


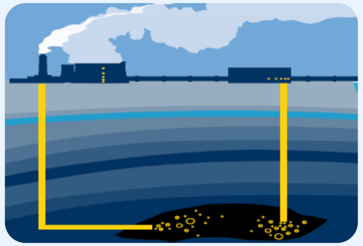

HICP
HUMBER INDUSTRIAL CLUSTER PLAN

# HICP Water Study

UK Research and Innovation

HEY Hull and East Yorkshire Local Enterprise Partnership

CATCH

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ERM

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# Contents

# Context & Objectives

## Context

- A study conducted by the Environment Agency[1] in early 2022 has indicated that **the South Humber region is 'seriously' water stressed** in their assessment of water availability.
- Water stress in the Humber region is forecast to increase due to climate change and growing demands for water from domestic and industrial use. Current pathways forecast that the Humber could be in a **water deficit before 2030[2].**
- Excessive extraction and usage of water could impact local biodiversity and compete with agricultural and municipal usage.
- Since fresh water is a finite natural resource, **water could be a limiting factor for the commercial-scale deployment of decarbonisation technologies**, which could potentially require significant amounts of water and could lead to certain areas of the UK becoming water stressed.
- Unsustainable water use within the Humber region could lead to long-lasting damage to the local ecosystems without proper management.
- **Carbon capture** and **low-carbon hydrogen production** technologies are expected to play a significant role in ensuring the Humber cluster achieves its Net Zero target.
- This study considers water usage from **CCS enabled hydrogen, electrolytic hydrogen and carbon capture technologies**.

## Objectives

- Identify the key industrial water sources in the Humber region and their capability to supply the increased water demand arising from the deployment of core decarbonisation technologies between now and 2040.
- Review the water demand from the main energy intensive industries (and power generation facilities) currently operating in the Humber.
- **Estimate future water requirements associated with carbon capture and low-carbon hydrogen production** in the four scenarios developed in Lot 1.
- Identify the key differences in water demand for North and South Humber regions.
- Discuss to what extent water availability could be a constraint in the future deployment of these technologies in the Humber, and discuss potential ways to mitigate this constraint.
- Identify the potential environmental impacts of increased water demand on the local environment.

[1]Environment Agency 2022 – Pathfinder research project.

[2]Anglian Water – Water Resources Management Plan 2019 – see slide.

# Contents

# Water is a key resource required for the decarbonisation of the Humber and should be considered in parallel to plans to reduce $CO_2$ emissions

**Water – or, more precisely, its scarcity – is an issue that needs to be urgently addressed in the UK**

- Increased water stress in the UK is being driven by a range of factors including[1]:
  - Climate change
  - Over abstraction
  - Population growth
- Government, regulators, and industry (including public water companies) all have a role to play to address water scarcity.
- The deployment of low-carbon technologies such as carbon capture and hydrogen production that are likely to play a crucial role in achieving net-zero could further increase water stress in the Humber region unless managed sustainably.

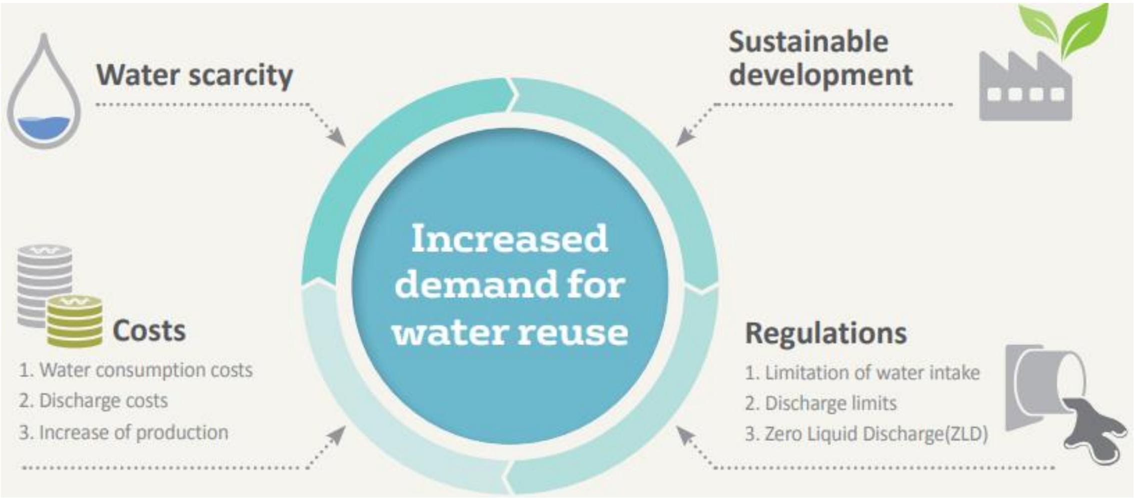
***The Humber must ensure future water abstractions are sustainable as low-carbon technologies are deployed***

**Groundwater is used to supply drinking and other water needs in the Humber region**

- Ground water is a hidden, yet precious stock that once polluted or depleted (via over use), is expensive and time consuming to restore.
- Over abstraction of groundwater in the Humber region could lead to saline intrusion, where salt water moves into freshwater aquifers.

***Groundwater sources can take decades to restore once polluted***

**Demand for water reuse[2]**




**Water reuse will be essential in the future management of water resources**

- Water reuse and recycling systems can minimise the requirement for new water abstractions and are likely to be suitable for both new and existing facilities.
- Deploying water reuse / recycling systems is likely to **require the installation of additional plant** at a site level or transport infrastructure to connect to a third party treatment facility.
- Optimal water management has the potential to replenish ground and surface water bodies at times of water surplus, to ensure there are supplies available during periods of water scarcity.

[1]Environmrnt Agency 2020 - Meeting our Future Water Needs: a National Framework for Water Resources
[2]Veolia – Sustainable water management for recycling & reuse

# Over consumption of groundwater today can have a delayed impact on surface water flows in the future, with negative impacts potentially occurring hundreds of years from now[1]

**The challenge for future water management is to store more green water in soil and plants, as well as storing more blue water in surface and ground water bodies**

- Global blue water withdrawals have increased by roughly 1% per year since the 1980s as demand in developing countries has surged.
- Groundwater supplies are being systematically diminished by a rate of extraction at 1-2% per year globally, outpacing recharge rates.
- There is increased uncertainty about future water availability and the impact that climate change will have on water resources including surface water flows and groundwater recharge.
- Even non-consumptive use may render the water unavailable to other potential users, simply because it needs to be available for temporary withdrawal.

***Water consumption can have more damaging environmental impacts than water abstraction as there is a net removal of water from the local ecosystem[2]***

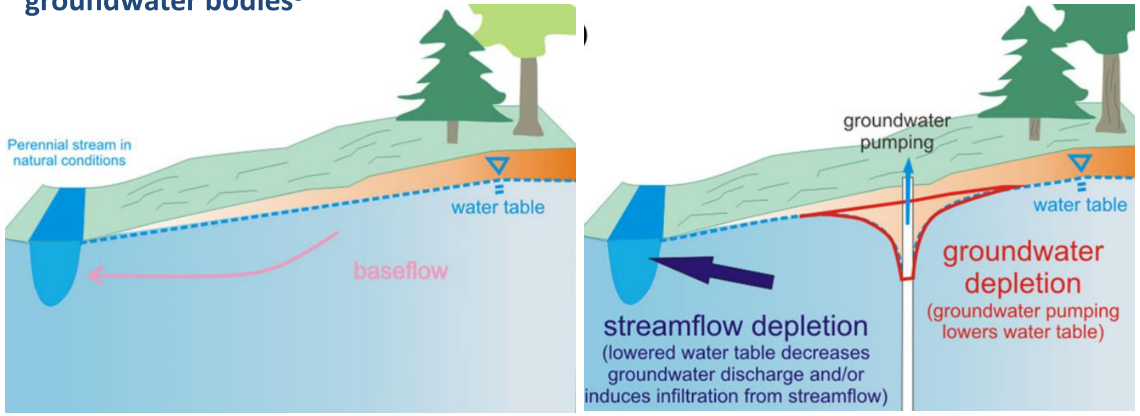
***Sustainable abstraction***

- Sustainable water withdrawal can have minimal impact on the environment and local water balance.
- Sustainable water consumption relies on surface or ground water bodies recharging faster or at the same rate as water consumption.

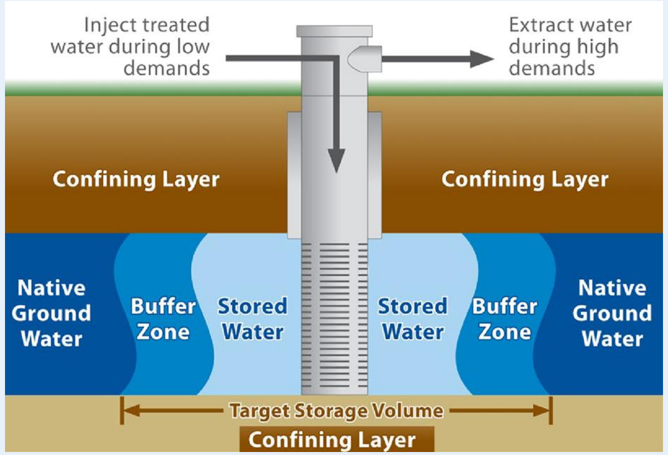
***Sustainable water abstraction in the Humber is managed by the Environment Agency through Catchment Abstraction Management Strategies (CAMS)***

***While climate change can cause dramatic changes to weather and ecosystems on the surface, the impact on the world's groundwater is likely to be delayed, representing a challenge for future generations[1]***

**Unsustainable abstraction can result in the depletion of both surface and groundwater bodies[3]**




**Managed aquifer recharge system[4]**




Managed aquifer recharge (MAR) is a technique for improving groundwater recharge and maintaining aquifer levels to support water storage.

MAR is an effective buffer against future fluctuations in water demand, drought, and climate change.

***There are no known MAR systems operating in the Humber today***

[1]CarbonBrief 2019 - Climate change's impact on groundwater could leave 'environmental timebomb' [2]IEA 2016 - Water-Energy Nexus [3]Gleeson and Richter 2017 - How much groundwater can we pump and protect environmental flows through time? [4]Agriculture Policy Review 2021 - Potential Adoption of Managed Aquifer Recharge Systems

# Contents

# Public water services in the Humber are provided by Yorkshire Water and Anglian Water

## Water supply and sanitation services in the Humber region are provided by two water and sewerage companies

### Yorkshire Water[1]

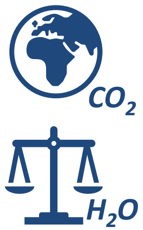
- Yorkshire Water already has a grid network that allows water to be moved around Yorkshire to help balance supply with demand.
- The interconnected nature of the Grid surface water zone (SWZ) means that even areas mainly supplied by groundwater sources have the same level of service as those supplied by surface water sources.

### Anglian Water[2]

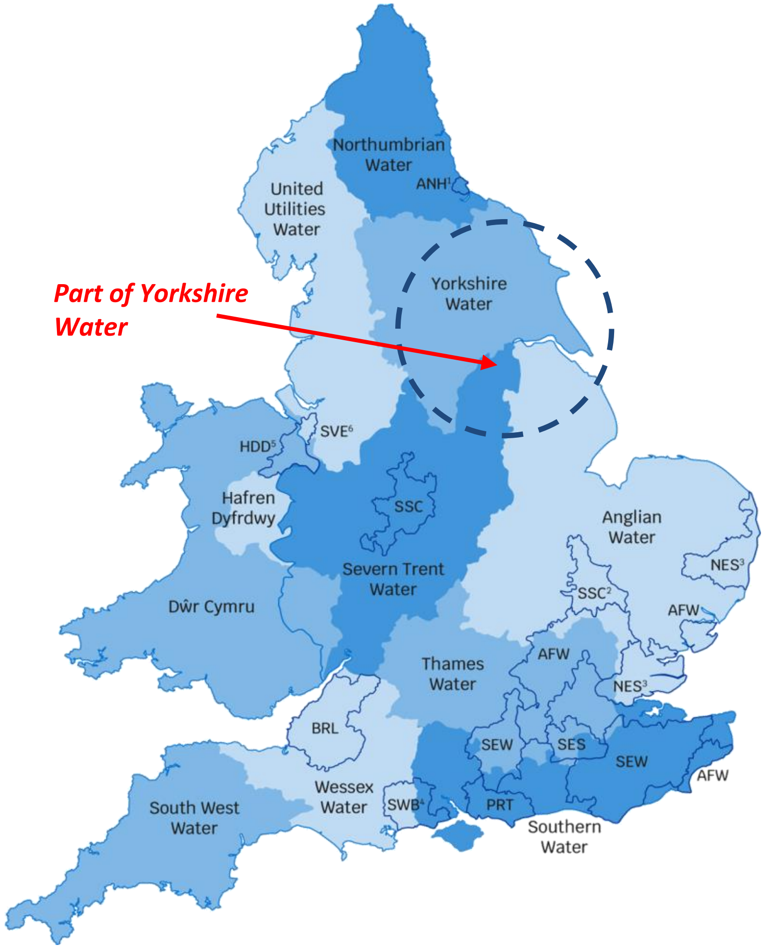
- 50% of supply is from surface water (reservoirs and rivers).
- 50% of supply is from groundwater stored in underground aquifers.

*Climate change = <u>Global</u> challenge*

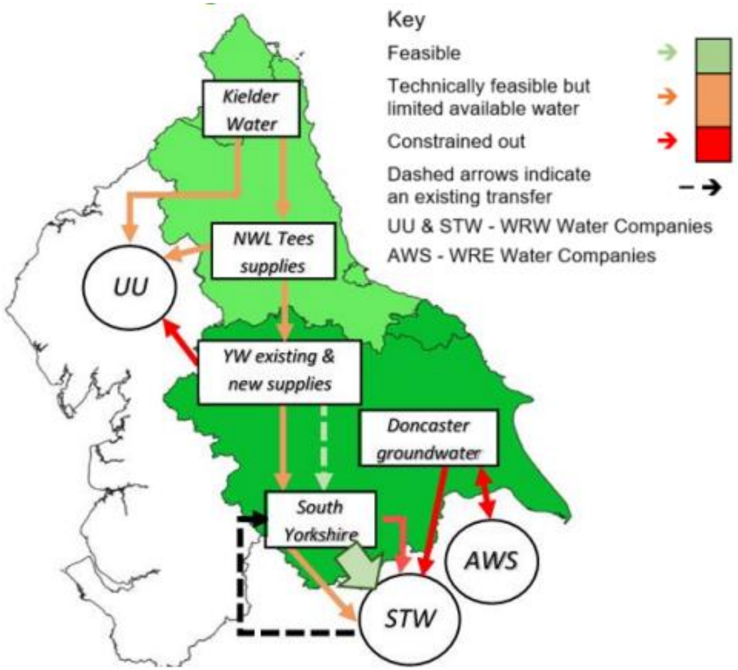
*Water balance = <u>Local</u> challenge*




## Water and Sewerage companies in the UK[3]




## Water Resources North – options for water transfers[1]




**Water Resources West (WRW)**

- **UU** United Utilities Water
- **STW** Severn Trent Water

**Water Resources East (WRE)**

- **AWS** Anglian Water

***Water transfers are possible and already operational in some regions***

# Catchment Abstraction Management Strategies (CAMS) are developed by the EA to maintain sustainable regional water abstraction

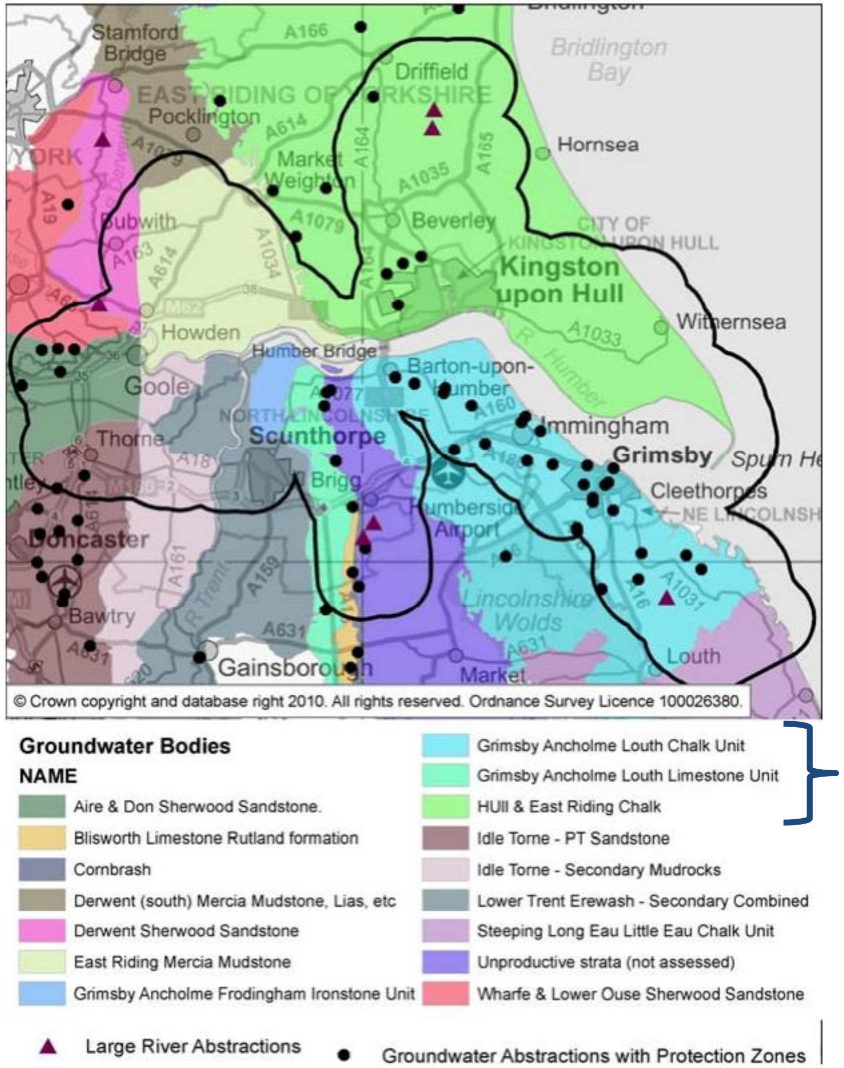
**The availability of water for abstraction from inland resources is assessed as part of Catchment Abstraction Management Strategies CAMS**

- The Environment Agency regulate the abstraction of surface and groundwater to ensure water resources are managed sustainably, avoiding unnecessary water use and damage to the environment.
- The river abstractions on the Ancholme provide potable water and non-potable water for industries on the south bank of the Humber[1]. Abstractions on the rivers Ouse, Hull and Derwent are particularly important for potable supply on the North Bank of the Humber.
- The most important groundwater bodies in the vicinity of the river Humber are the **Hull and East Riding Chalk, the Grimsby Ancholme Louth Chalk and the Grimsby Ancholme Louth Limestone[1].** This is due to the higher quality water that can be abstracted from these groundwater bodies.

