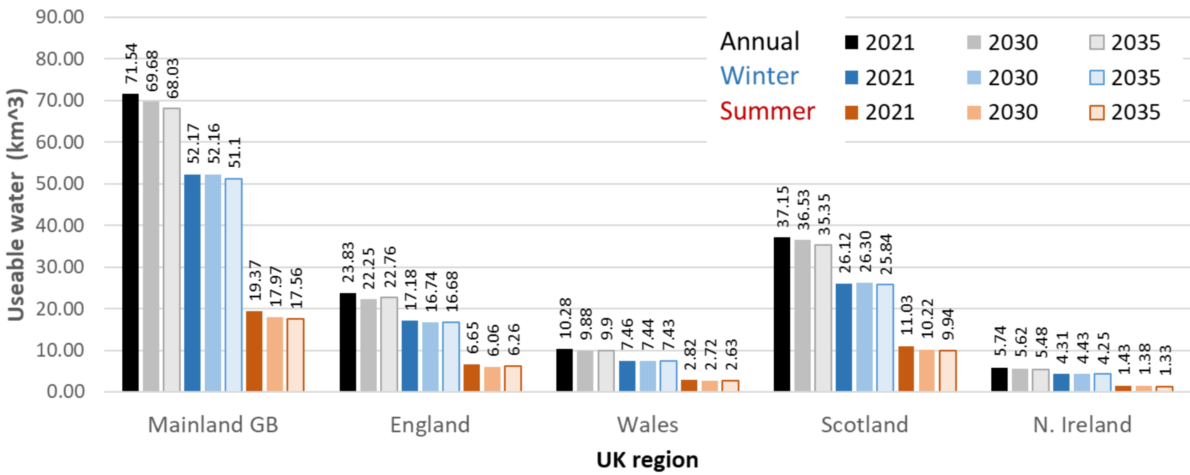


Figure 12 Bar chart of estimated Annual, Winter and Summer nominal useable surface-water (km3) for a baseline period (ending 2021), and two future periods (ending 2030 and 2035). For clarity, each bar is labelled with the useable water (km3).

(a) Annual (b) Winter (c) Summer

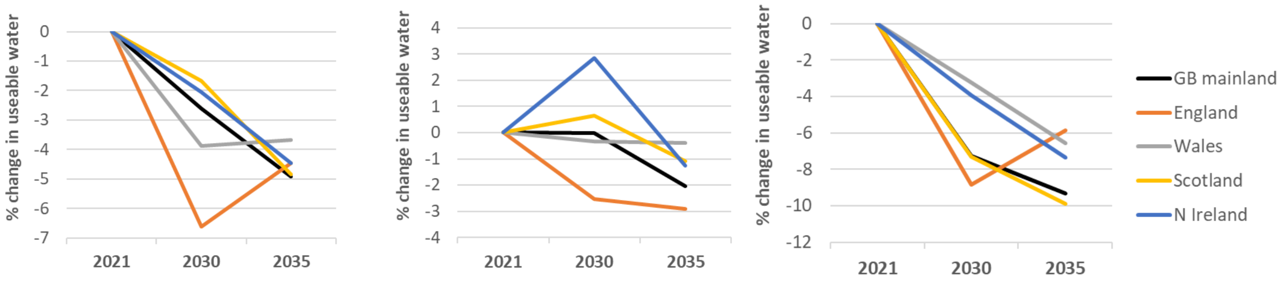


Figure 13 Projected change (%) in nominal usable river water for each UK region from 2021.

It is important to note however that the values presented in Table 26 and Figures 12 and 13 are *theoretical maximum useable water* for each region. It would be impossible for all the useable water from every river in every region to be used for hydrogen generation. Only by considering the hydrological regime alongside existing protected water rights as well as environmental requirements at specific locations would it possible to provide realistic estimates of actual usable water rather than the nominal figures presented in this report.

10.4 Impact of artificial influences on future projections of nominal useable water

The G2G/RCM-derived % future change factors used to derive nominal useable surface-water for 2030 & 2035 from the (observation-based) 2021 values are based on G2G hydrological model estimates of *natural* river flows, i.e. river flows unaffected by artificial influences such as abstractions, discharges and reservoir impoundments. These are available on a 1 km × 1 km resolution grid for rivers across the UK so can readily provide the future projections of *regional-scale river flow changes* required here. However, these projected future changes in G2G natural flows do not take account of current or future artificial influences (AI) and this omission provides another source of uncertainty in the future projections of useable water. Currently, baseline and future projections of UK-wide abstraction and discharge data are not readily available for distributed hydrological modelling, but the CS-N0W project has recently derived future AI projections for England. These were used in combination with UKCP18-RCM climate projections to estimate the impact of both climate and AI on future river flows across England (Bell et al. 2023).

To understand the sensitivity of the near-future results to artificial influences, the English projections of nominal useable water (Table 26) were recalculated using CS-N0W AI-impacted G2G flow projections (Business as usual. Table 27 presents the new estimates of useable water, alongside the original values, and Figure 14 illustrates the relative changes as bar-charts (future volumes of usable water that include AI are highlighted in red). Typically, taking account of changes in future AIs results in slight increase in projected volumes of water available for hydrogen production in 2030 and 2035, however the increases themselves are very small (<1% impact on annual water volumes, and <3% impact on summer water volumes). There are no AI data available to support a similar analysis for other UK regions, but the sensitivity analysis for England suggests that the impact of AI on useable water in the other UK regions will also be modest.

Table 27: Volumes of nominal usable surface-water on an average annual and seasonal basis for England for a baseline period (ending 2021), and two future periods (ending 2030 and 2035). For the two future periods, useable water volumes are presented with and without including projected changes in AI.

	Nominal useable surface-water for 2021 (derived from NRFA data)	Nominal useable surface-water for 2030	Nominal useable surface-water for 2030, inc. future changes in climate and AI	Nominal useable surface-water for 2035	Nominal useable surface-water for 2035, inc. future changes in climate and AI
Units	km^3	km^3	km^3	km^3	km^3
Annual	23.83	22.25	22.39	22.76	22.90
Winter	17.18	16.75	16.79	16.68	16.72
Summer	6.65	6.06	6.18	6.26	6.34

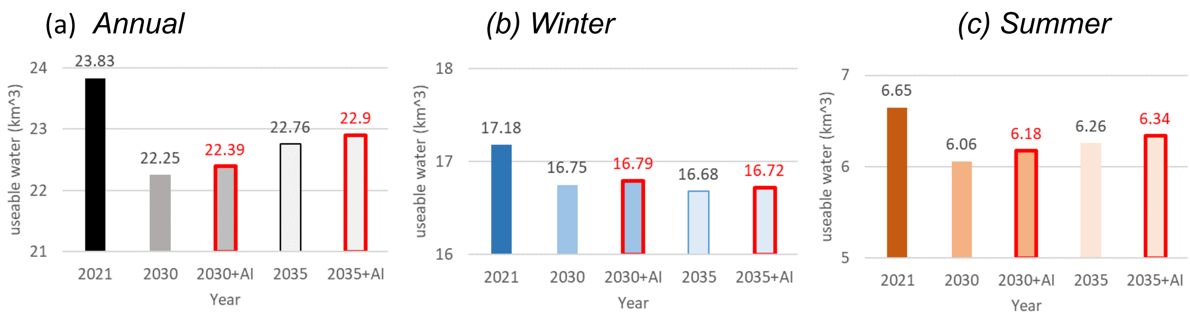


Figure 14. Projected volume of nominal usable river water (km^3) for England for 2021, 2030 and 2035, highlighting how abstractions and discharges impact on the future projections of nominal useable water. Future projections of nominal useable water that include AI are shown in red.

10.5 Background: groundwater resources in the UK hydrogeological setting, and rationale for the derivation of estimates of usable groundwater

Groundwater currently provides about a third of the public water supply in England with abstractions averaging 2.2 billion cubic metres per year between 2000 and 2018 (UK GOV, 2023). In Wales and Scotland although public water supplies are largely sourced from surface waters (about 95%), groundwater is an important strategic resource for rural towns and also underpins private water supply (about 73% in Scotland). Licensed abstractions amount to 0.3 billion cubic metres per year in Scotland (SEPA) and 0.01 billion cubic metres per year in Wales (Farr et al., 2022). In Northern Ireland, groundwater abstraction for public water supply was relevant up to the 2000s accounting for 11% of total demand in the 1990s (0.04 billion cubic metres per year, Robins et al., 2004). Despite a relative abundance of this resource, today almost all the public water supply in Northern Ireland is sourced from surface supplies.

From a regional and more local perspective, there are significant variations in term of percentage of water supply depending on geology and availability of surface water and groundwater (BGS, 2023). In parts of the south east of England for instance, groundwater abstracted from the Chalk aquifer can account for almost 100% of the public water supply. The Permo-Triassic sandstones in central England are also heavily abstracted providing 25-50% of the total water supply. These differences in aquifers exploitation are reflected in regional differences in terms of sustainability of the current abstracted volumes (BGS, 2023) and aquifers in certain parts of England are already over-abstracted. It is estimated that abstraction rates in 28% of groundwater bodies in England are already not sustainable with an additional 15% at risk of becoming over-abstracted if abstractions continue to increase (DEFRA and EA, 2017). Furthermore, water companies are required by the regulators to reduce abstractions in the future to alleviate environmental impacts such as low river flows or water levels in wetland areas.

In the UK, groundwater is mostly naturally discharged as baseflow to rivers. For certain rivers, such as chalk streams, the baseflow can represent almost 100% of the total river flow and is particularly significant during the summer months. The fraction of the total river flow accounted by the groundwater baseflow depends on the geology of the catchment as well as on seasonal factors. The fraction of baseflow is highest during summer months when the volume of groundwater stored in aquifers during winter is released to rivers. British aquifers are generally in a condition of water surplus (recharge from precipitations > outflows) during the autumn/winter months when a rise in groundwater levels is generally observed. Conversely, a deficit in recharge usually occurs during the summer months resulting in a decline in groundwater levels as stored groundwater is discharged to rivers. However, interannual variability in the amount and timing of groundwater recharge is an important control on the variability of groundwater levels and river baseflow, and consequently on groundwater availability.

While river flows can be measured, groundwater flows can only be estimated from analytical or numerical modelling. For this study, historical and projected future groundwater flows were simulated using BGS's British Groundwater Model (BGWM; Bianchi et al., 2023) – a 1 km gridded groundwater flow model. Given the critical contribution of baseflow to river flow and for consistency with the methodology used to estimate nominal usable river water, the criterion applied for the estimation of nominal usable groundwater was also based on the preservation of $Q_{residual}$ (Q90) in rivers. The developed methodology focussed then on estimating the baseflow contribution to total river flow. For the quantification of the "nominal usable groundwater" that could be abstracted from aquifers for hydrogen production, it was assumed that the volume of baseflow exceeding the Q90 can represent a reasonable estimate of the groundwater excess. This assumption is conservative since in certain rivers not 100% of the Q90 consists of baseflow.

As with the estimation of nominal usable river water, groundwater availability was estimated as aggregated values for each of England, Wales and Scotland, and Great Britain, while smaller aquifer-scale variability and related considerations about the sustainability of the current and future abstractions were not considered. In addition, there has been no consideration of the effect of groundwater quality on the useable groundwater volumes. The BGWM currently only covers the British mainland and so estimates for Northern Ireland could not be calculated.

10.6 Methodology: estimation of nominal groundwater availability

The BGWM simulates transient groundwater flow dynamics and budgets components over mainland Great Britain (England, Wales, and Scotland). The model considers geological heterogeneity, exchanged flows between aquifers and rivers, groundwater discharge to the sea, and abstractions. The model is driven by monthly *recharge* (i.e. water infiltrating downwards from the base of the soil) data simulated by BGS's national-scale ZOODRM recharge and surface water runoff model (Mansour et al., 2018).

For the purpose of this work, the recharge and BGWM models were run for the following three 10-year periods:

- Baseline period: 2009-2018 (ending 2018)
- Future period: 2021-2030 (ending 2030)
- Future period: 2026-2035 (ending 2035)

For the baseline, or historical period, monthly recharge estimates driving the groundwater flow model were calculated based on historical observed measured precipitation (HadUK 1km gridded rainfall; Hollis et al., 2018) and evapotranspiration data (MORECS; Hough and Jones, 1997). For the two future periods, daily recharge rates were derived from the simulations of the national recharge model performed by the eFLaG project (Hannaford et al., 2023; Mansour et al., 2023). This project applied the same 12-member ensemble of UKCP18 climate projections described above. Daily recharge data for each UKCP18 ensemble member was then averaged on a monthly basis and used as input to the BGWM.

Both the recharge model and BGWM provide monthly values of components of water budget for each cell of their numerical grids. For the three simulated periods, single cell values were aggregated to produce time series of total simulated total surface runoff (Q_{ro}) and total river baseflow (Q_b) for each British nation. The Q_b and Q_r time-series were then added to produce monthly time-series of modelled total river flows (Q_r) from which a Q90 value was calculated. The volume of usable groundwater flow (Q_u) was estimated then for each month according to the following criteria:

$$\begin{cases} \text{If } Q_b > Q_{90} \text{ then } Q_u = Q_b - Q_{90} \\ \text{If } Q_b \leq Q_{90} \text{ then } Q_u = 0 \end{cases}$$

Q_u values were multiplied by number of days of each month to obtain annual and seasonal volumetric monthly estimates of usable groundwater. With this approach, these volumetric estimates represent a fraction of the volumetric estimates of useable surface water.

Seasonal estimates assumed that summer season is the half-year period April to September. The winter season is October to March. In the estimation of the volume of available groundwater during the different seasons, it was assumed that river flows respond instantaneously to groundwater pumping. This is generally not the case since a delay is generally observed. The real responses will vary depending on the hydrogeological properties of the aquifer and on the proximity of the abstractions to the rivers.

Estimates of total nominal useable groundwater (km^3) for the baseline period are based on simulations considering measured precipitation data. For the two 10-year future periods ending 2030 and 2035, instead of calculating estimates based on BGWM runs driven by projected future recharge estimates, % changes from the baseline volumes of usable groundwater were calculated for each ensemble member. The mean ensemble % changes were then applied to the observation-derived baseline estimates of useable groundwater to derive 2030 and 2035 estimates. This approach is consistent with the estimation of nominal surface water availability.

10.7 Results: estimates of nominal usable groundwater

Average annual and seasonal volumes of usable groundwater for the different regions are reported in Table 28 and in Figure 14. For England it is estimated that the total annual usable groundwater is 6.3 km^3, corresponding to 23% of the estimated recharge from precipitation. For Scotland and Wales, the volume of total available groundwater is 10.0 km^3 and 2.6 km^3. These volumes correspond to 24% and 27% of the estimated recharge for the two regions. Estimated volumes show a clear seasonality in nominal water availability. On average, about 92% of the total annual volume is available during the winter months and the remining 8% in the summer. Given the known effects of interannual variability in recharge on groundwater drought generation, then these estimates of the limited availability of groundwater over the summer months in Britain emphasise the limited resilience of groundwater resources during this season. This pattern in water availability follows the seasonality of groundwater recharge in Great Britain. It is important to clarify, that these are theoretical maximum volumetric estimates assuming that all groundwater in the subsurface can be accessible by draining all of the pore space and collecting the water coming out of it, and it is of suitable quality. Of course, the accessibility of groundwater resources will vary substantially in different areas of the UK depending on local and regional geology. In areas characterised by low permeability rocks or where groundwater is contained in a network of discreet fractures, accessing groundwater can potentially be technically not viable or limited to some specific areas. This is likely to be true of Scotland and Wales especially over higher grounds where the geology is mostly low permeability crystalline rocks. In addition, a significant amount of groundwater in these areas is discharged in the form of springs at high altitude, and although they make part of river baseflow volumes analysed here, the impact of pumping groundwater may be detrimental on these surface features and on the ecology that they support.