***A large part of the South Humber is regarded as over abstracted, particularly the chalk aquifer and associated surface water streams***

- The EA may have to add constraints to licences such as '[hands off flow](#)' (HOF) or '[hands off level](#)' (HOL) conditions to protect the environment and the rights of other abstractors*.
- As a result, a licence grant doesn't guarantee a supply of water.
- These conditions specify that if the flow in the river drops below what's needed to protect the environment, abstraction must reduce or stop.
- In dry years, restrictions are likely to apply more often, which will affect the reliability of supply.

**Groundwater resources and river abstractions in the Humber[1]**



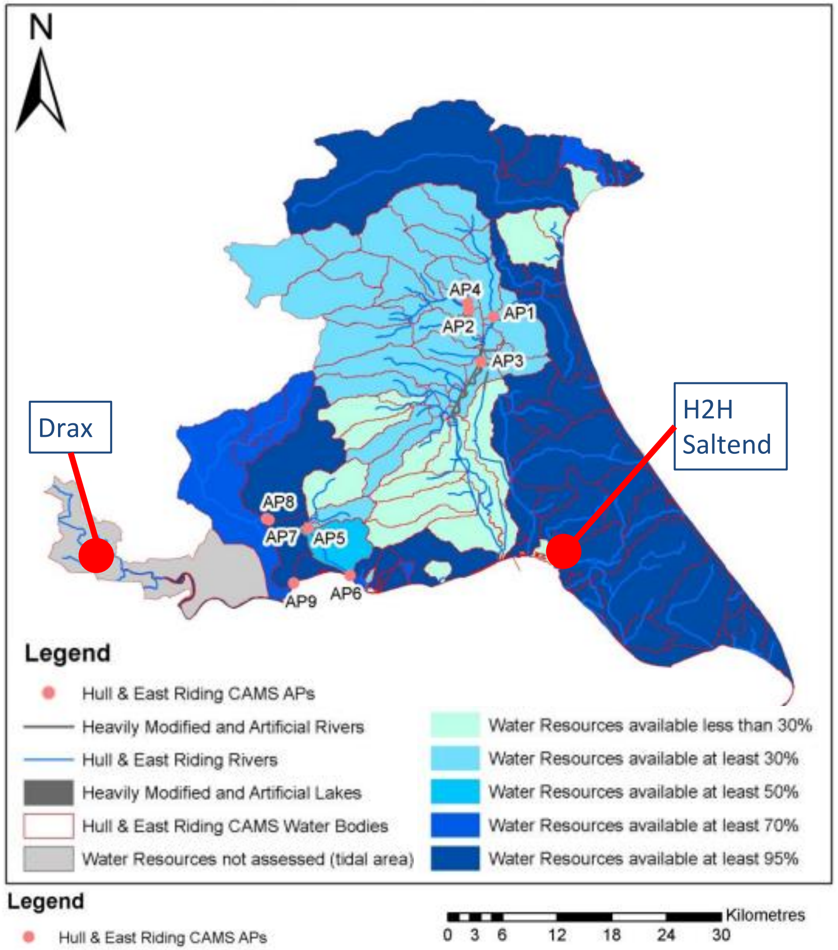

***Important ground water sources in the Humber***

[1][EA 2011 - The Humber environment in focus](#)

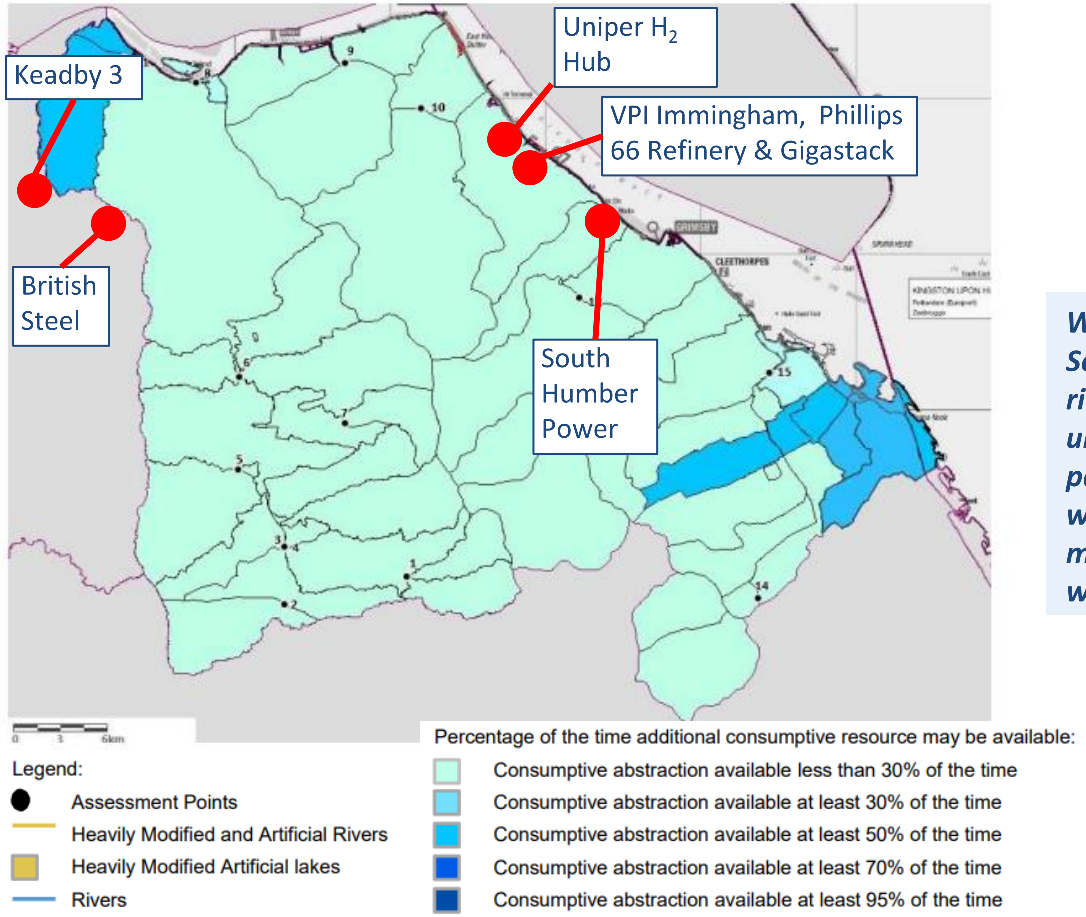
*HOF conditions are applied to surface water abstraction licenses. HOL conditions are applied to groundwater abstraction licenses.

# A large part of South Humber area is already regarded as over abstracted

### Hull and East Riding water resource reliability (% of time)[1]




### Grimsby, Ancholme and Louth water resource reliability (% of time)[2]




***Water abstraction South of the Humber river could be unavailable for large parts of the year without careful management of water resources***

[1]EA - Hull and East Riding Abstraction Licensing Strategy 2013
Water abstraction sources in the North Humber region (2013).

[2]EA - Grimsby, Ancholme & Louth Abstraction Licensing Strategy 2020
Water available for licencing in the South Humber region (2020).

# Regions surrounding the Humber could be in a water balance deficit by 2040

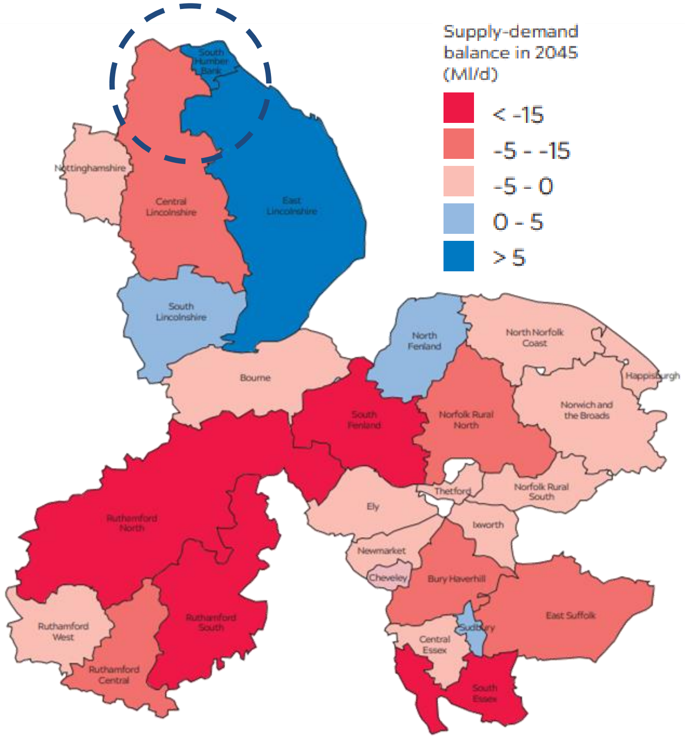
### Yorkshire Water[1]

- Yorkshire water supply / demand balance forecast predicts there will be sufficient supply to meet household demand to 2040.
- This will require: water system leakage reduction energy efficiency improvements and climate change adaption measures

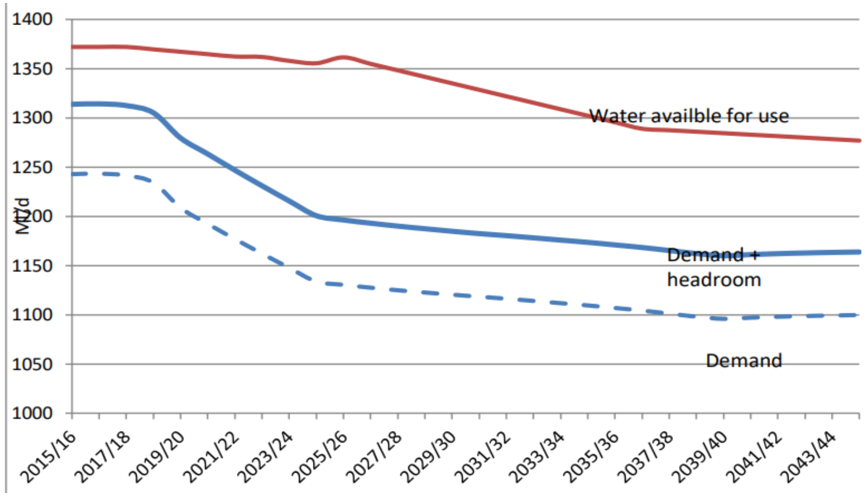
### Anglian Water[2]

- Anglian water supply / demand balance forecast predicts that water demand is likely to exceed available supply.
- This water balance mismatch is driven by a number of factors in Eastern England including:
  - It is the driest region in the UK
  - It has the highest forecast population growth outside of London
  - Increasing water will be required for periods of extreme drought
  - 30% of the land is below sea level

**Anglian Water supply-demand balance in 2045[2]**

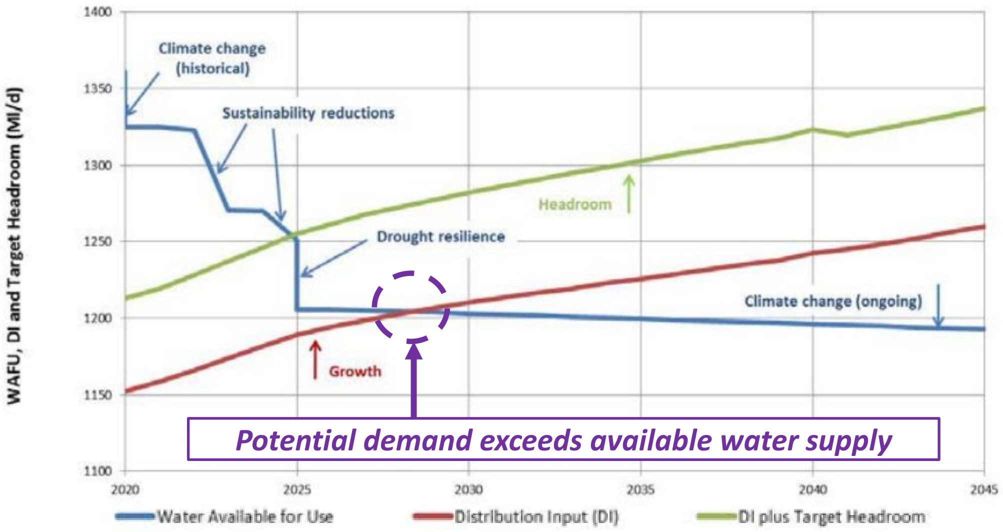



**Water resource management – supply demand balance forecasts[1,2] (M litres/d)**




*Yorkshire Water[1]*

*(Grid water zone)*




*Anglian Water[2]*

# Contents

# Public water supply (PWS) makes up approximately half of abstractions in England

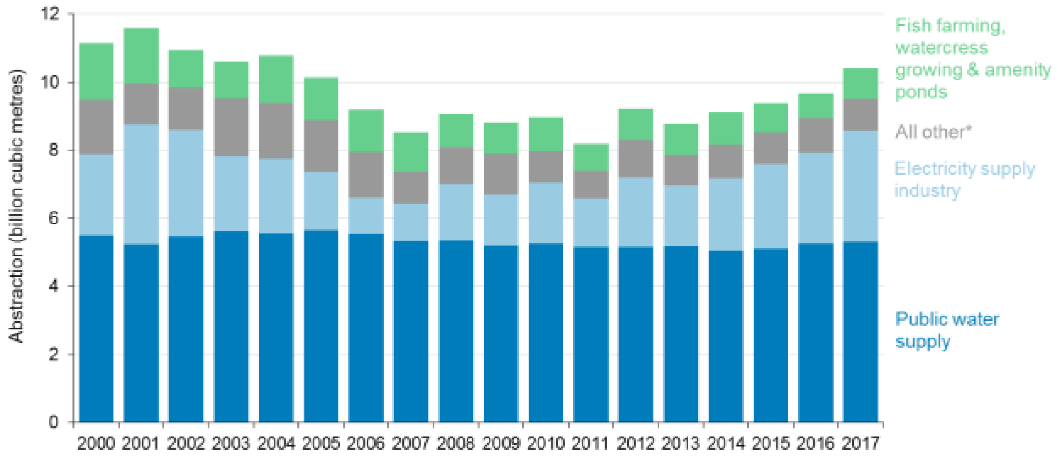
### Public water supply (PWS)[1]

- In England, water supply and sewerage services are provided to customers by privately owned water companies.
  - Water companies' regulatory duties are primarily laid down in the Water Industry Act 1991.
  - These include the duties to supply wholesome potable water, treat wastewater and protect the environment.
- Abstraction for public water supply (PWS) makes up over 50% of total abstraction in England, including the Humber region.

### Reasons for changing water abstraction[1]

- **Weather conditions** - for example, drier and warmer years could result in an increase in abstraction for agriculture and spray irrigation.
  - The highest 2 years for abstraction for the purpose of spray irrigation correspond with the lowest 2 years of annual levels of rainfall since 2000 (see figure right).
- **Changes in sector activity** - changes in the level of activity in different sectors or the deployment of new technologies such as capture and hydrogen production.
- **Efficiency of usage** - improvements being made in the efficiency of water usage for existing operations.
- **Changes to abstraction licences** - such as the issue of new licences and modifications to, or revocation of, existing licences.
  - The EA issues abstraction licences for water bodies where water is considered to be available.

### Estimated abstractions from non-tidal surface water and groundwater in England, 2000 to 2017[1]




**Note**:* 'All other' includes Spray irrigation, Agriculture, Private water supply, Other industry and Other
**Source**: Environment Agency

### Electricity generation[2]

- In the UK (2016), 63% of the thermoelectric generation capacity is located on rivers, two-thirds of which is on non-tidal freshwater reaches.
- The consumption of freshwater from thermal power could rise considerably with widescale adoption of power CCS.
- The River Trent (which connects to the Humber estuary) is an important cooling water source, supporting the most generation capacity of any river in the UK.

***Thermoelectric generation is responsible for the majority of non-public water abstractions in the UK – primarily for cooling***

[1]DEFRA 2019 - Water abstraction statistics: England, 2000 to 2017
[2]Byers et al 2016 - Water and climate risks to power generation with carbon capture and storage

# Water demand for cooling has been the primary driver for water usage in power and industrial sectors

**In the UK, electricity generation from non-renewable sources comes primarily from thermoelectric power stations that have significant water abstraction demands for cooling[1]**

- Power CCS could be crucial for supporting increased renewable deployment and supplying dispatchable power at times of low generation.
- However, carbon capture is an energy-intensive process resulting in parasitic loads and reductions of net thermal efficiency output on a power plant.
  - Carbon capture can increase cooling water use by 44-140%.
  - **Carbon capture can also produce water** when the flue gas is cooled, resulting in condensation of water. If this volume of condensed water is greater than the consumptive losses of the capture system, the capture facility can be a net producer of water.
- **Once-through (open loop)** cooling uses water to cool a power station's exhaust heat directly and is recognised as the Best Available Technique (BAT) due to its relatively high efficiency, and therefore low cost and $CO_2$ burn.
  - There are alternative cooling methods which withdraw less but these are less efficient and consume more (see table right).