Moreover, in areas where aquifers are already subject to intense abstractions, accessibility may not be problematic, but considerations in terms of sustainability of the groundwater resources will have to be taken into account for planning additional abstraction for hydrogen production. Furthermore, this analysis does not consider any of the complexity associated with the interaction between the human infrastructure (e.g. wastewater returns to rivers) and the natural system.

The amount of available sustainable water calculated for England (6.3 km^3/yr) is less than the maximum licensable volume of water calculated by the Environment Agency before it takes into account other constraints (e.g. water quality and ecology). This maximum licensable volume is determined from a groundwater balance which considers only the long-term average recharge, the net environmental flow allocation (Q50 of river flows multiplied by baseflow index), groundwater fluxes in and out of the groundwater bodies, and the long-term average abstraction (EA, 2022). Our estimates in Table 28 take into account a river low flow threshold and therefore are expected to be less than the EA's maximum licensable volume.

Total annual volumes of usable groundwater are generally predicted to decrease in the future with estimated % changes ranging from -3.9% to +1.2% for the near future period (2021 – 2030) and from -6.1% to -1.5% in the far future period (2026 – 2035). Greater % changes were estimated for the summer months in both future periods illustrating the projected decreasing future resilience of groundwater resources in Britain during the summer months. These high values (up to -71%) however, have little effect on the estimated total annual volumes given the low volumes of available groundwater in the summer and the fact that the % changes estimated for the winter months, when most of the total volumes are nominally available, are much smaller and comparable to the annual estimates. These predicted changes are small compared to the uncertainty in the calculations.

Table 28 Estimated annual, winter and summer nominal useable groundwater (km^3) for the baseline period (ending 2018), and two future periods (ending 2030 and 2035).

	Estimated volume of nominal useable groundwater for baseline period (2009 – 2018)	Estimated % change from baseline for 2021 - 2030	Estimated volume of nominal useable groundwater for 2021 - 2030	Estimated % change from baseline for 2026 - 2035	Estimated volume of nominal useable groundwater for 2026 - 2035
Units	km^3/yr	%	km^3/yr	%	km^3/yr
			Annual		
Mainland GB	19.0	-0.9	18.8	-3.9	18.2
England	6.3	-3.9	6.1	-6.1	5.9
Wales	2.6	-1.4	2.6	-1.5	2.6
Scotland	10.0	1.2	10.2	-3.2	9.7
			Winter		
Mainland GB	17.5	0.6	17.6	-2.0	17.1

England	5.8	-4.3	5.6	-5.5	5.5
Wales	2.4	-1.5	2.4	-0.8	2.4
Scotland	9.2	4.2	9.6	-0.1	9.2
			Summer		
Mainland GB	1.5	-32.7	1.0	-49.6	0.8
England	0.5	6.6	0.5	-21.3	0.4
Wales	0.2	1.6	0.2	-32.7	0.1
Scotland	0.8	-64.6	0.3	-70.8	0.2

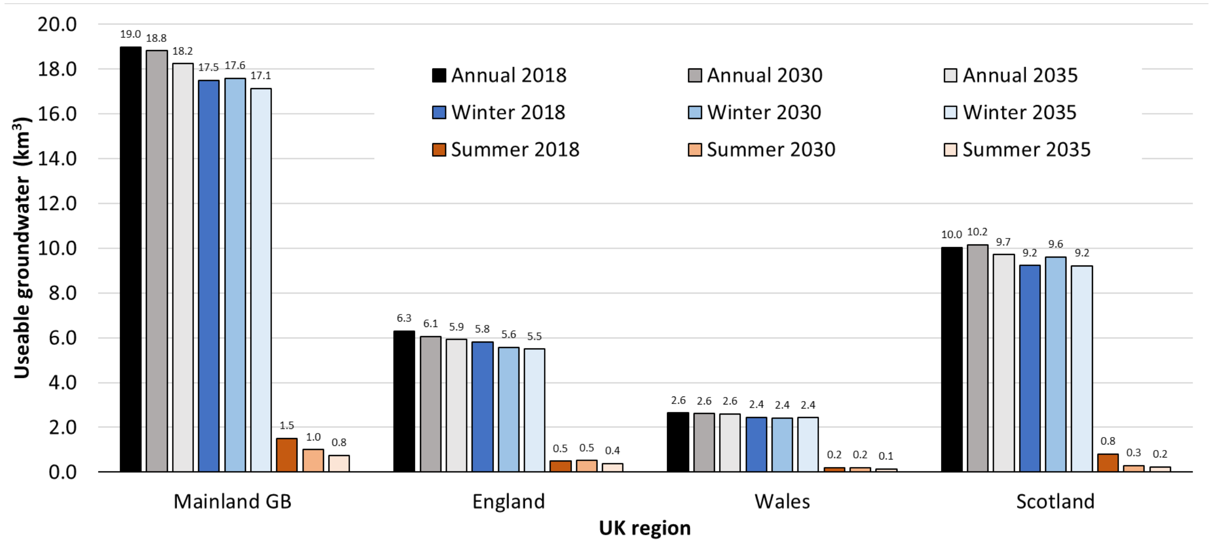


Figure 14. Bar chart of estimated annual, winter and summer nominal useable groundwater (km^3) for a baseline period (ending 2018), and two future periods (ending 2030 and 2035). For clarity, each bar is labelled with the estimated value (km^3).

10.8 Background: the importance of maintaining environmentally beneficial flows

"*Having the right flow in our rivers and protecting groundwater levels is essential to supporting healthy ecology, enhancing natural resilience to drought, and ensuring that rivers continue to support wellbeing and recreation. Sustainable water abstraction is therefore essential to ensure that river flows and groundwater levels support ecology and natural resilience*" (HMG, 2021)

10.9 Example impacts

The potential impacts of surface-water and groundwater abstractions on river, riparian and wetland ecology are varied and well documented (e.g. Acreman et al., 2007; English Nature, 1996; Carolli et al., 2017; Poff and Zimmerman, 2010; WWF, 2017; etc.). Any abstraction results in a change to river flows and levels, which, in turn, can affect local water quality, stream morphology, habitats, flora and fauna.

Abstraction reduces the volume of water in a river and, hence, the amount that is available for the dilution of pollutants. Higher concentrations of nutrients, for example, combined with longer residence times (as a result of reduced river flows), can lead to problems of eutrophication, algal blooms and outbreaks of toxic cyanobacteria (blue-green algae) (EA, 2019). Enhanced vegetation growth, due to an excess of nutrients, can cause dissolved oxygen levels in rivers to drop, sometimes catastrophically, resulting in fish kills in the most adversely effected stretches.

Abstraction of river or groundwater can also affect surface-water-groundwater interactions, lowering the water-table locally, resulting in the drying of wetlands, reduced water available for bushes, trees and other vegetation and degrading habitat quality for animals (Acreman et al., 2007). Agriculture can be affected as reduced soil moisture levels limit the amount of water naturally available for crops.

Morphologically, changes to the distribution of stream velocities result in silt and sediment being deposited where naturally it wouldn't be. River cross sections are altered; new pools, sediment banks, and riffles can form (Viets and Finlayson, 2017). Bank erosion and the natural tendency for meanders can be affected. Such morphological changes can alter local habitats, including the occurrence and growth of in-stream vegetation, reducing habitat suitability (altered bed and flow conditions) for breeding or spawning of aquatic animals, and local food webs. Longitudinal connectivity of habitats can also be lost, which can influence biodiversity and species' lifecycles and affect local extinctions.