***Future freshwater scarcity could compromise UK thermal power stations' ability to generate electricity***

**Characteristics of power generation cooling systems[2]**

| Cooling system | Description | Abstraction Volumes ($m^3$/MWh) | Consumptive losses (% of abstraction) | Energy penalty (% of electrical output) |
|---|---|---|---|---|
| **Once through (open loop)** | Involves the withdrawal of water for single use in the cooling process, after which it is immediately returned to its source. | 43-168 | 0-1% | 0.7-2.3% |
| **Closed loop (re-circulatory)** | Heat is removed to the air by recirculating water cooled in ponds or under cooling towers that may be fan-assisted or natural draught. | 1-5<br>*22-67* | 61-95% (wet tower)<br>*4-9% (pond)* | 1.8-6.3% |
| **Air-cooled (dry)** | Heat is removed by air circulation via fans and radiators. A setup that can operate without water. | 0 | - | 3.2-11.2% |
| **Hybrid** | Cooling towers that can operate both with and without cooling water – either combining a wet/dry cooling tower, or a dry then wet system in series. | 1-67 | 61-95% | 1.8-11.2% |

Cooling water configurations are shown in the appendix.

[1]Byers et al 2016, Water and climate risks to power generation with carbon capture and storage

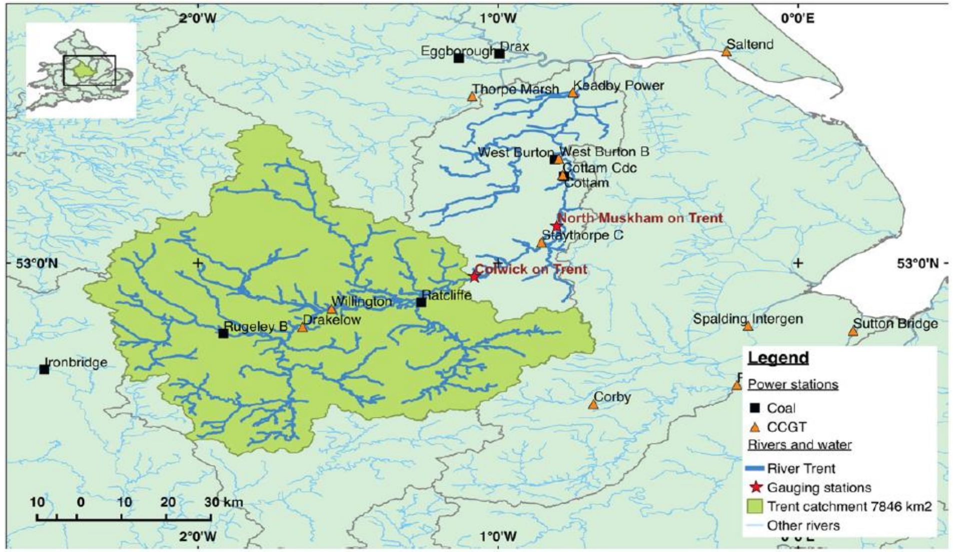
[2]Murrant et al 2017, Water use of the UK thermal electricity generation fleet by 2050

# Rivers and ground water abstractions are a key source of cooling water in the Humber region for power and industry

### Cooling systems for power stations in the Humber region[1]

| Cooling Type | Power station | Capacity (MW) | Type | Cooling Source |
|---|---|---|---|---|
| Open Loop | Keadby | 735 | CCGT | Estuarine Water |
| | South Humber Bank | 1,365 | | |
| Closed loop | Drax | 1,800 | Coal/Biomass | Estuarine Water |
| | Glanford Brigg | 150 | CCGT | Fresh Water |
| | Saltend | 1,200 | | Estuarine Water |
| Hybrid | Immingham CHP | 1,240 | CCGT CHP | Estuarine Water |
| | Killingholme A | 470 | CCGT | |
| | Killingholme B | 900 | | |

### UK power stations on the River Trent[3]




**The Humber has plans to develop power CCS and hydrogen power that will replace many existing unabated facilities[2]**

- Several coal power stations have recently been decommissioned or converted to biomass feedstock, such as Drax. Drax plans to develop the world's largest carbon capture facility.
- SSE and Equinor plan to develop two new power stations in the Humber to replace the existing unabated power station. Keadby 3 will have CCS, whereas Keadby Hydrogen will run on 100% low-carbon hydrogen. The cooling systems that these power stations will deploy have not yet been determined.
- SSE and Equinor have also acquired Triton Power which includes the acquisition of the Saltend power station. Plans have been announced that will convert the power station to run on a 30% hydrogen blend by 2027.
- VPI Immingham plan to deploy CCS on two of their CHP trains, converting the third to run on low-carbon hydrogen.

***Further work is required to understand how the decommissioning of existing plants and the deployment of new projects will impact the local water supplies***

[1]Murrant et al 2017 - Water use of the UK thermal electricity generation fleet by 2050

[3]Byers et al 2016 - Water and climate risks to power generation with carbon capture and storage

[2]HICP 2022 - News

# The industry and power sectors make up 5% and 4 % of the total water demand in the North and East of England

**Data on water availability and use is produced by public water companies and regional groups**

- **Water resource management plans (WRMPs)** are developed by public water companies. These include Yorkshire Water and Anglian Water in the Humber.
  - WRMPs are statutory plans developed which address the availability of future water resources, focusing on maintaining a reliable supply for customers of the water company.
  - WRMPs are published every 5 years, with the most recent plans published in 2019. The draft for 2024 is expected to be published in 2024 with lower water availability in the Humber regions expected.
- **Water resource regional plans (WRRPs)** are developed by five regional groups that bring together the water companies that operate in each of England's regions.
  - WRRPs aim to deliver the right strategic water solutions for the region as a whole.
  - The Humber sits between Water Resources East (WRE) and Water Resources North (WReN)

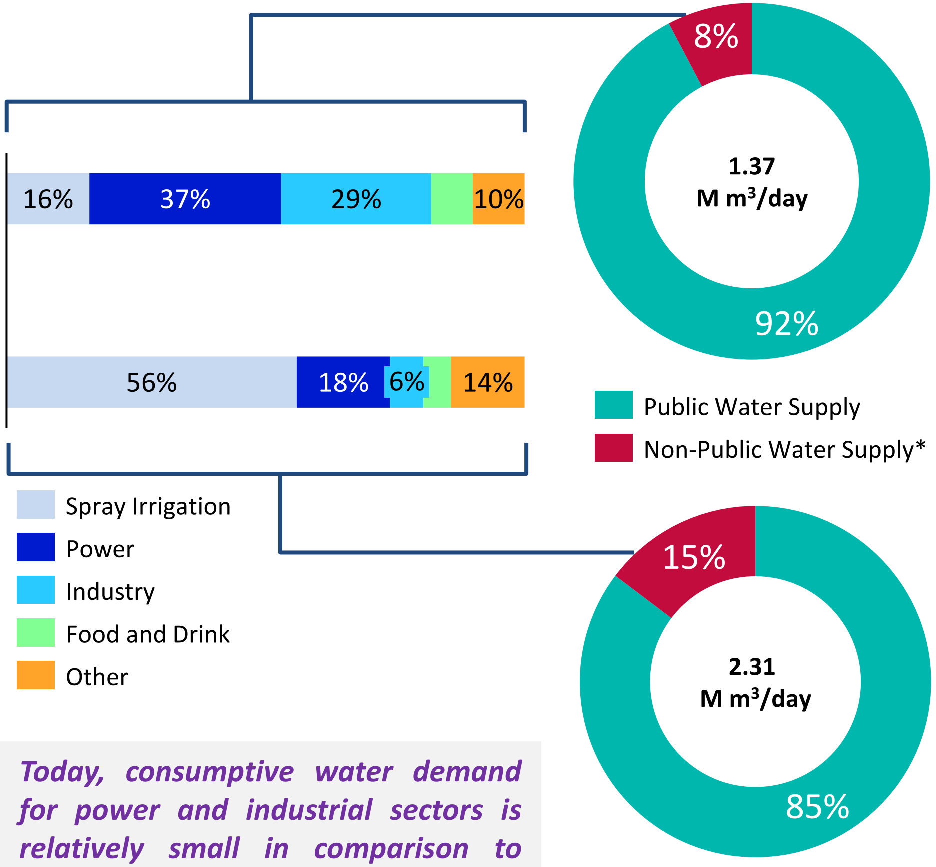

**Consumptive water demand for industry in the Humber**[1]

**0.20 M m³/day**

*North Humber = 0.10 M m³/day*

*South Humber = 0.11 M m³/day*

## Average daily regional *consumptive* water use (2020)[2,3]




**Water Resources North**

(inc Yorkshire Water, Northumbrian Water and Hartlepool Water)

***Non-public water supply includes all supply not provided by public water companies**

**Water Resources East**

(inc Anglian Water, Essex and Suffolk Water, Cambridge Water, Severn Trent Water and Affinity Water)

***Today, consumptive water demand for power and industrial sectors is relatively small in comparison to public water supply***

[1]Environment Agency 2022 – Pathfinder research project

[2]WRE 2022 - The Emerging Water Resources Regional Plan for Eastern England     [3]WRN – Emerging Plan for Consultation

# Contents

# Water consumption for $CO_2$ capture systems is primarily driven by cooling requirements

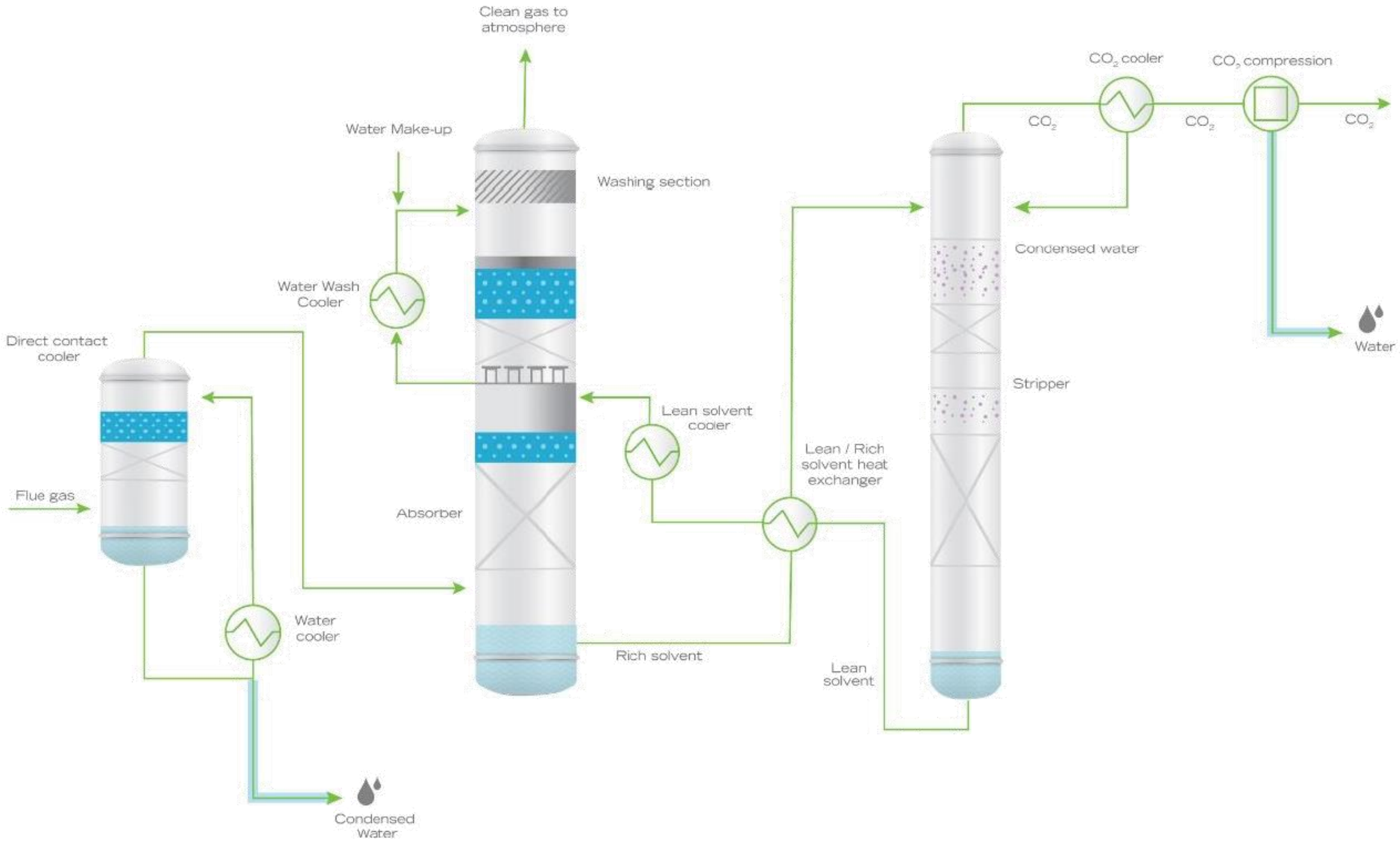
**Adding a $CO_2$ capture system to an existing power station or industrial facility can increase water use**

- This is largely due to $CO_2$ capture system cooling requirements and, to a smaller extent, for process makeup water.
- Each capture technology has specific water requirements depending on process equipment and configuration.
- Amine based solvents use a chemical absorption/desorption cycle to separate $CO_2$ from the flue gas. The solvent binds with the $CO_2$ in an absorber which is then routed to a stripping column where the temperature is increased, releasing the absorbed $CO_2$. The number of coolers in a post-combustion capture system will vary by application.
- Developing capture systems such as oxy-combustion, membrane or sorbent systems will require less water.

**The most significant need for makeup water is associated with the water wash section at the top of the absorber[1]**

- Fresh water is needed to limit the concentration of amines in the washing loop.
- The process of cooling the flue gas also produces water by condensation in the direct contact cooler.
- After proper treatment, this water can be used in the industrial facility or externally. Since this water is contaminated with flue gas impurities, it can however not be reused directly for make-up in the capture process without previous purification.

**Amine-based post-combustion $CO_2$ capture[1]**




***Water volumes required for process makeup are much smaller than the volumes of water required for cooling***

[1]Global CCS Institute 2016 – Water use in Thermal Power Plants Equipped with $CO_2$ Capture Systems

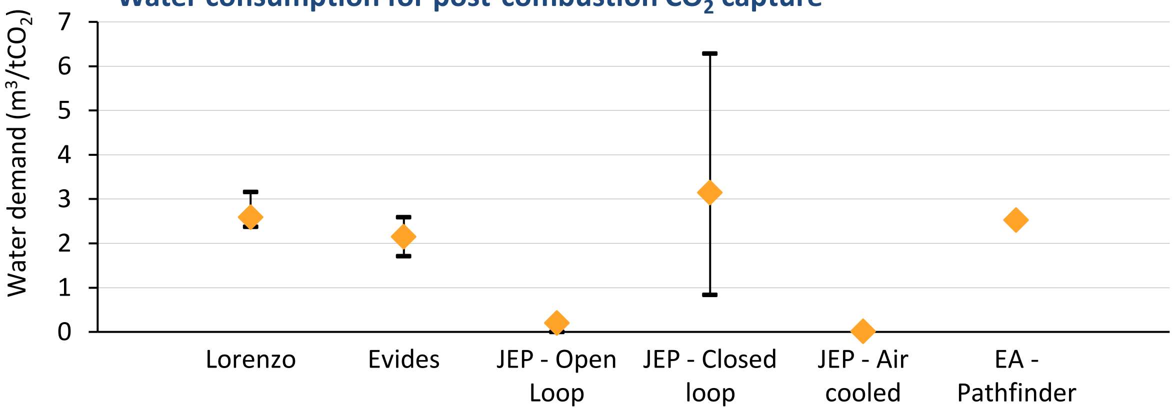
# Water consumption for $CO_2$ capture is highly dependent on cooling configuration

**Post-combustion $CO_2$ capture with an open-loop cooling system can actually lead to a reduction in water consumption[1,*]**

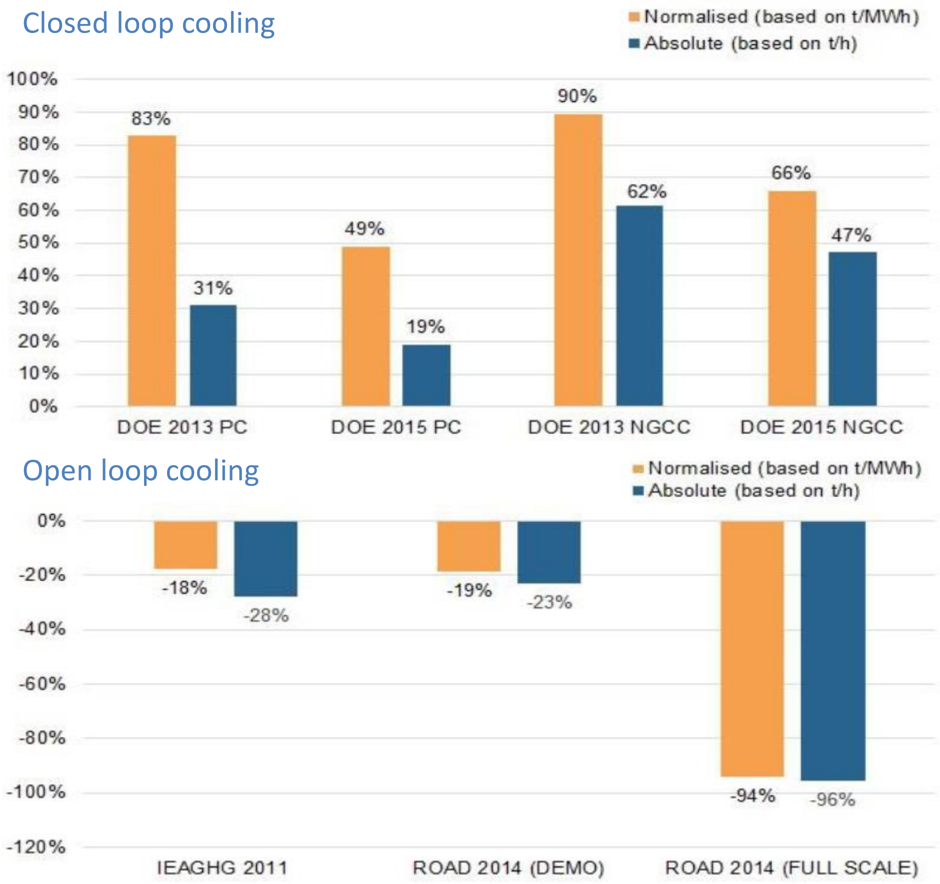
- With the addition of a $CO_2$ capture system, water is produced in the direct contact cooler (DCC) installed upstream of the absorber, where flue gas water is condensed and collected (see slide).
- Some water is also recovered from the $CO_2$ compression system.
- After proper treatment (to remove impurities), most of this water can be returned to the local ecosystem, offsetting the increased makeup requirements associated with the addition of the $CO_2$ capture system.
- If this water is recycled rather than returned to the local ecosystem, it would reduce external water supply needs.