10.10 Regulation and long-term planning

In the UK, environment legislation is in place to safeguard freshwater ecosystems from unsustainable and ecologically harmful surface-water and groundwater abstractions. A permitting regime exists whereby licences/consents are granted to abstractors, limiting the amount of water they can remove (abstract) from the environment. An abstraction licence generally is required for abstractions greater than 20 m^3 per day (HMG, 2023a). The licensing regime is intended to ensure the flow along any stretch of river never falls below a minimum “environmental flow” value. Traditionally in the UK, this value has been set universally at no less than the Q95 flow, i.e. the flow that is exceeded 95% of the time (EA, 2020a). The national environmental regulators (EA, SEPA, NRW, NIEA), who have the statutory duty to secure the proper use of water resources, are responsible for issuing licences and monitoring abstractions. Hefty fines can be imposed for non-compliance and over-abstraction. The biggest abstractors nationally are the water companies, farmers, energy producers and industry. Under certain extreme drought conditions, water companies may gain authorisation to abstract more than their daily allowances.

In England and Wales, the environmental regulators (EA and NRW respectively) are required to produce every 6 years river basin management plans (RBMPs) that set out legally binding, locally specific, actions they will undertake to ensure rivers achieve “good ecological status”, as defined by the Water Environment (Water Framework Directive) (England and Wales) Regulations 2017 (HMG, 2022a). These plans often will further limit the amount of water that can be abstracted from rivers and groundwater, especially in ecologically sensitive areas (e.g. protected conservation areas, Sites of Special Scientific Interest (SSSIs), salmon rivers, chalk rivers, Groundwater Dependent Terrestrial Ecosystems (GWDTEs), etc.).

With mounting concerns over the effects of unsustainable abstractions on the environment, and considering increasing pressures of climate change, population growth and economic growth, in 2020, the Environment Agency launched a national framework for water resources (EA, 2020c). The framework identifies the strategic needs for water up to 2050 and beyond across all sectors in England and five newly defined water resources management regions, which incorporate the relevant water companies (EA, 2020a). The framework builds on Defra’s 25 Year Environment Plan (HMG, 2018) and previous work by Water UK (Water UK, 2016) and the National Infrastructure Commission (NIC, 2018). It sets clear expectations for achieving sustainable abstractions and promotes the use of regional water resources plans aimed at “the delivery of an environmental destination for water resources that address known environmental issues related to all aspects of water abstractions”. As part of the framework, a set of environmental scenarios were produced showing how climate change and demand might affect the environment in future. The scenarios were designed to support regional planning and “used an ‘environmental flow indicator’ to assess how much water would be needed to protect the environment in future” (EA, 2020a).

According to the Water Industry Act of 1991, water companies in England and Wales are required by law to prepare a water resources management plan (WRMP) at least every 5 years (HMG, 2023b). The plans require water companies to set out how they will meet future supply and demand needs over a minimum statutory period of 25 years, whilst ensuring there is sufficient water to improve and sustain healthy river ecosystems. In 2020, Defra, the EA and Ofwat led a review of the water industry national environment programme (WINEP) ahead of the next water resources management plans (WRMP24). WINEP defines a set of actions water companies are required to undertake to achieve “greater environmental benefit” (HMG, 2022b). WINEP espouses the concept of “environmental destination”. In their latest WRMPs, water companies thus were required to specify their environmental improvement goals and how they would achieve them. Ofwat, EA and Natural England are statutory consultees for WRMPs in or affecting England. The latest WRMPs by water companies and the 5 regional resource management groups were published in the summer of 2023.

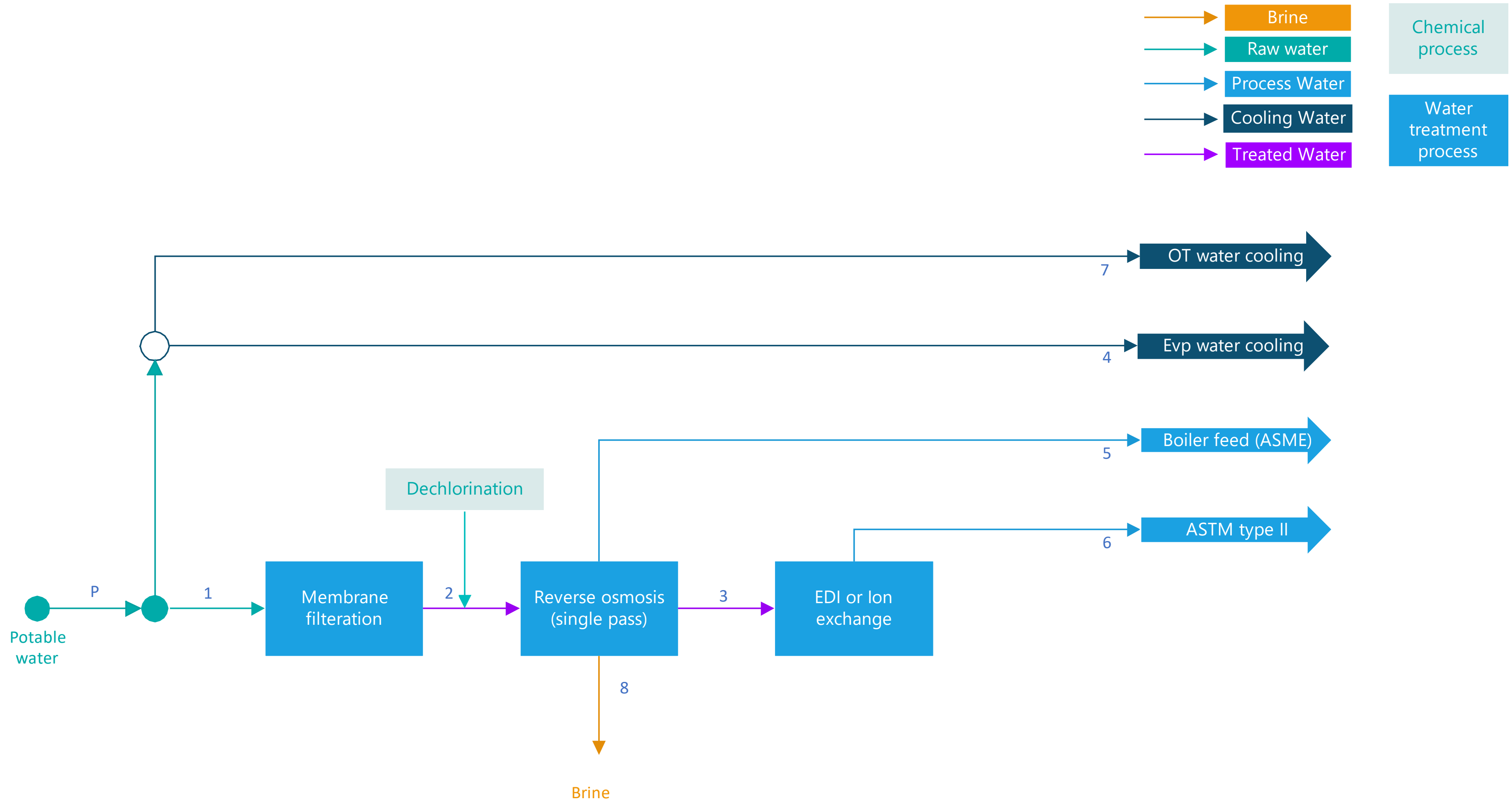
10.11 Implications for hydrogen generation

Earlier we presented figures that estimated the “theoretical maximum useable water” for the UK as a whole and for each of the four home nations. As was mentioned, it is impossible to harness all of the usable water from rivers and aquifers for hydrogen production. In practice, the amount of water available for any new scheme will be dictated by local conditions, existing protected water rights, local demands and local environmental concerns. The relevant environmental regulator would need to take a view and factor-in the hydrogen abstraction demand in their river basin management plans (RBMPs) and likely would assess, on a case-by-case basis, how much water it believes could/should be made available, considering other users’ demands within a catchment and the need to protect the environment and ensure environmental resilience. Adaptation to climate change should be taken into account when considering cooling technology selection. The relevant water company and regional water resource management group similarly would need to be consulted, as any new scheme is likely to affect the water supply options (water sources) they have considered and their “environmental destination”; any additional demand further would need to be accommodated in their long-term planning. There are then many non-environmental practical and logistical issues to consider, e.g. proximity to infrastructure (road, rail, electricity distribution), planning constraints, etc.