***The normalised increase in water consumption is typically reported for $CO_2$ capture systems. However, the impact on local water resources will be associated with the absolute increase in volume of water consumption required for permitting (see figure right)***

**Water consumption for post-combustion $CO_2$ capture[1,2,3,4]**




**Percentage increase in water consumption for post-combustion $CO_2$ capture[1]**




*Open loop cooling systems have the highest rate of water withdrawal*

*Absolute refers to the actual amount of water ($m^3/h$)*

*Normalised refers to a quantity of water normalised to the output of the plant ($m^3/MWh$).*

[1]Global CCS Institute 2016 [2]Lorenzo et al 2020 - The water footprint of carbon capture and storage technologies [3]Evides 2022 [4]JEP 2021 – Projections of Water use in Electricity and Hydrogen Production *Water consumption volumes are very low as compared to the values for closed loop systems. Thus, relatively small changes in consumption result in large percentage changes.

# Contents

# CCS enabled hydrogen production consumes water as feedstock

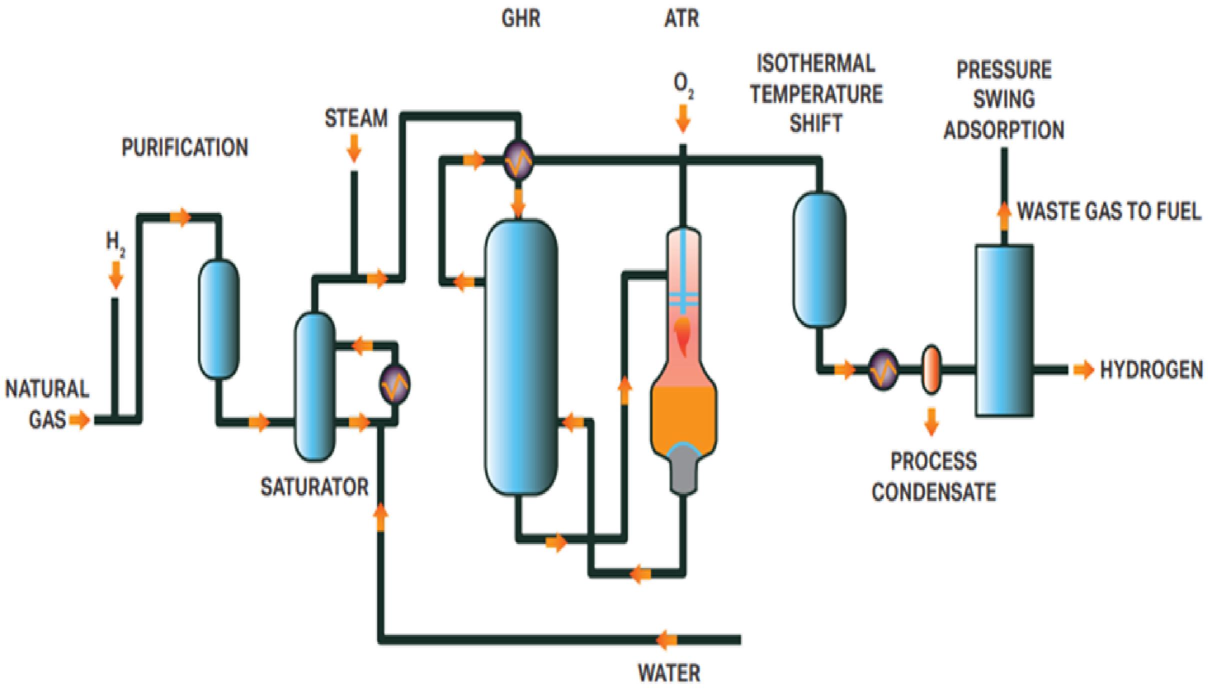
**Water is used as feedstock to generate steam in the CCS enabled hydrogen production process[1]**

- Auto Thermal Reforming (ATR) has been used commercially to produce grey hydrogen. However, the it has only recently been developed with the aim of producing CCS enabled hydrogen.
- In the UK, the Low Carbon Hydrogen (LCH) configuration (including a gas heated reformer (GHR)) is the primary configuration selected for major CCS enabled hydrogen projects.
- ATR is a combination of SMR (endothermic) and POX (exothermic) reactions.
  - Auto Thermal Reforming (ATR) adds steam to the catalytic partial oxidation (POX) process, increasing the hydrogen yield.
- Steam and natural gas are fed into the reformer at high temperatures to produce a mixture of hydrogen and carbon monoxide known as Syngas.
  - Steam reforming: $CH_4 + H_2O \rightleftharpoons CO + 3H_2$

**Water condensate is produced during the pre-combustion capture process[2]**

- Water use associated with pre-combustion $CO_2$ capture systems comes from process cooling and makeup water requirements.
- Makeup water may play a more significant role for pre-combustion systems compared to post-combustion systems due to the addition of the water gas shift (WGS).
- The WGS **consumes** a significant quantity of water, as steam is required to sustain the shift reaction.

**Low carbon hydrogen (LCH) process configuration[1]**



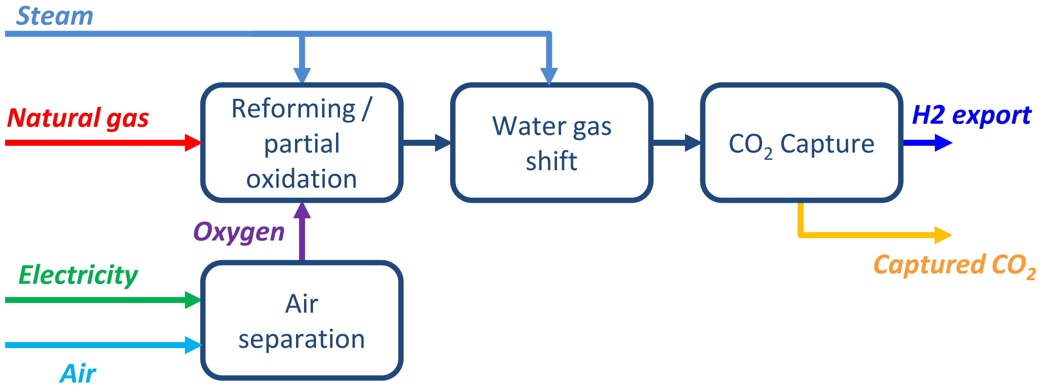

*Water is lost from the system during the pre-combustion $CO_2$ capture process*

Only LCH configurations will be considered in this study as this is the primary CCS enabled hydrogen production configuration in development in the UK / Humber.

[1]iChemE 2020 – Hydrogen: The future fuel today [2]Global CCS Institute 2016 – Water use in Thermal Power Plants Equipped with CO2 Capture Systems

# Feedstock water consumption for CCS enable $H_2$ is approximately half that of electrolytic $H_2$ production. However, the cooling requirements for CCS enabled $H_2$ are more water intensive

**Pre-combustion $CO_2$ capture process for CCS enabled hydrogen production[1]**

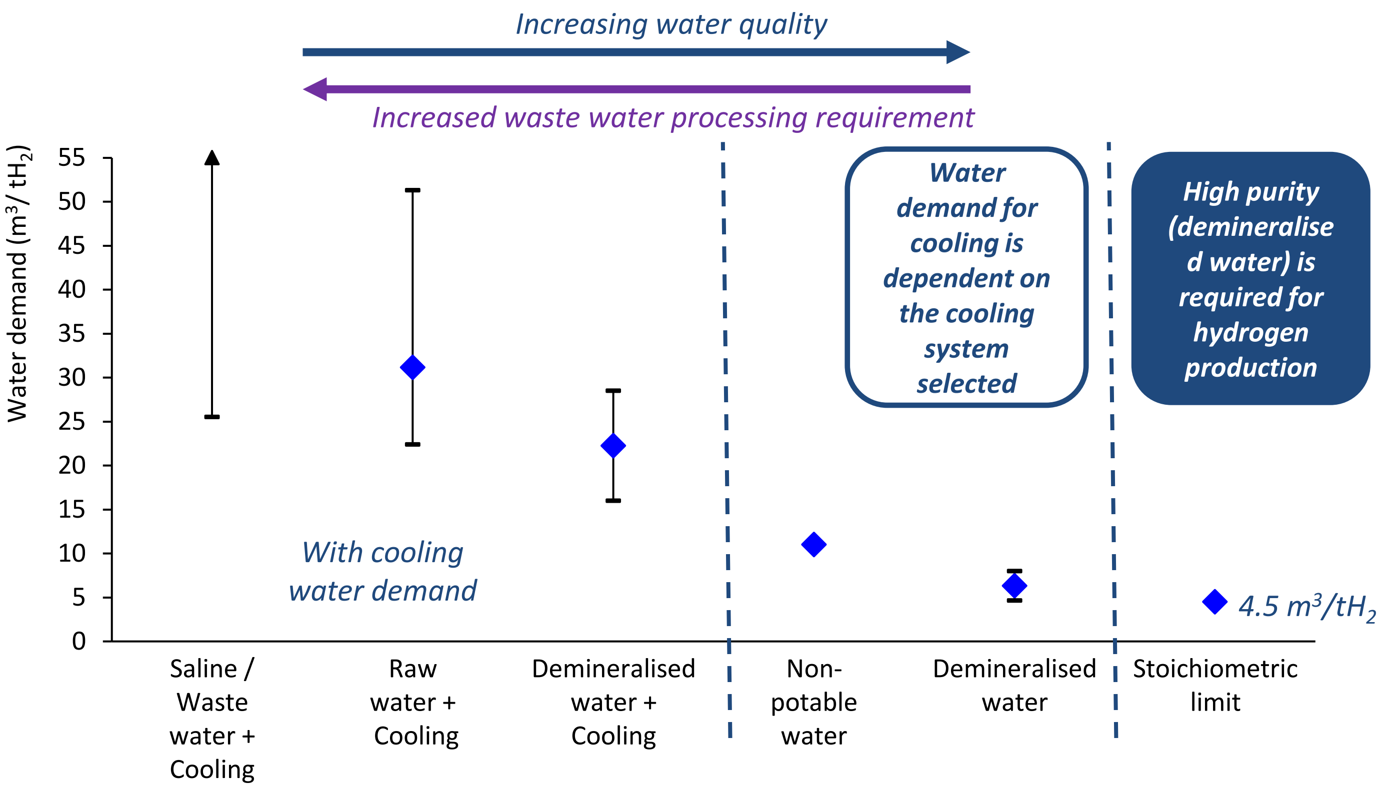



**Water quality impacts the volume of water that must be consumed in the hydrogen production process[4]**

- Raw (fresh water) needs to be demineralised before it can be used for hydrogen feedstock.
- The demineralisation process can result in significant waste water streams (up to 80% of input) – depending on the source water quality.

***Approximately 1.4m³ of raw water are required to produce 1m³ of demineralised water suitable for hydrogen production[5]***

**Water inputs for the CCS enabled hydrogen production process[2,3,4,5]**




- Water processing results in an increased concentration of impurities being fed into the waste streams.
- This water may not be able to be discharged to the environment without further treatment.


[1]Global CCS Institute 2016 – Water use in Thermal Power Plants Equipped with $CO_2$ Capture Systems
[2]H21 2019 – North of England
[3]CE Delft 2018 - Feasibility study into blue hydrogen
[4]GHD 2020 - Water for Hydrogen
[5]Silhorko-Eurowater 2022

# Contents

# Water consumption for electrolytic $H_2$ varies significantly with the purity of the water feed

**Water is used directly as a feedstock in the production of electrolytic hydrogen**

- An electrolyser is a device which splits liquid water ($H_2O$) into Hydrogen ($H_2$) and Oxygen ($O_2$) gases using electricity.
- The minimum water electrolysis can consume is about 9 $m^3/tH_2$.
- However, taking into account the process of water de-mineralisation, water consumption can be as high as 24 $m^3/tH_2$.

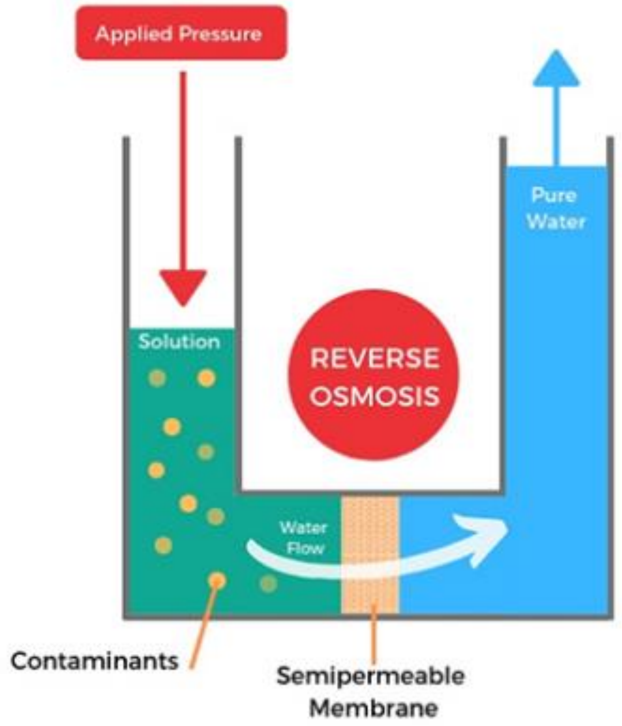
**Electrolysers need high-quality water which requires water treatment**

- A low-quality water can lead to faster degradation and shorter lifetime.
- Seawater can be purified by the desalination processes before being utilised for electrolysis feedstock.
- The leading desalination technology today is **reverse osmosis**, which uses an applied pressure and a semipermeable membrane to reject ions present in the water.
- Manufacturers typically quote water consumption of 10.5 $m^3/tH_2$ for demineralise water.
- Tap water requires treatment via the reverse osmosis process, increasing water consumption to 18-22 litres/$kgH_2$. This is increase further if greywater is utilised.

***Minimising water consumption in the pre-treatment process is crucial to reducing overall water consumption from electrolytic hydrogen production***

- Some water that is fed into the desalination process cannot be utilised, and the recovery defines the percentage of usable clean water that is produced by the process out of the total amount of feedwater.
- Today, recoveries of up to 50% are achievable, meaning that twice the amount of water desired at the outlet must be fed into the process.

**Reverse osmosis desalination process**

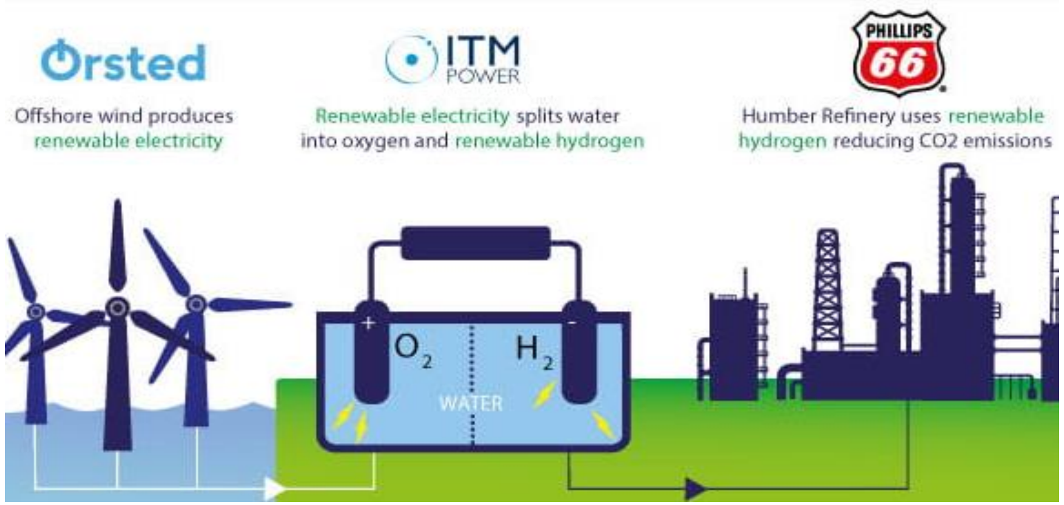



Energy Post EU 2021 - Hydrogen production in 2050
IEA 2019 – Future of Hydrogen
Element Energy 2018 – Hydrogen supply chain evidence base
BEIS 2021 – Gigastack Phase 2
ACS Energy Letters 2021 - Does the Green Hydrogen Economy Have a Water Problem?