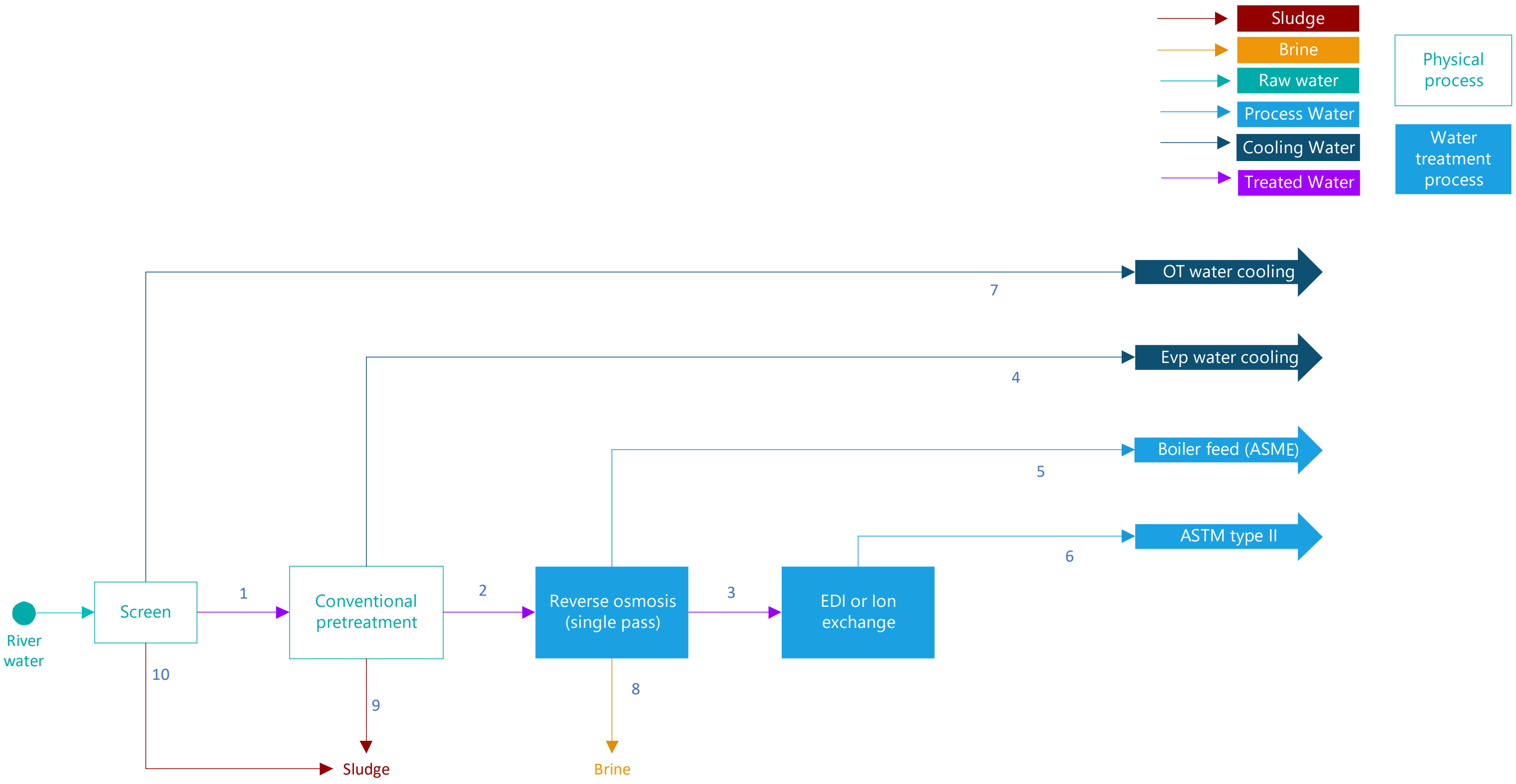
Having considered the theoretical availability of water at the broadest, regional levels, the next step we recommend would be to conduct a series of more detailed assessments at specific locations where water abstractions for hydrogen production are considered most likely. With existing energy and distribution infrastructure and proximity to water sources, thermal generating plants, such as Drax (on the Trent) and Didcot (Thames), to name but a few, would be a good place to start.

Annex 4: Flow Diagrams

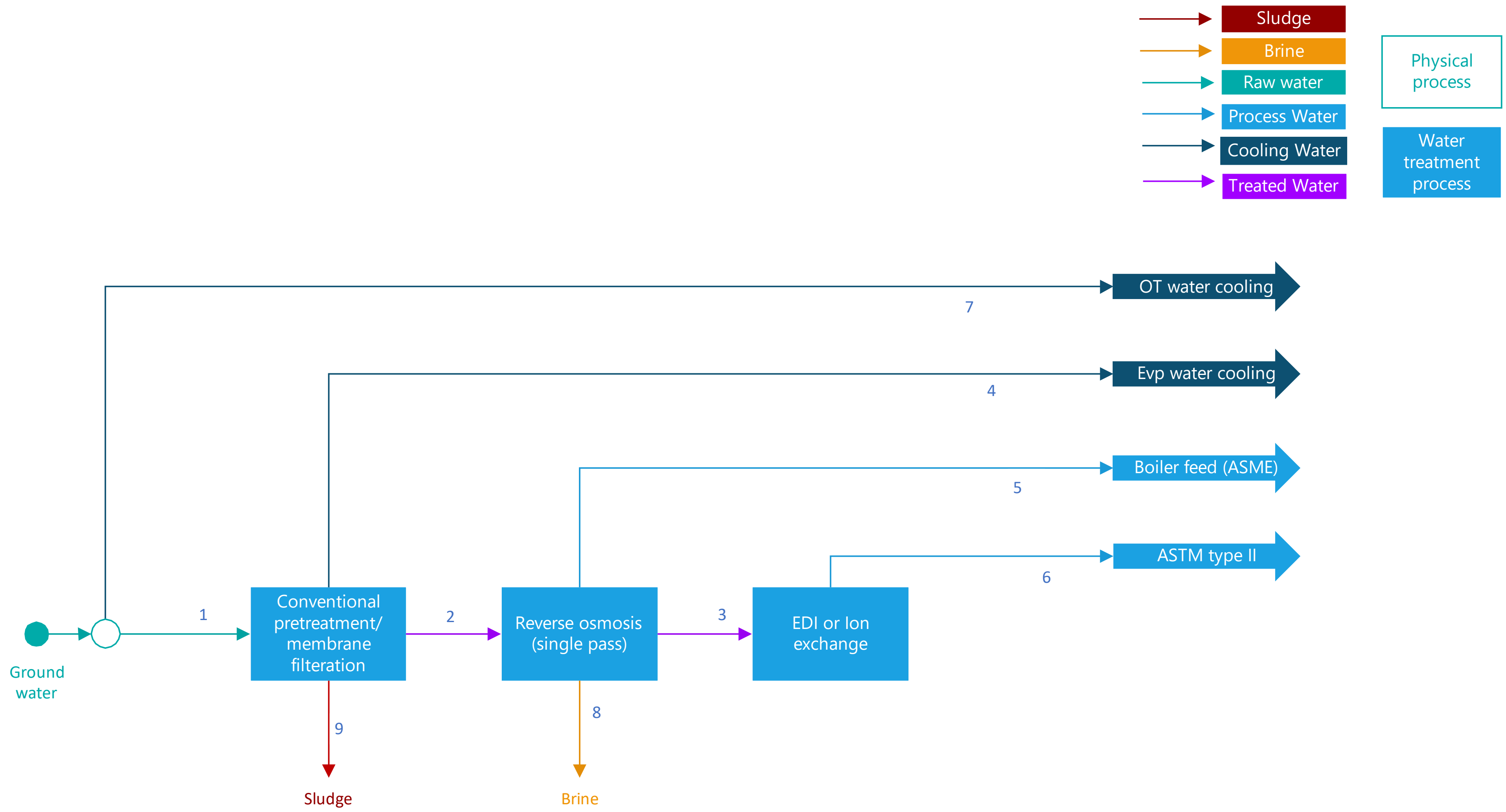
Treatment process for potable water



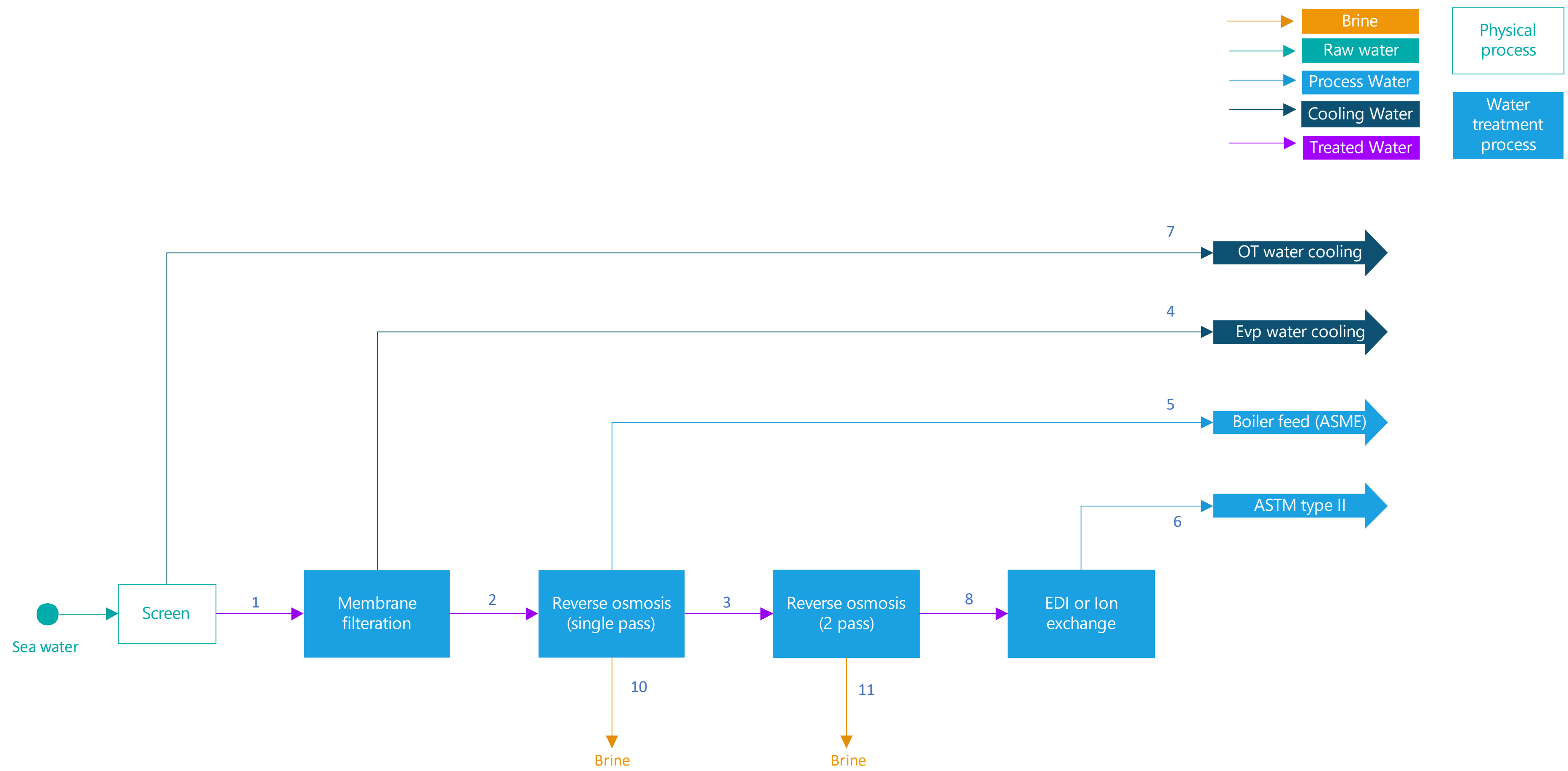
Treatment process for river water



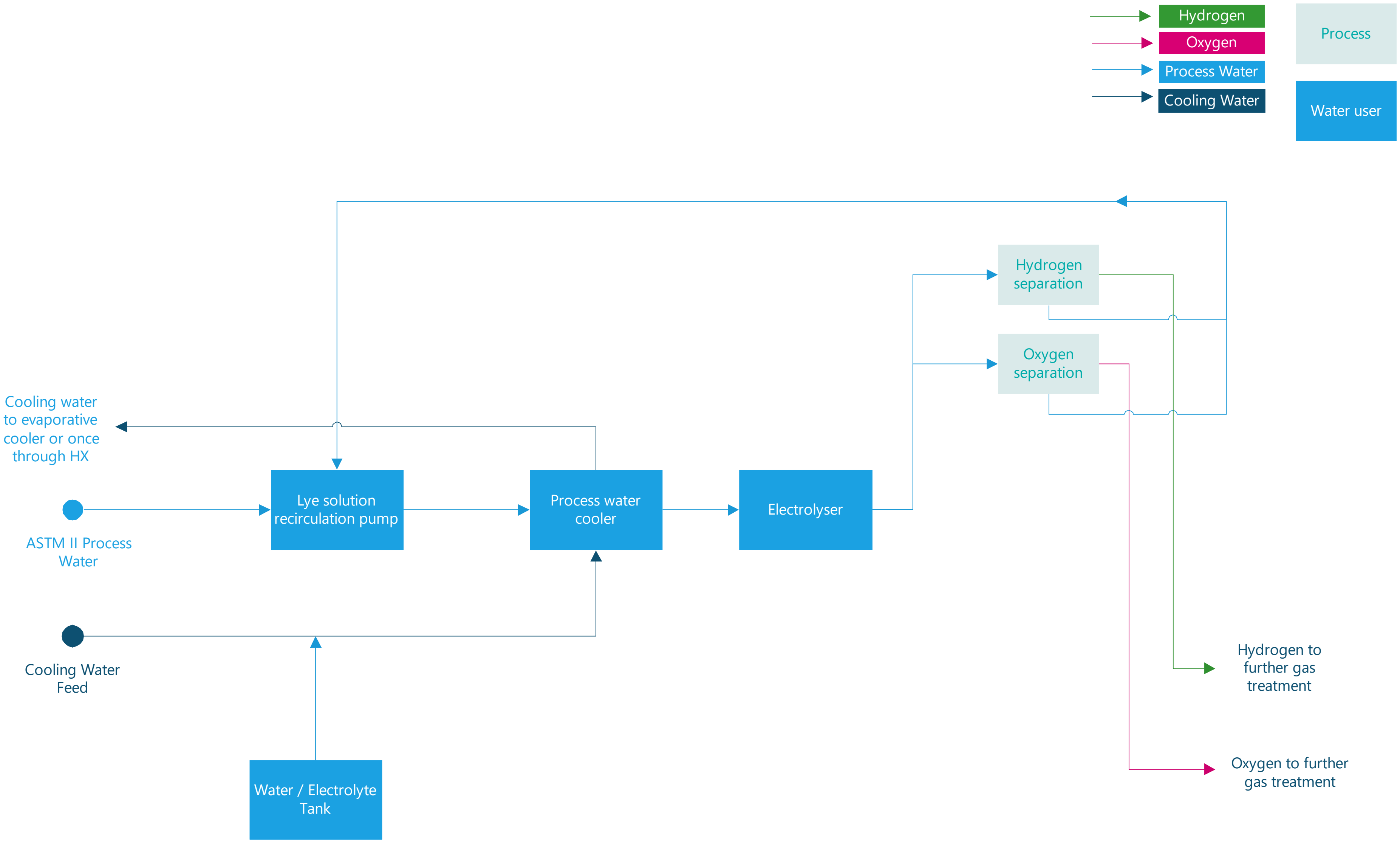
Treatment process for borehole water



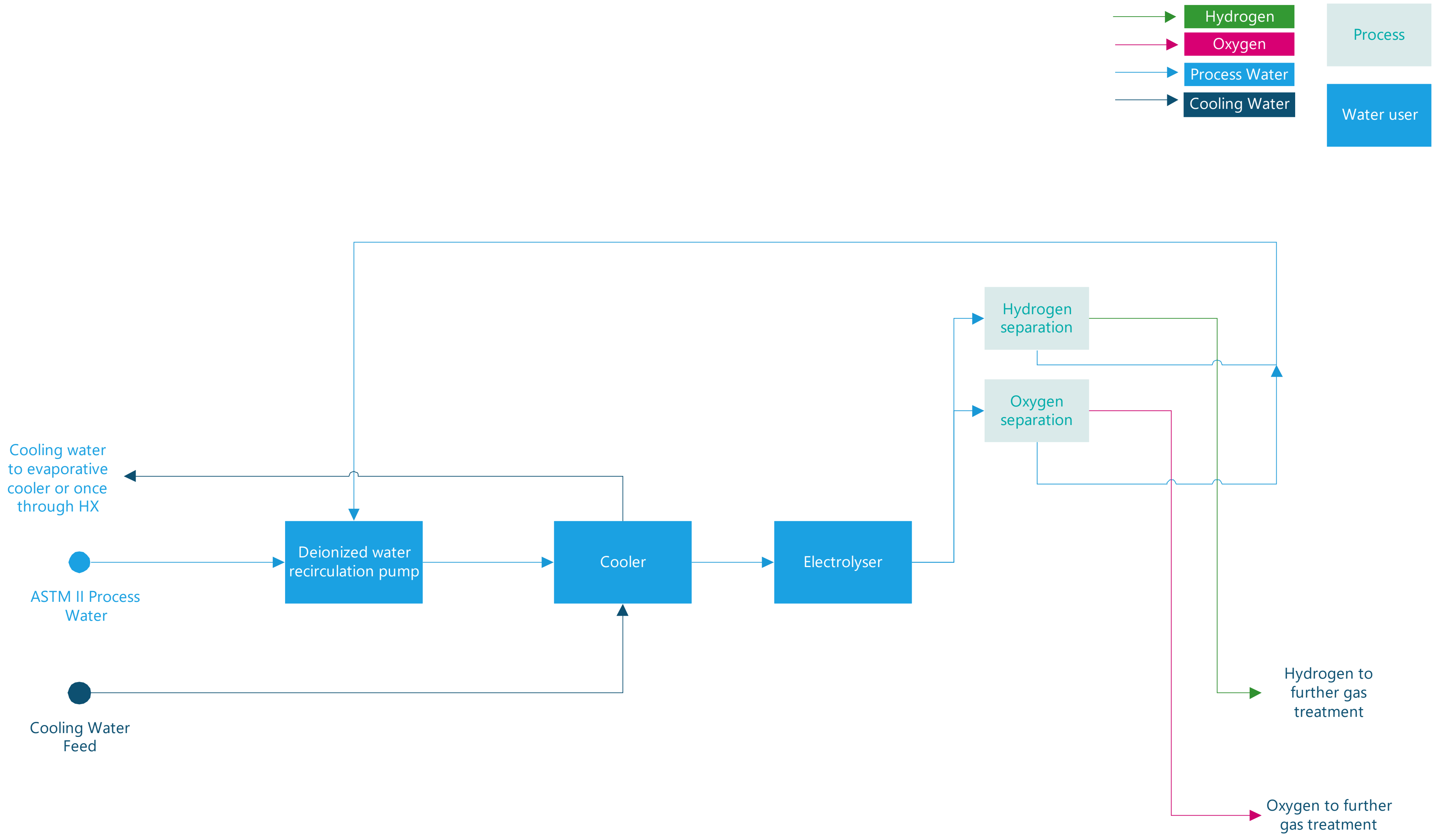
Treatment process for seawater



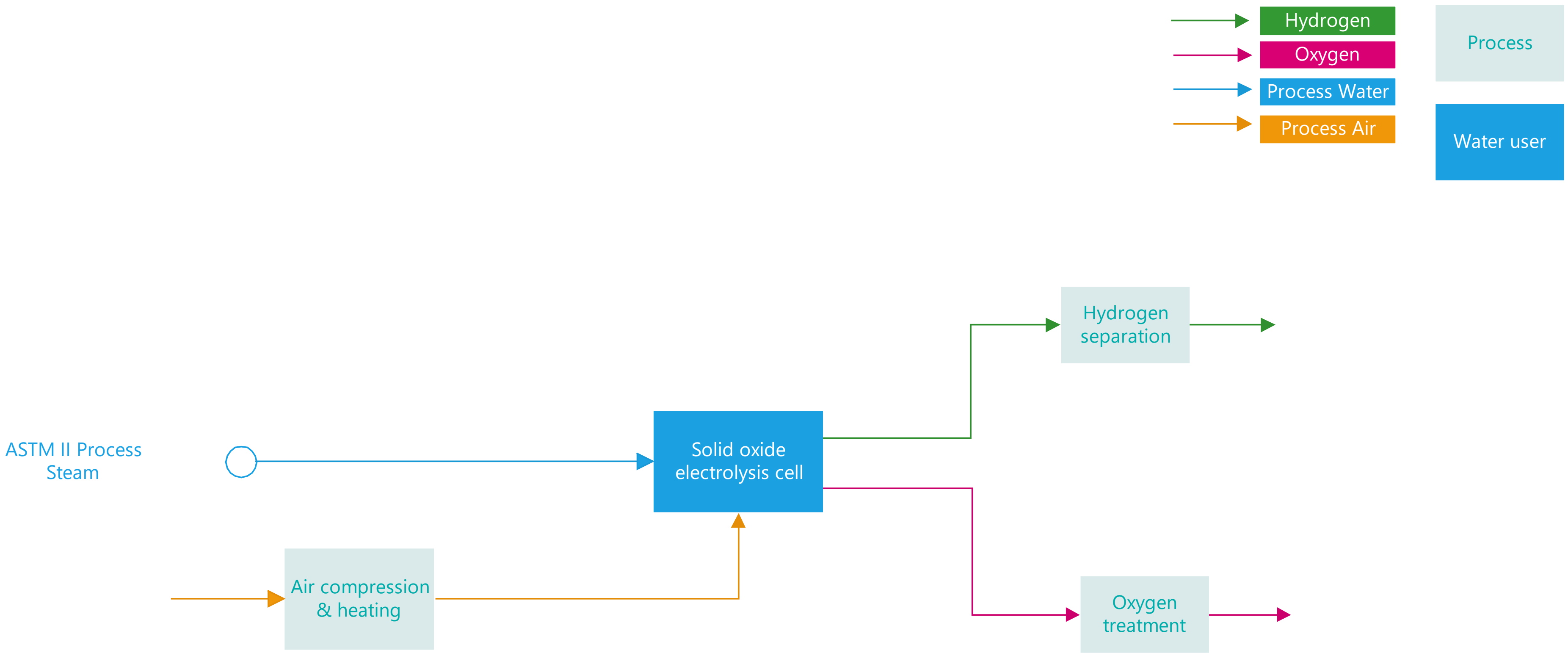
Alkaline electrolyser