# Industrial effluent waste water (“grey water”) can be utilised as feedstock for electrolytic $H_2$ production after water treatment in the Humber region

**Gigastack will use treated effluent waste-water from the Humber Refinery based on a cost benefit analysis[1]**

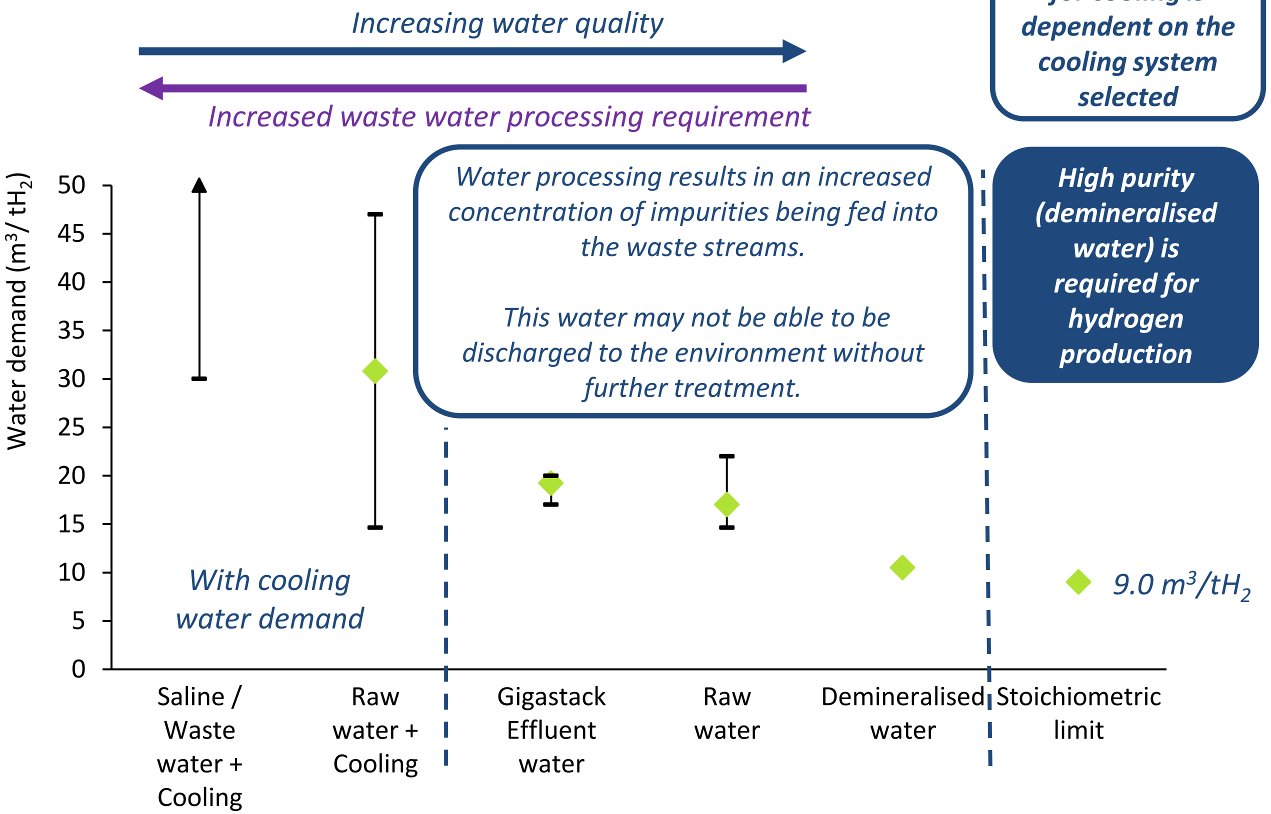
- The Gigastack concept explored additional supply, recycling effluent waste-water from the Humber Refinery and desalination.
- Effluent waste water utilisation ensures that there is no increase to the industrial water demand in the region and provides an innovative way of recycling refinery effluent water.




- Although waste water is more expensive to treat than raw / fresh water, co-location of electrolytic hydrogen production with industry will significantly reduce water transmission costs.
- Additional cooling water may also be required (~12.5 $m^3/tH_2$) depending on the plant configuration.

**Water consumption for electrolytic hydrogen[1,2,3,4,5]**

*Water demand for cooling is dependent on the cooling system selected*




- Over time, the **stack efficiency of the electrolyser decreases**, and most of the efficiency losses report to additional heating of the stack; resulting in an increased cooling load.
- Desalination typically accounts for less than 1% of electrolytic hydrogen production costs, which could enable sea water to be utilised as feedstock in the future.

[1]BEIS 2021 – Gigastack Phase 2 [2]CE Delft 2018 - Feasibility study into blue hydrogen
[3]Element Energy 2018 – Hydrogen supply chain evidence base [4]IEA 2019 – Future of Hydrogen [5]Environment Agency 2022 – Pathfinder research project

# Contents

# Cooling configuration and water quality have the largest impact on the water demand for CCS and hydrogen production technologies

**Cooling system type will play a significant role in the water demand for each decarbonisation technology**

- Open loop cooling systems have low water consumption but rely on large volumes of water to be extracted from the environment (that is subsequently returned).
- Closed loop (evaporative) cooling could result in very high water consumptions in the Humber if deployed art scale.

**Water feedstock quality has a significant impact on the water demand for hydrogen production technologies**

- Both CCS enabled and electrolytic hydrogen production technologies require high quality (de-mineralised) water.
- Utilising waste (grey) water streams can reduce water demand on the environment, however, significant processing stages may be required as well as processing of any waste water streams.

## Summary overview of water footprint from selected decarbonisation technologies

| Technology | Units | Low | Central | High | *Comments* | *Sources considered* |
|---|---|---|---|---|---|---|
| **CCS enabled hydrogen** | *$m^3/MWh$* | 0.57 | 0.79 | 1.30 | • Scenarios include raw water feedstock and water demand for cooling (non-air cooled).<br>• Sea water feedstock is not considered*. | • H21 North of England 2019 – North of England<br>• CE Delft 2018 - Feasibility study into blue hydrogen<br>• Uniper – hydrogen hub<br>• Equinor – H2H Saltend |
| | *$m^3/tH_2$* | 22.4 | 31.15 | 51.3 | | |
| **Electrolytic hydrogen** | *$m^3/MWh$* | *0.43* | 0.78 | 1.19 | • Low scenario assumes raw water feedstock with air-cooling system.<br>• Central scenario assumes raw water feedstock with non-air cooled system.<br>• High scenario assumes effluent water feedstock with non-air cooled system.<br>• Sea water feedstock is not considered*. | • BEIS 2021 – Gigastack Phase 2<br>• Element Energy 2018 – Hydrogen supply chain evidence base<br>• Uniper – hydrogen hub |
| | *$m^3/tH_2$* | 17.0 | 30.81 | 47 | | |
| **Carbon capture** | *$m^3/tCO_2$* | 0.01 | 0.20 | *2.63* | • Low scenario assumes air-cooling / hybrid / open loop system.<br>• Central scenario assumes a non-air cooled system.<br>• High scenario assumes evaporative cooling system. | • JEP 2021 – Projections of Water use in Electricity and Hydrogen Production<br>• Lorenzo et al 2020 - The water footprint of carbon capture and storage technologies<br>• Evides 2022 - Sustainability Managers Forum (Water efficiency) |

*Seawater feedstock for hydrogen production would result in a water feedstock requirement up to 136% greater than raw water – see slide.

# Contents

# Energy and cost saving optimisations can have the additional benefit of reducing water demands from carbon capture systems

### Carbon capture technology innovation

- Post-combustion $CO_2$ capture membranes require minimal cooling and process water, and therefore they have little impact on water consumption.
- Sorption Enhanced Water Shift Reaction (SEWGS) for pre-combustion systems (including CCS enabled hydrogen production via ATR) combines the WGS reaction with $CO_2$ separation, reducing the energy and the additional steam required by the $CO_2$ capture process.

### Waste heat integration

- Waste heat utilisation of the amine-based $CO_2$ capture process in the steam cycle of the host power plant can warm-up condensate or boiler feed-water in the preheating section of the steam cycle.
- Such integration is primarily targeted to improve the efficiency of the whole system. However, implementing waste heat integration reduces the cooling duty of the $CO_2$ capture system, and thus the volume of cooling water used.

### Water recovery and recycling

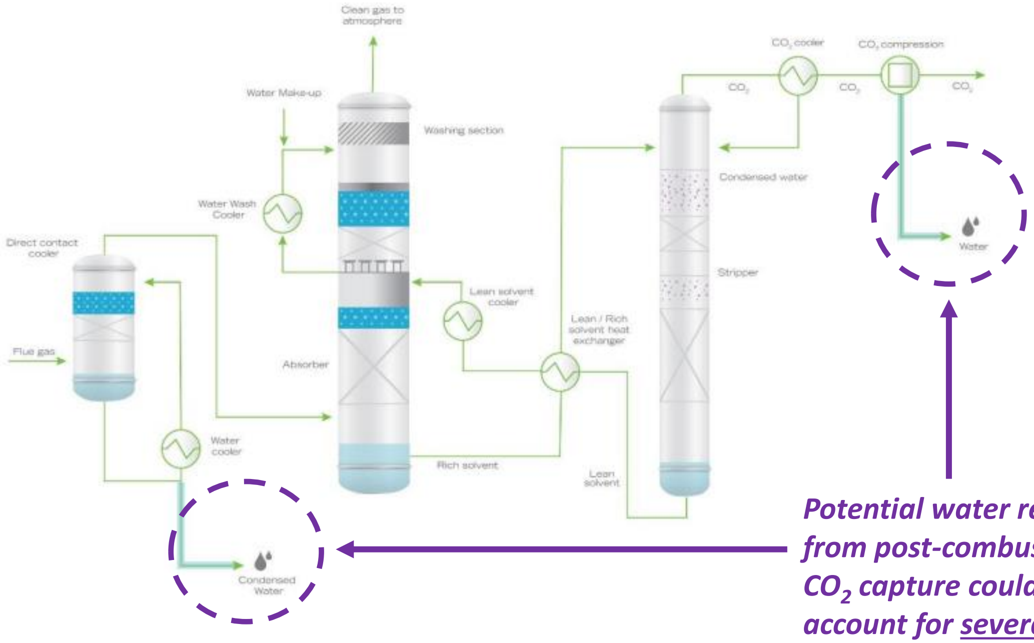
- Water recovery and recycling can have significant impacts on the need for process makeup water.
- In post-combustion systems, water can be recovered in the:
  - flue gas cooler installed upstream of the absorber to cool the flue gas to about 30-40°C (significant potential for water recovery)
  - condenser that cools the $CO_2$ stream leaving the top of the stripper
- Water extracted from the $CO_2$ capture system can be collected and reused as makeup water in the capture system.

### Cooling systems

- Dry cooling systems reduce water consumption, however, are expensive in terms of capital and operational costs.

***Today, the primary target of technology developers is usually to reduce cost and energy requirements***

### Amine-based post-combustion $CO_2$ capture[1]




***Potential water recovery from post-combustion $CO_2$ capture could account for <u>several t/h*</u>***

***The potential volumes of recovered water have the potential to supply all the process makeup water and significantly reduce the cooling water requirements.***

[1]Global CCS Institute 2016 – Water use in Thermal Power Plants Equipped with CO2 Capture Systems

*18 t/h of water can be captured from a post-combustion capture system with open loop cooling applied to a 750-1,000MW power plant.

# Grey water recycling / reuse provides an opportunity to make use of valuable waste water in industrial processes

**Domestic greywater can make up between 50-80% of an individual's daily water usage[1,2]**

- Greywater is created from the potable water received from the utility provider but after being used in showering or bathroom uses then contains heavy surfactants and other contaminants which give it a 'grey' colour.
- Grey Water Recycling takes discharge water from the waste bath, sink and utility water.
- Grey water is processed through specialist equipment and then reused, mainly for toilet flushing.

**Industrial grey water reuse and recycling is already operational in many sectors**

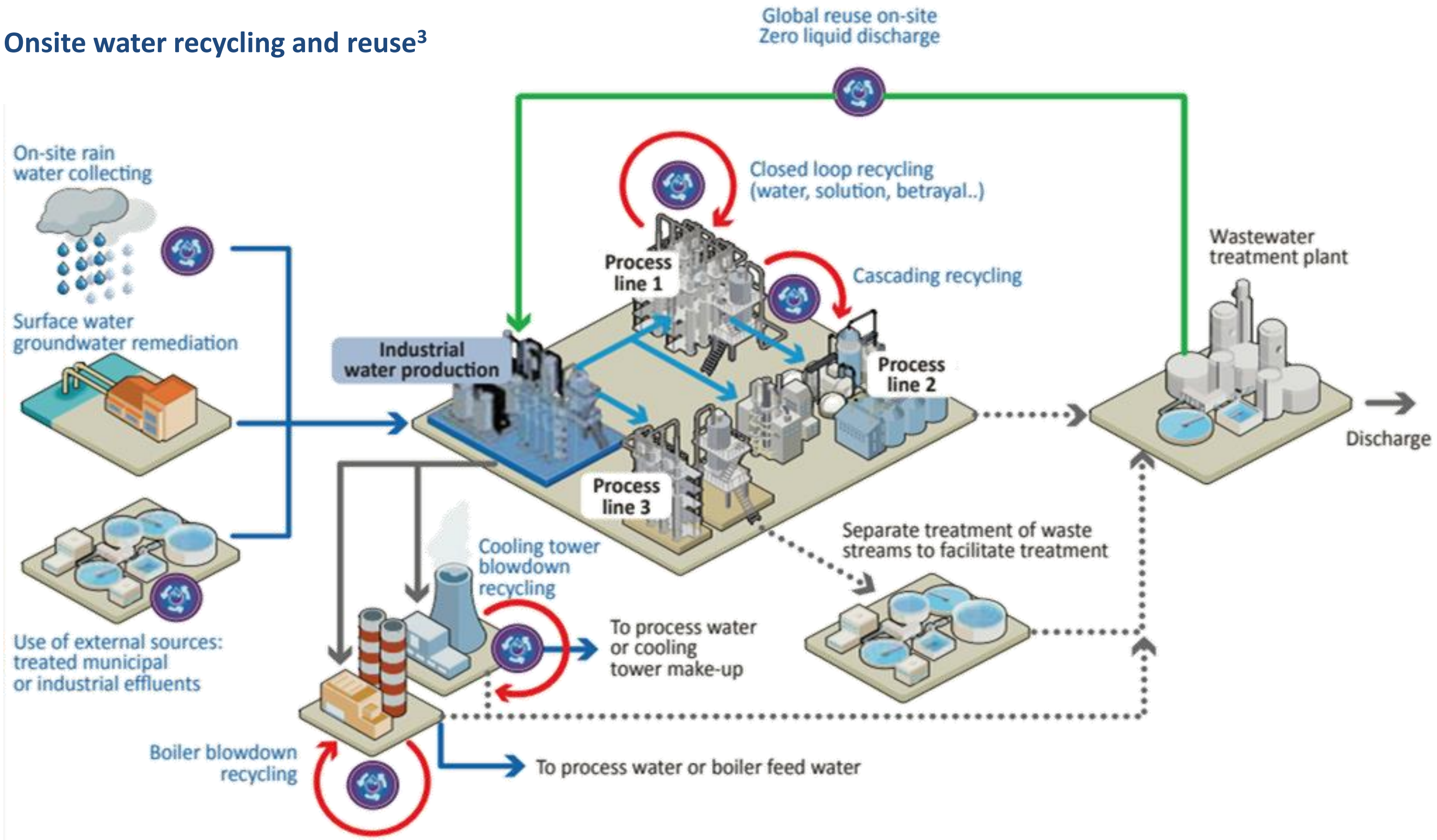
- Many industrials incorporate reuse/recycling of water streams to reduce onsite costs and optimise resource efficiency.

***Potential to transfer grey water streams between industrials is largely unexplored and could present a significant opportunity for reducing water consumption***

**Grey water system benefits**

- Reduction in mains water and sewage charges
- Can be combined with rainwater harvesting
- Grey water systems are not weather dependant
- Return on investment can be better than other renewable or low-carbon technologies
- Decline in over-reliance and pressure on existing freshwater sources

**Onsite water recycling and reuse[3]**




**Water Recycling** - only involves one use, where the effluent stream is treated and redirected back into the same loop for the same use.

**Water Reuse** - is the use of treated wastewater for beneficial purposes other than the initial use, such as **cooling systems, boilers, process water**, irrigation, cleaning or ground water recharge.

[1]Ecovie – Grey water Recycling [2]Aquality – Grey water recycling [3]Veolia – Sustainable water management for recycling & reuse

# Contents

# Scenarios from the *Industrial Decarbonisation Systems Model* are multiplied by technology water footprints to calculate the additional water demand in the Humber

**Water demand calculation method**

- Water footprints (shown right) are multiplied against results based on the four demand scenarios developed in the *Industrial Decarbonisation Systems Model* to determine the additional water demand for each technology ($m^3$/year).
- The Lot 1 scenarios for hydrogen and CCS demand are shown in the appendix – see slide.

**Lot 1 Scenarios**

**A: CCUS Commitment**

**B: Innovation and Incentives**

**C: Barriers with Limited Enablers**

**D: Alternative Solutions**

- A detailed explanation of the Lot 1 scenarios is provided in the Appendix – see slide.