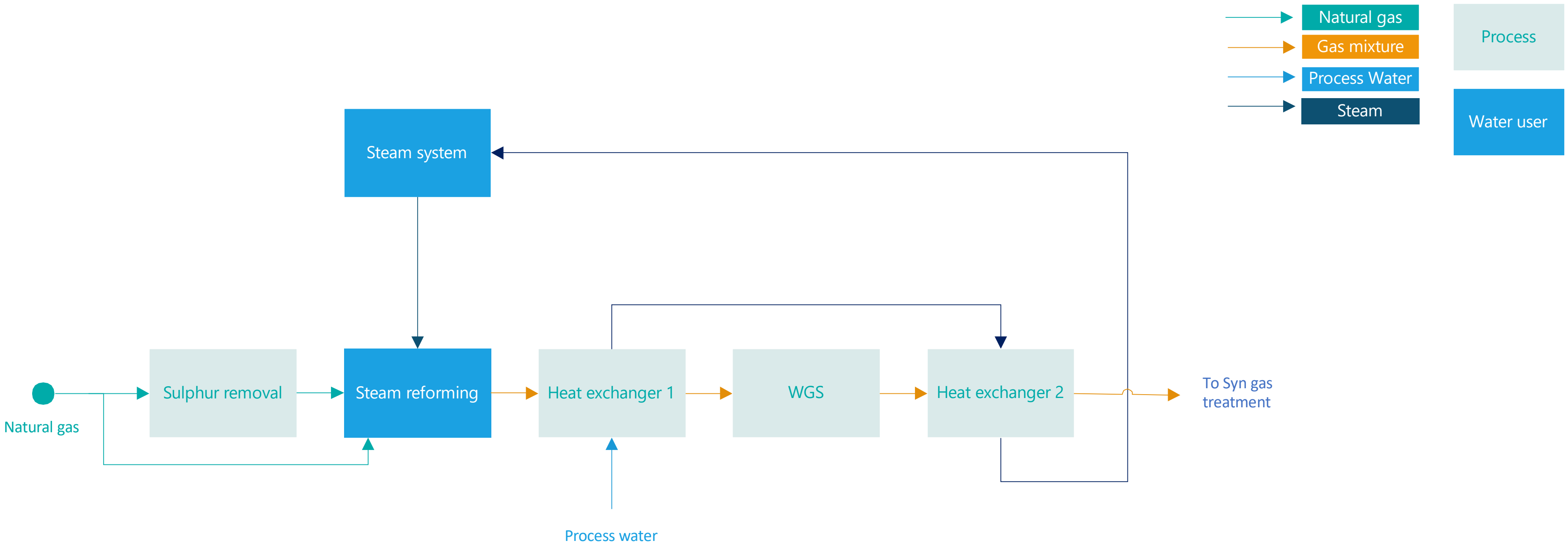
PEM electrolyser



SOEC

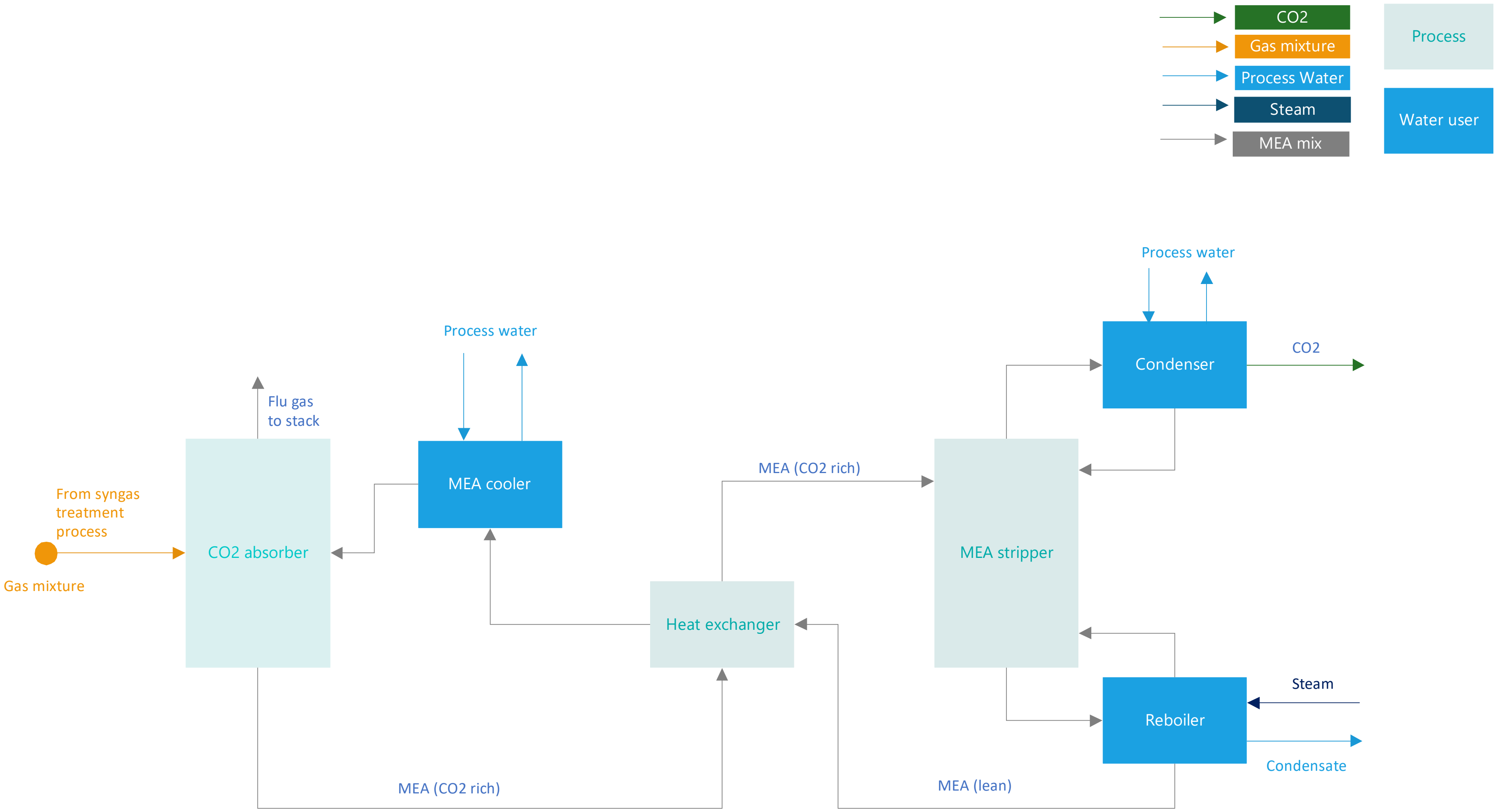

Hydrogen
Oxygen
Process Water
Process Air
Process
Water user
Hydrogen separation
ASTM II Process Steam
Solid oxide electrolysis cell
Air compression & heating
Oxygen treatment

SMR process



Natural gas
Gas mixture
Process Water
Steam
Process
Water user
Steam system
Natural gas
Sulphur removal
Steam reforming
Heat exchanger 1
WGS
Heat exchanger 2
To Syn gas treatment
Process water

CCU process



CO2
Gas mixture
Process Water
Steam
MEA mix
Process
Water user
Process water
Condenser
CO2
Process water
Flu gas
to stack
MEA cooler
MEA (CO2 rich)
From syngas
treatment
process
CO2 absorber
MEA stripper
Gas mixture
Heat exchanger
Steam
Reboiler
Condensate
MEA (CO2 rich)
MEA (lean)

UK Government

CS-NOW

Climate services for a net zero resilient world