***Lot 1 Scenarios*** — **Hydrogen / CCS demand**

**X**

***3 x cases*** — **Water footprint**

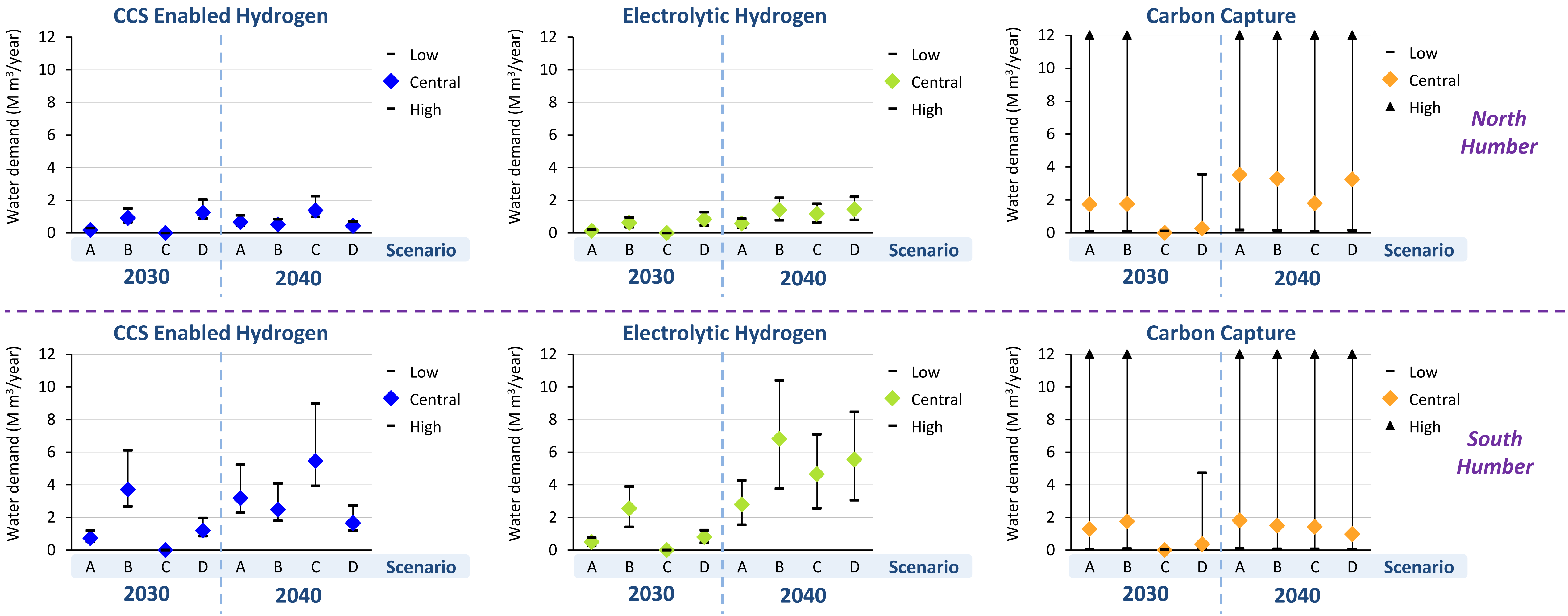
**=**

**Water demand**

**Water footprint from selected decarbonisation technologies**

| Technology | Units | Low | Central | High |
|---|---|---|---|---|
| **CCS enabled hydrogen** | *$m^3$/MWh* | 0.57 | 0.79 | 1.30 |
| **Electrolytic hydrogen** | *$m^3$/MWh* | *0.43* | 0.78 | 1.19 |
| **Carbon capture** | *$m^3$/$tCO_2$* | 0.01 | 0.20 | *2.63* |

# Electrolytic hydrogen is likely to develop the highest water demand in the Humber in the central case



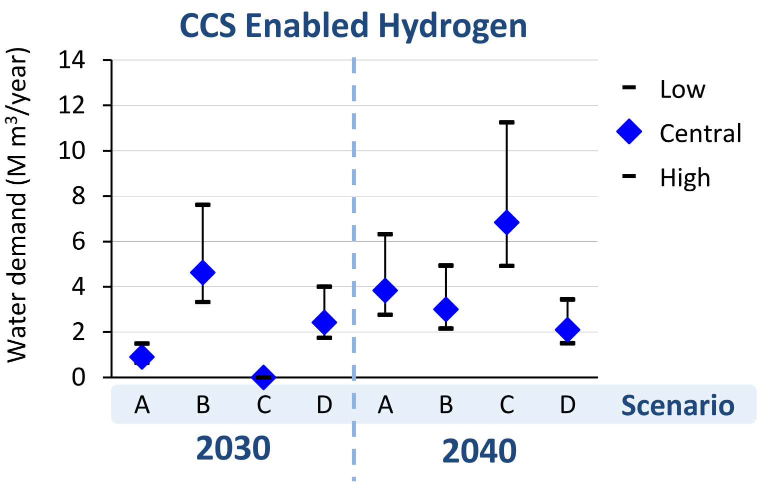

*Water demand for hydrogen production is significantly higher in the South Humber region, due to the increased demand for hydrogen from industry*

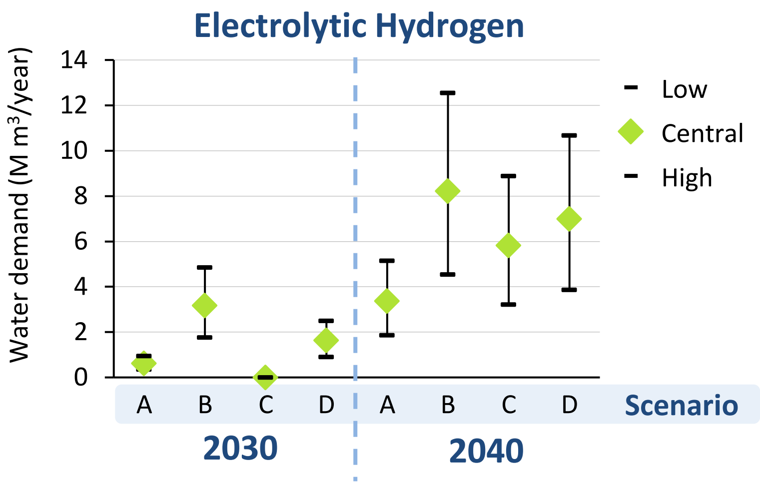
*Water demand for carbon capture is slightly higher in the North Humber region, as demand for carbon capture is relatively similar in both regions*

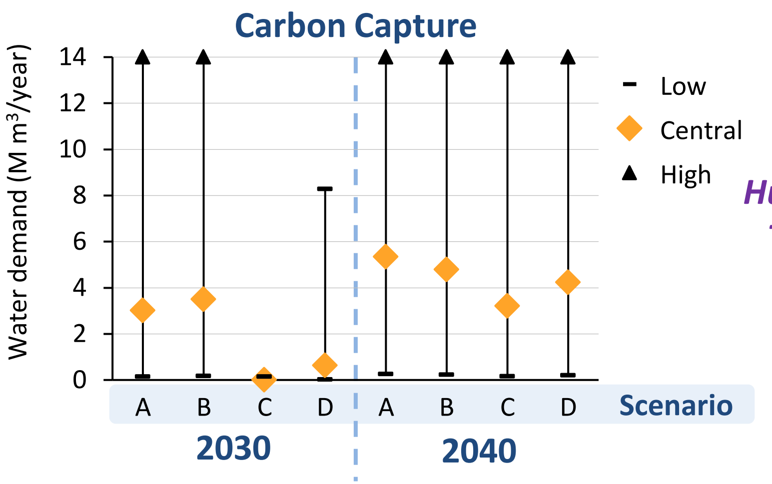
Uptake of hydrogen production and carbon capture by scenario – see slide.

Key carbon capture and hydrogen projects in the Humber – see slide.

# Water intensive cooling configurations and low quality water feedstock are the primary causes of high water demand for low-carbon technologies




***Humber Total***

**Water demand for electrolytic hydrogen is higher than CCS enabled hydrogen in two out of the four scenarios**

- This is primarily due to the assumption that there will be greater demand for electrolytic hydrogen than for CCS enabled hydrogen in the Humber. Particularly in Scenarios B and D where water demand reaches 8.2 and 7.0 M $m^3$/year in the central case.
- The large range for hydrogen related water demand is due to the dependence on the type of cooling configuration deployed, alongside the water feedstock quality.
- Even higher water demands could be required if seawater feedstocks are utilised.

***The Phillips 66 Humber refinery produces ~4 million $m^3$/year of effluent water. This could be utilised to produce ~8 TWh/year of electrolytic hydrogen in the Humber***

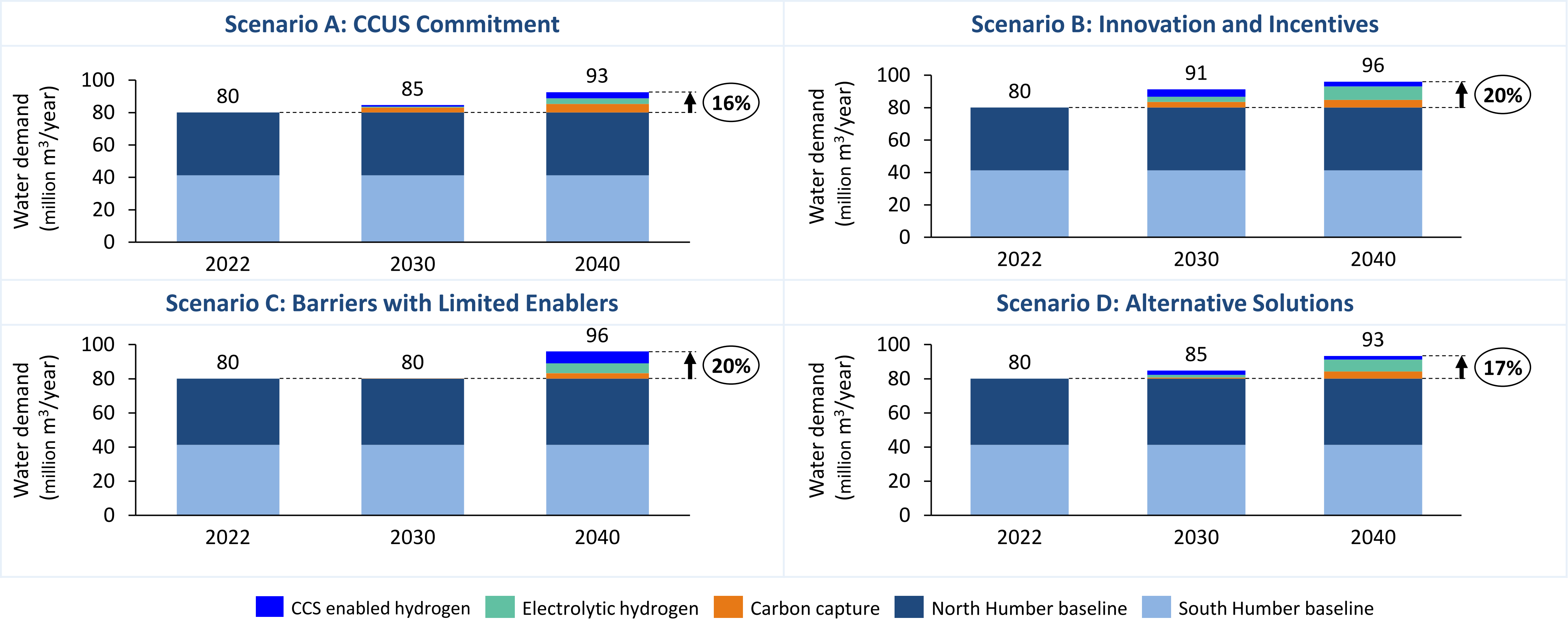
**Water demand for carbon capture is highly dependent on the cooling system configuration**

- Additional water demand for CCS remains below 6 M $m^3$/year in all scenarios for the central case by 2040.
- Air cooling has the lowest water demand – however, air cooled systems are typically the most energy intensive to operate and can be costly to install.
- Closed loop (evaporative cooling) is the most water intensive option and would result in the greatest water demand if widely deployed in the Humber.
- Hybrid systems combine the air cooled and closed loop configuration, allowing water demand to be minimised at times of low availability, whilst enabling higher efficiencies to be achieved when water is widely available.

***Scenario C shows low water demand due to very low levels of hydrogen and carbon capture deployment***

Uptake of hydrogen production and carbon capture by scenario – see slide.

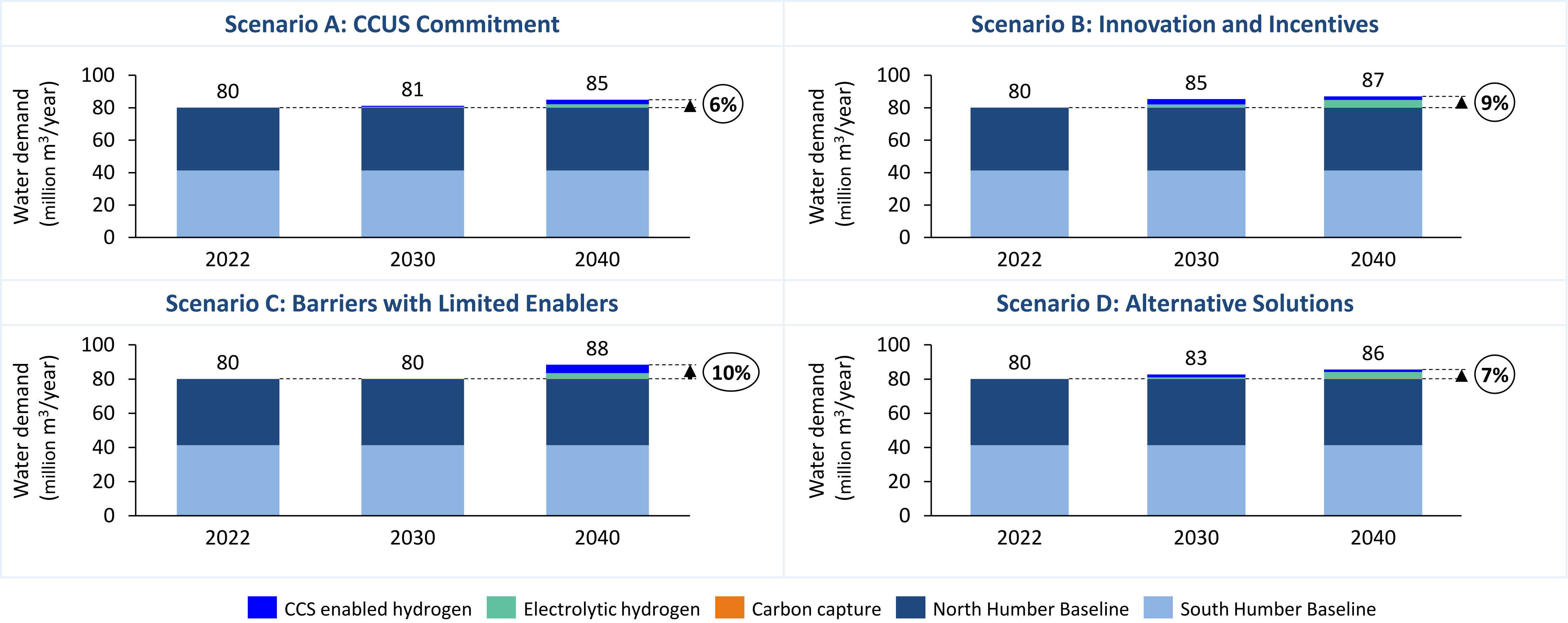
# Industrial water demand in the Humber could increase by 16-20% by 2040




***The above examples are shown for the central water footprint case – however, there is significant uncertainty in the water intensity of both carbon capture and hydrogen production technologies***

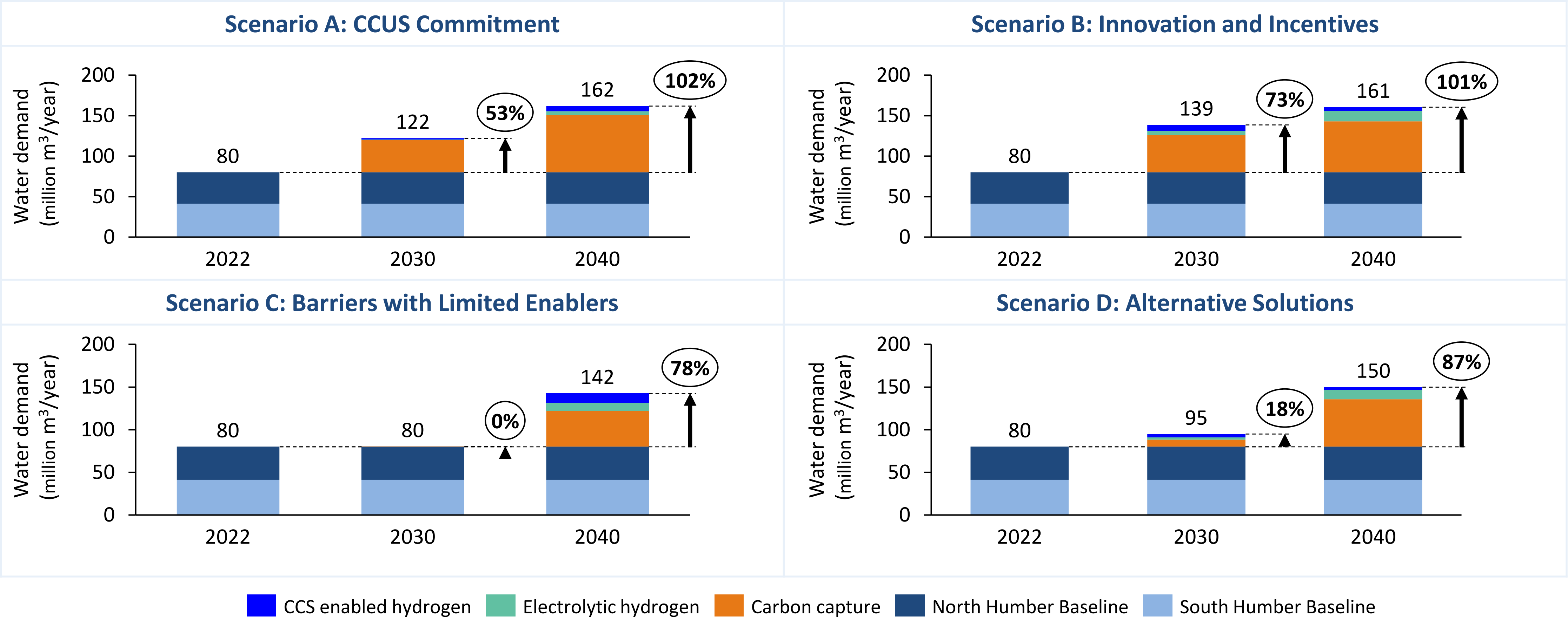
A detailed explanation of the Lot 1 scenarios is provided in the Appendix – see slide.

# The low water intensity technology case could result in an increase in industrial water demand of only 6% - the majority of which would be required for hydrogen production




***The above examples are shown for the low water footprint case***

# Closed loop (evaporative) cooling at capture facilities could increase the industrial water demand in the Humber by 78-102%




***The above examples are shown for the high water footprint case***

A detailed explanation of the Lot 1 scenarios is provided in the Appendix – see slide.

# Contents

# Water availability is likely to be a significant constraint in the Humber region without effective management of supply and demand

**The Humber (particularly south of the river) is forecast to be a water stressed region where no new abstraction licenses are likely to be granted**

- The EA's current priority is the environment. It is unlikely that a new consumption licence would be granted.
- Yorkshire Water and Anglian Water, the two public water companies servicing the Humber region forecast that available water supplies will decline in the future. This is driven by:
  - **Extreme droughts occurring more frequently** and for longer durations
  - Increased water supplies being reserved to meet demand during drier periods
  - Increased demand from population growth
- Both public water companies and private abstraction licenses will face lower water availability in the future.
- Over abstraction of ground water resources could lead to saline intrusion, where salt water moves into fresh water aquifers. **Once polluted, groundwater sources could take decades to restore**, therefore significantly impacting access to high-quality water in the region.

**By 2040, water demand due to carbon capture and hydrogen production could account for an additional 4.9-81.8 million $m^3$/year**

- Solutions for carbon capture and hydrogen production technologies need to minimise levels of additional water consumption.
- The EA may require trials of low-carbon techs before permits can be issued. Necessary infrastructure will be required prior to low-carbon tech deployment (primarily sewage and waste water infrastructure capacity).

***Future water balance in the Humber region***

**The Humber has a significant water challenge – managing declining water supplies with increased water demand**

- Climate change is driving a reduction in available water supplies across the UK, including the Humber region.
- **Water availability is likely to be a significant constraint in the Humber region without careful management** of local resources and efforts to reduce demand.

**To maximise water availability in the Humber region, a range of measures can be adopted, including:**

- Reduce water demand from existing sources through process optimisation and water efficiency improvements.
- Minimise water losses in transport and distribution infrastructure through increased maintenance and monitoring of assets.
- Increase water circularity in industrial processes via reuse and recycling of waste water streams.
- Develop water storage capacity to build up stores during wet periods, to improve water resilience during times of drought.

# Water is a key resource required for the decarbonisation of the Humber and should be considered in parallel to plans to reduce $CO_2$ emissions

**Project developers should engage with the EA early to check if water availability is likely to be a constraint for their hydrogen or carbon capture project**

- Water demand should be considered in early stages of project development.
- Pre-applications offer project developers the opportunity to discuss water sourcing strategies. Advice/response from the EA will depend on the quality of information provided (e.g. water volume, quality, return, waste stream treatment, seasonal variations)

**Electrolytic hydrogen is likely to require more water than CCS enabled hydrogen per kg$H_2$ produced**

- This is due to the increased water feedstock requirements. However, cooling demands for CCS enabled hydrogen production are likely to make the differences relatively small.

**The water demand for carbon capture is most dependent on the type of cooling configuration deployed**

- Air cooled, hybrid and open loop systems have the lowest levels of water consumption.
- Evaporative cooling is the most water intensive cooling technology and could exacerbate water stress in the Humber region if widely deployed.
- Carbon capture has the potential to produce water in certain configurations – this should be further investigated to reduce the demands on the environment.

**Industrials and project developers should focus on *water resilience and methods to reduce water demand***

- Water resilience can be improved via storage, reuse and recycling methods to ensure users are not reliant on one source.
- The utilisation of 'grey water' streams is a strategy that will ensure additional water demand from the environment is minimised.
- Water purification / treatment plants may require large scale deployment to ensure there is sufficient high quality water in the Humber region.

**Greater consideration of alternative decarbonisation pathways should be considered by industrials and project developers**

- Electrification is likely to be the least water intensive decarbonisation pathway and should be considered as an alternative to carbon capture and hydrogen fuel switching in water stressed regions.

**Hydrogen may be produced where water is most available**

- Hydrogen will not necessarily be produced near the point of demand
- South Humber should assess opportunities for sourcing water from existing grey water sources / sea water via desalination.
- If demand for hydrogen exceeds demand in the South Humber hydrogen may need to be imported from areas with greater water availability (e.g North Humber).

# Water availability may increase as a co-benefit of decarbonisation

**Policy makers should demand that assessment of decarbonisation pathways include more holistic evaluation of impacts to water supply and quality**

- Investors in $CO_2$ capture projects should review water quality related issues during their due diligence processes.

**New technologies have the potential to become increasingly water efficient whilst also reducing carbon emissions**

- Research institutions and technology developers may develop innovative carbon capture or hydrogen production solutions that also provide co-benefits to the local water supplies.

**The Humber (and the UK) should investigate where water availability is likely to increase as a result of the transition to net zero**

- The transition from thermal power generation to renewables is likely to increase water availability in certain regions.
- Transitions within industry could also increase water availability (e.g. shift from blast furnace to electric arc steel production)
- Further analysis is required to asses how existing decarbonisation plans will impact water availability. The EA should engage with project developers and stakeholders involved in cluster decarbonisation planning to identify opportunities where existing water demand can be reallocated.

**Public water supply companies are likely to supply significant quantities of water to new projects**

- Yorkshire water and Anglian water will play a key role in supplying water to carbon capture and hydrogen production projects.
- Infrastructure may be required to transfer water across regions to meet the water demands of new projects.

**Water availability could be a significant constraint to decarbonising industry in the Humber if water intensive technologies are deployed – particularly if these rely on fresh (high quality) water**

- The deployment of carbon capture and hydrogen production technologies will be crucial to decarbonising industry in the Humber region.
- A reduction in the available water supply will be driven by climate change and domestic demand due to a growing population.
- Project developers should focus on technologies that can operate with low-quality or minor water demands to safeguard water supplies in the Humber region in the future.

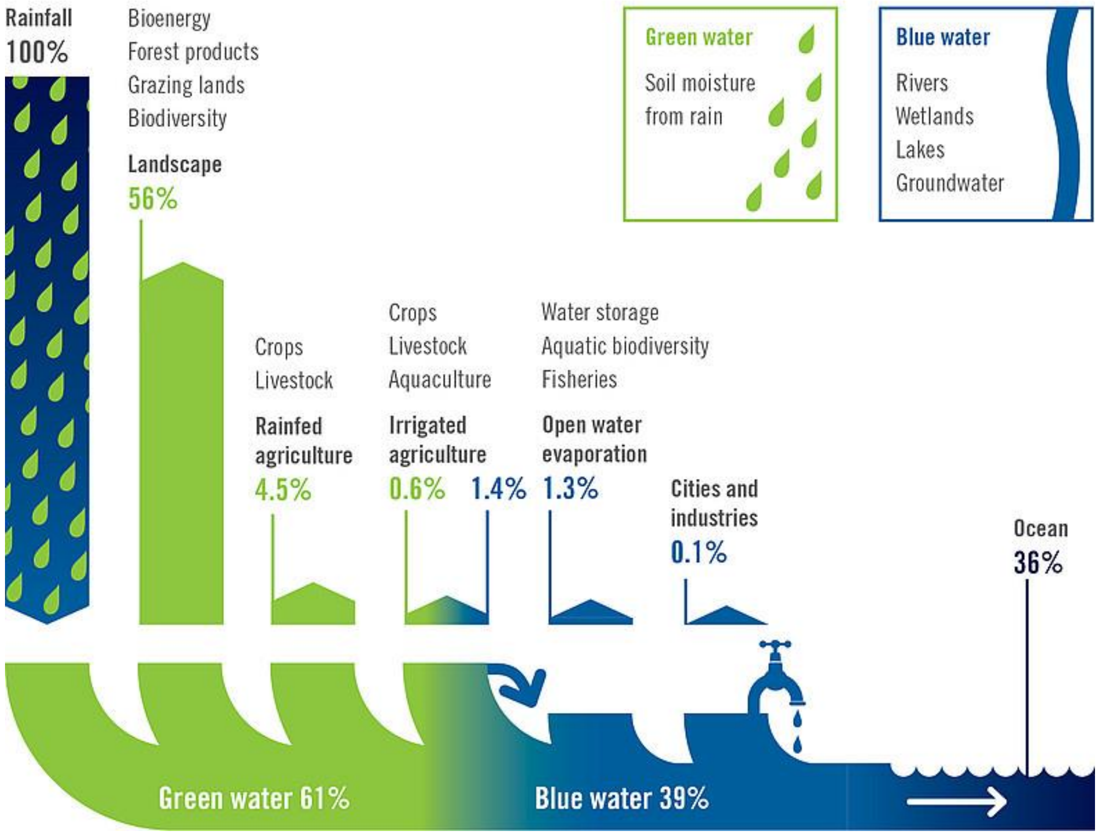
# Contents

# The majority of the worlds water resources are stored as green water. However, core decarbonisation technologies will utilise blue water.

**Fresh water resources can be categorised as either 'green' or 'blue'[1]**

- **Green water*** - is the water held in soil and available to **plants**. The majority of rainfall comes down on the earth's surface and either:
  - evaporates directly (known as unproductive evaporation) or,
  - is absorbed by roots and used by plants, and released back to the atmosphere through the process of transpiration (productive evaporation).
- **Blue water** – includes the surface water in rivers and lakes as well as groundwater in aquifers.
  - Blue water is used for all industrial applications, including carbon capture and hydrogen production.
  - ***Blue water footprint*** **–** is the volume of fresh water consumed from surface and groundwater bodies to produce goods or services during their life cycle.

**Green vs blue water[2]**




***How a river or aquifer is managed or used in one location can drastically affect other locations further up or downstream***

[1] IEA 2016 - Water-Energy Nexus [2] Global Agriculture - Water

*Green water - represents between 55% and 80% of the total available freshwater supply globally, depending on the region.

# Two commonly used metrics to measure water use  are withdrawal and consumption

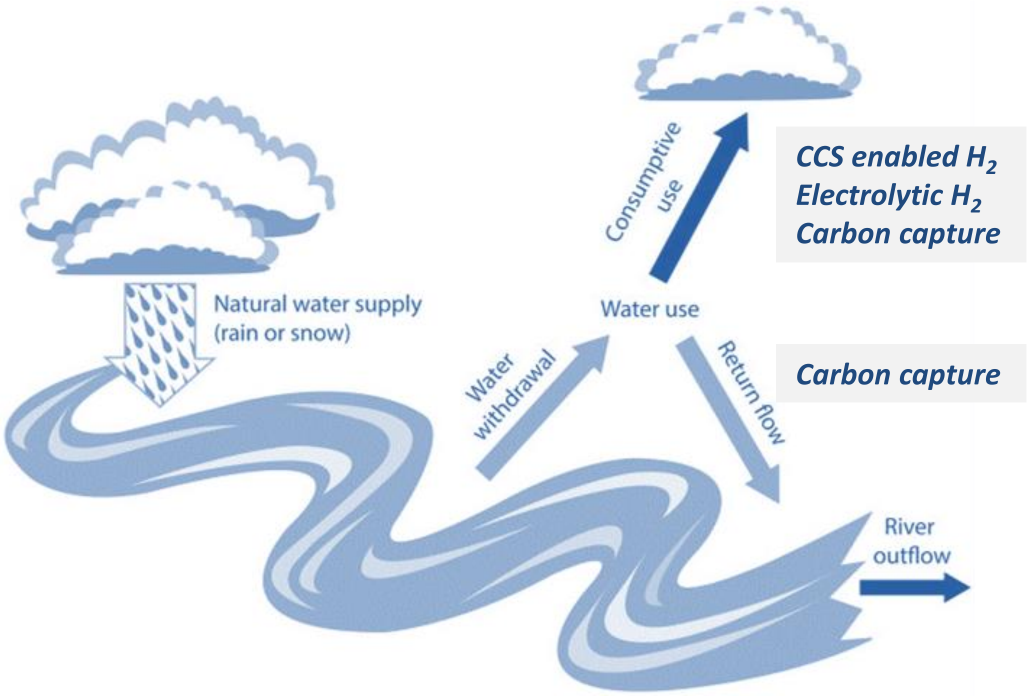
- **Water abstraction**[1] - is the removal of water resources, permanently or temporarily, from rivers, lakes, canals, reservoirs or from underground strata. Water abstraction includes both consumption and withdrawal – these are sometimes collectively referred to as **water use.**

- **Water consumption**[1] **-** is the volume of <u>net</u> water abstracted that is used by human activities and returned to the atmosphere as water vapour.
  - This water becomes unavailable for short-term reuse within the same watershed.

- **Water withdrawal**[1] **-** is the <u>gross</u> volume of water abstracted from a water body (e.g. lake/river). This water is partly consumed and partly returned to the source or other water bodies, where it is available for future uses.
  - Water withdrawals are always greater than or equal to consumption.

***Carbon capture and low-carbon hydrogen production technologies (consume water during operating processes***

**Water withdrawn from a source is returned to the source or other water body**[2]



# Concepts and definitions about water systems

- **Surface water** - natural water in lakes, rivers, streams or reservoirs.
- **Groundwater** - water that is below the land surface in pores or crevices of soil, sand and rock, contained in an aquifer.
- **Water stress** - Defined as when renewable annual freshwater water supplies fall below 1,700 $m^3$ per person; water scarcity is below 1,000 $m^3$ per person; and absolute scarcity below 500 $m^3$ per person.
- **Water consumption -** is the volume of net water extracted that is used by human activities and returned to the atmosphere as water vapour. Therefore, this water becomes unavailable for short-term reuse within the same watershed.
- **Water withdrawal -** is the gross volume of water abstracted from a water body (e.g. lake/river). This water is partly consumed and partly returned to the source or other water bodies, where it is available for future uses.
- **Water footprint -** is the volume of fresh water consumed to produce goods or services during their life cycle. Based on the source of the water, the water footprint can be divided in green and blue water footprint.
- **Green water -** root-zone soil moisture that is available for uptake by plants. Biomass plantations use green water during the photosynthesis process.
- **Blue water -** freshwater in surface and groundwater bodies available for human use. All CCS technologies use blue water during the $CO_2$ capture process at the power-plant level.
- **Green water footprint** - refers to water from the unsaturated root zone of the soil profile that is used by plants and soil microorganisms. It is relevant for the assessment of the water footprint of BECCS because of the evapotranspiration of water by biomass feedstock.
- **Blue water footprint -** refers to water from surface and groundwater bodies, it is relevant for the assessment of the water footprint of DACCS, and pre and post-combustion CCS because of the evaporation of water at the power plant level during the capture and sequestration process.
- **Hands-Off Flow (HOF) -** condition on a licence which requires abstraction to stop when the river flow falls below a certain amount.
- **Hands-Off Level (HOL) -** condition on a groundwater abstraction licence that impacts a surface water feature. This is the groundwater level below which an abstractor is required to reduce or stop abstraction.

IEA 2016 - Water-Energy Nexus    Lorenzo et al 2020 - The water footprint of carbon capture and storage technologies

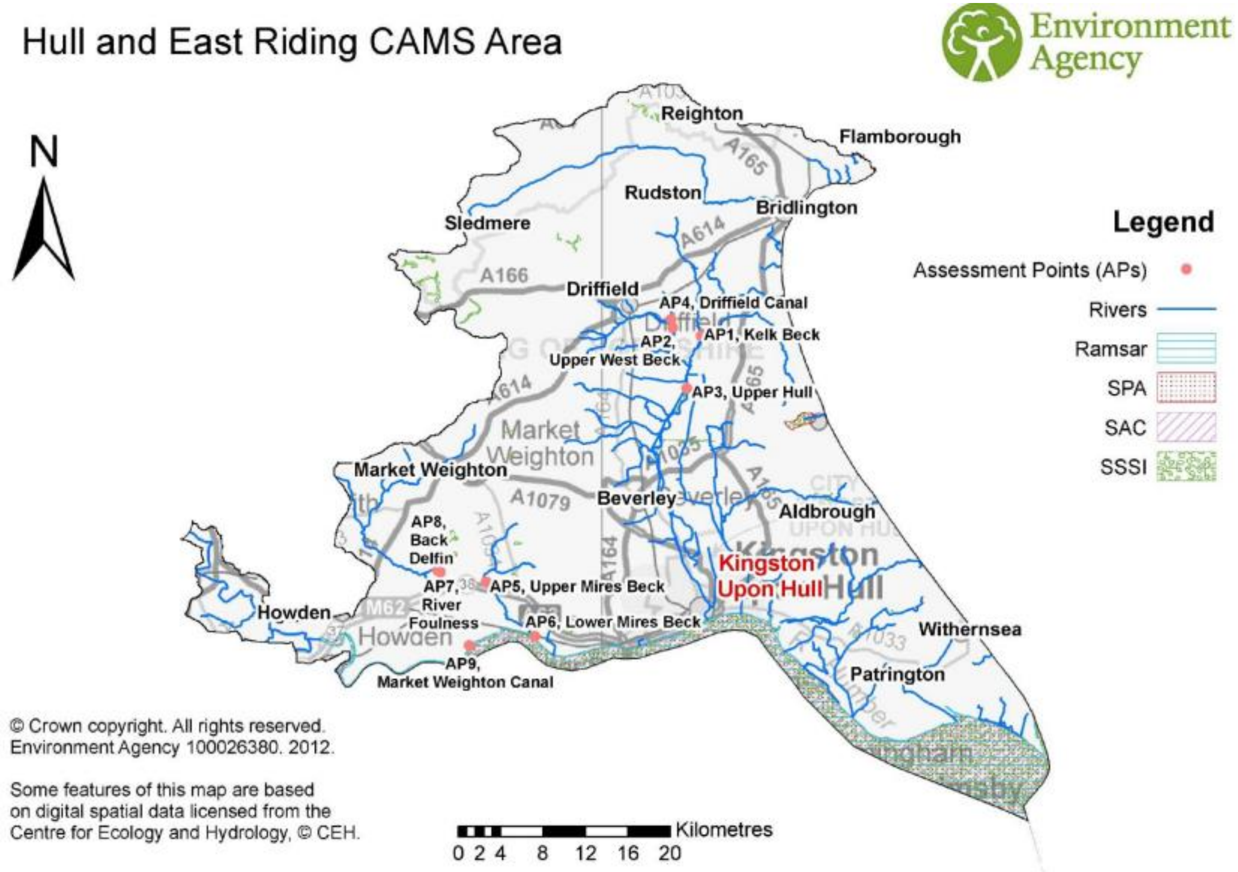
# Contents

# North Humber - Hull and East Riding CAMS area

### Water sources in the North Humber region

- The River Hull flows for 32km from Driffield to the Humber. Draining waterways include:
  - The Driffield Canal and Frodingham Beck in the north
  - Beverley Beck and the Leven Canal in the south
  - River Foulness, Market Weighton Canal and Mires Beck to the west
- Cretaceous chalk forms the prominent ridge of the Yorkshire Wolds and provides a primary aquifer, with uses ranging from public water supply and agriculture to industry.
- Groundwater within the outcrop area is of high quality and can be used for many purposes without treatment. Once confined beneath the clay, the groundwater rapidly becomes mineralised and is less heavily abstracted because it is unfit for many uses.
- The major uses for abstracted water are power generation, agriculture, public water supply and industry. Around one fifth of the water abstracted in this area comes from groundwater.

**Hull and East Riding Catchment Abstraction Management Strategy (CAMS) area[1]**




[1]EA - Hull and East Riding Abstraction Licensing Strategy 2013

# South Humber - Grimsby, Ancholme & Louth CAMS area

**Water available for licensing**

- Groundwater unit balance shows groundwater available for licensing.
- New licences can be considered depending on impacts on other abstractors and on surface water.

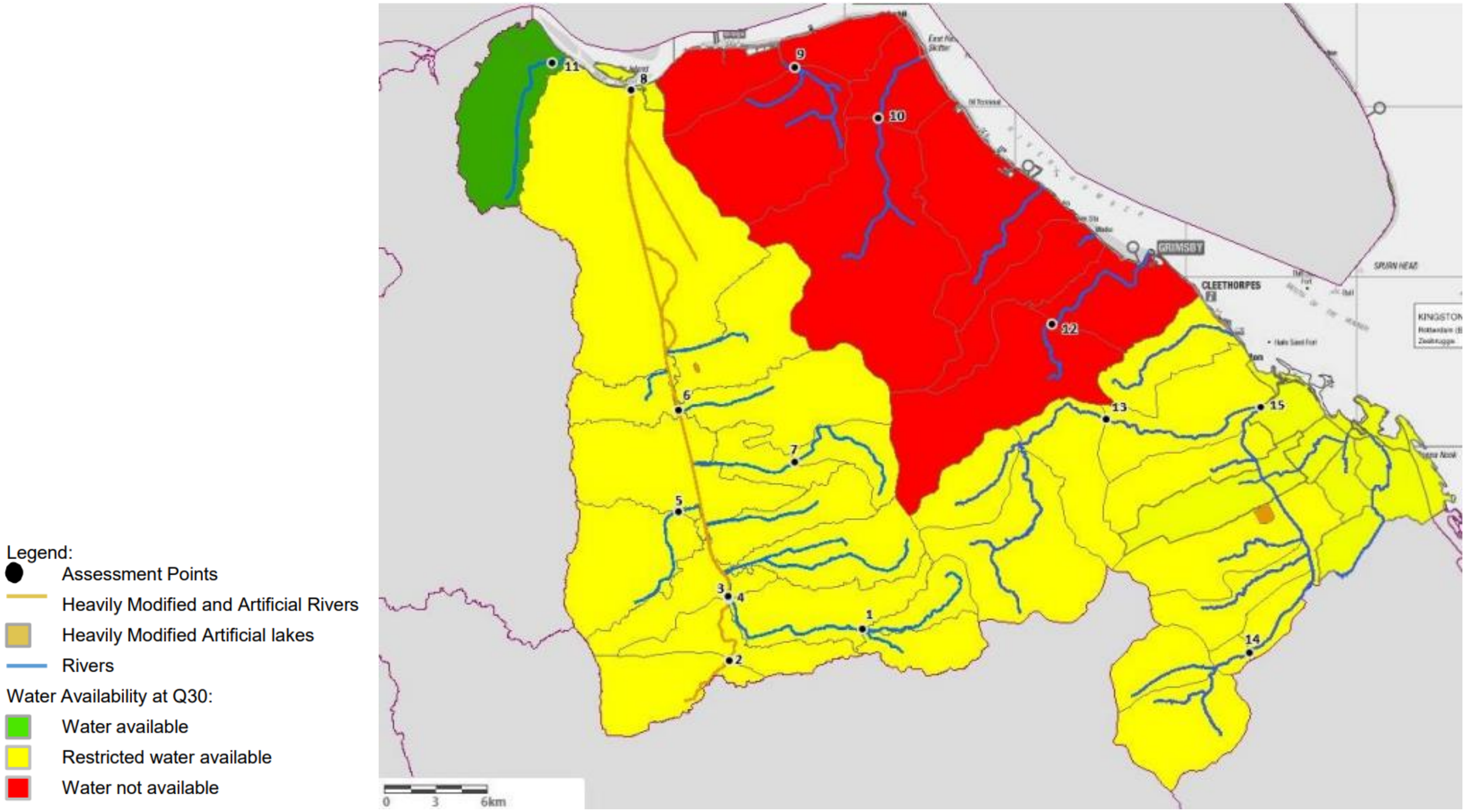
**Restricted water available for licensing**

- Groundwater unit balance shows more water is licensed than the amount available, but that recent actual abstractions are lower than the amount available.
- In restricted groundwater units no new consumptive licences will be granted.

**Water not available for licensing**

- Groundwater unit balance shows more water has been abstracted based on recent amounts than the amount available. No consumptive licences granted.

**Water resource availability colours at Q30 (higher flow) for Grimsby, Ancholme & Louth ALS[1]**



# Contents

# Agriculture is the primary source of water demand globally, but most crops in England rely on rainfall

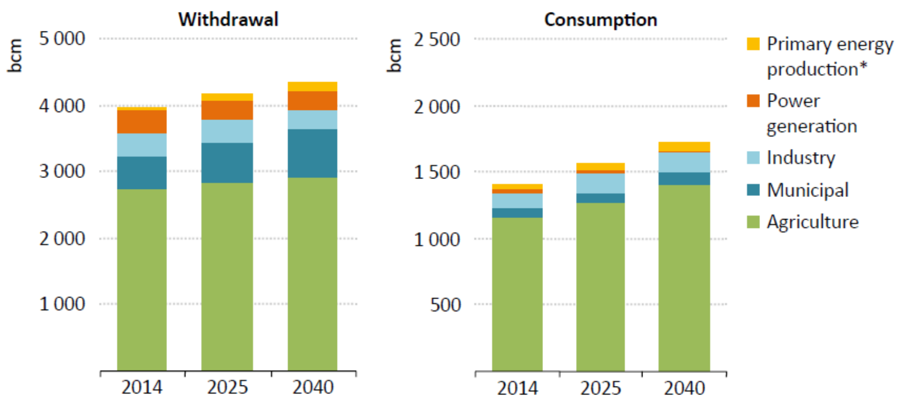
**Global water demand is dominated by Agriculture**

- Today, irrigated agriculture is the world's largest water user, accounting for roughly 70% of total global freshwater withdrawals
- Agriculture is also responsible for the bulk of water consumption, stemming from evaporation from land surfaces during irrigation and transpiration from plants.
- Industry accounts for ~12% of water withdrawals in advanced industrial nations.
- Primary energy production and power generation account for ~10% of total worldwide water withdrawals and around 3% of total water consumption.

**The power sector withdraws significant amounts of water** – mostly from surface water sources – after which much of it is returned (often at a different temperature ***[thermal pollution]***).

- Thermal pollution from the discharge of hot water into rivers, streams, lakes, and ponds can damage aquatic ecosystems. However, treatment of waste water prior to discharge can mitigate negative impacts.
- Thermal power plants made up 70% of total installed power generation capacity worldwide in 2014 and are the main source of water demand in the power sector.
- The type of cooling technology used is a key determinant of how much freshwater is withdrawn and ultimately consumed and the overall efficiency of thermal power plants.

**Figure 1 ▷ Global water demand by sector to 2040**




*Agriculture remains the primary source of global water demand, but other sectors gain ground*

* Primary energy production includes fossil fuels and biofuels.

**The majority of the water withdrawn for hydropower generation is returned to the surface water body**

- Hydropower is water intensive by virtue of using water as its actual energy source.
- Water consumption varies depending on a range of factors such as: technology type (reservoir versus run-of-river), reservoir size, climate, evaporation* and engineering. The amount consumed is highly site-specific and the measurement methodology is not agreed upon.
- Despite of the high level of water abstracted/withdrawn, net consumption is low because most of the water remains available downstream.

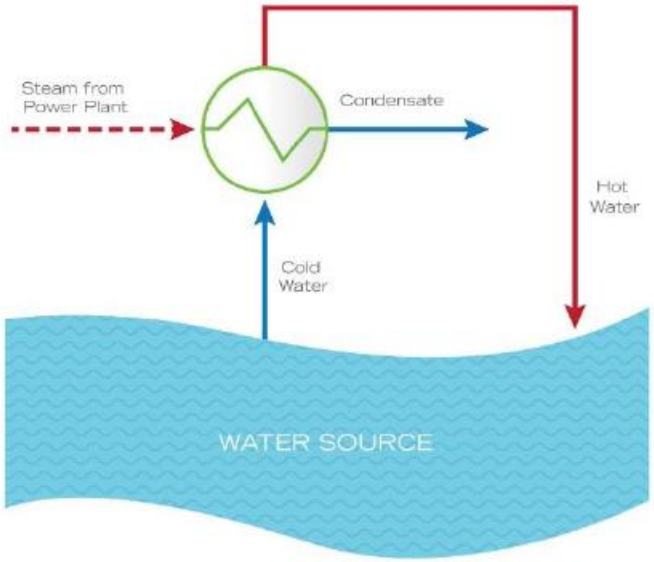
IEA 2016 - Water-Energy Nexus    NFU 2018 - Irrigation water strategy for UK agriculture and horticulture

*Today, the methodology for calculating water losses via evaporation from hydropower is not agreed upon.

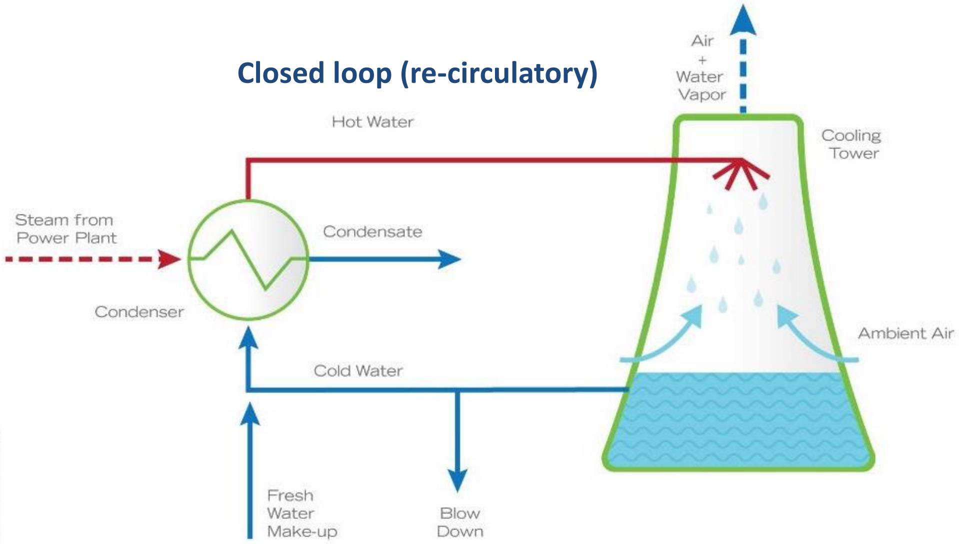
# Contents

# Cooling system configurations

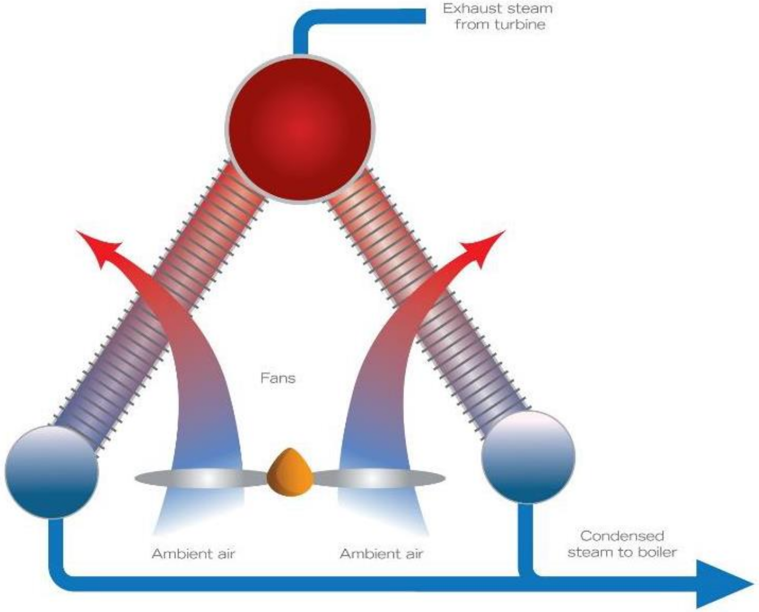
## Once through (open loop)




## Closed loop (re-circulatory)




## Air-cooled (dry)

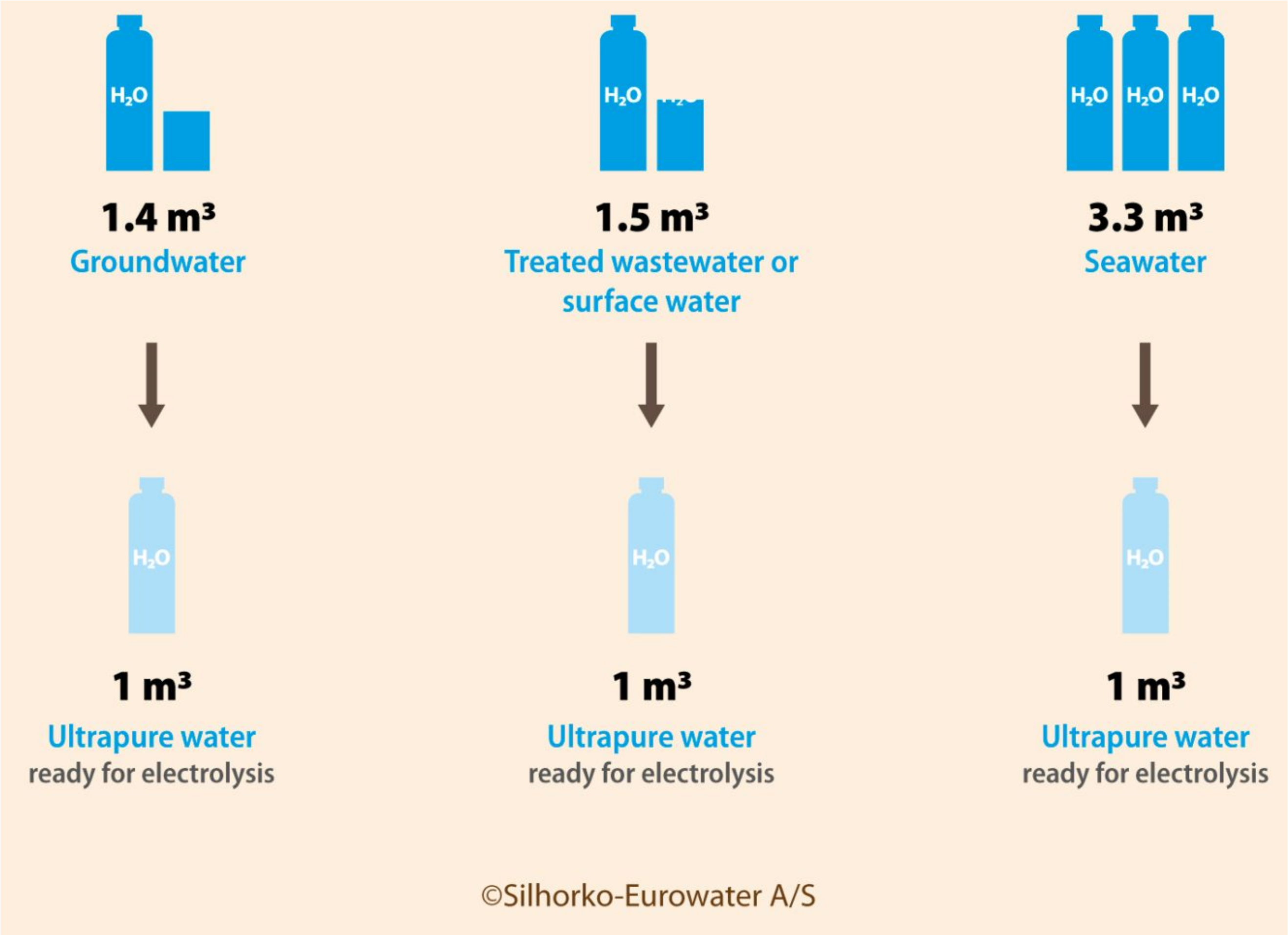



**Hybrid configuration**

# Contents

# Water purification requirements for hydrogen production

**Water purification requirements for hydrogen production**



# Contents

# Water saving measures such as passive cooling systems could potentially be adopted from alternative sectors and applied to low-carbon technologies

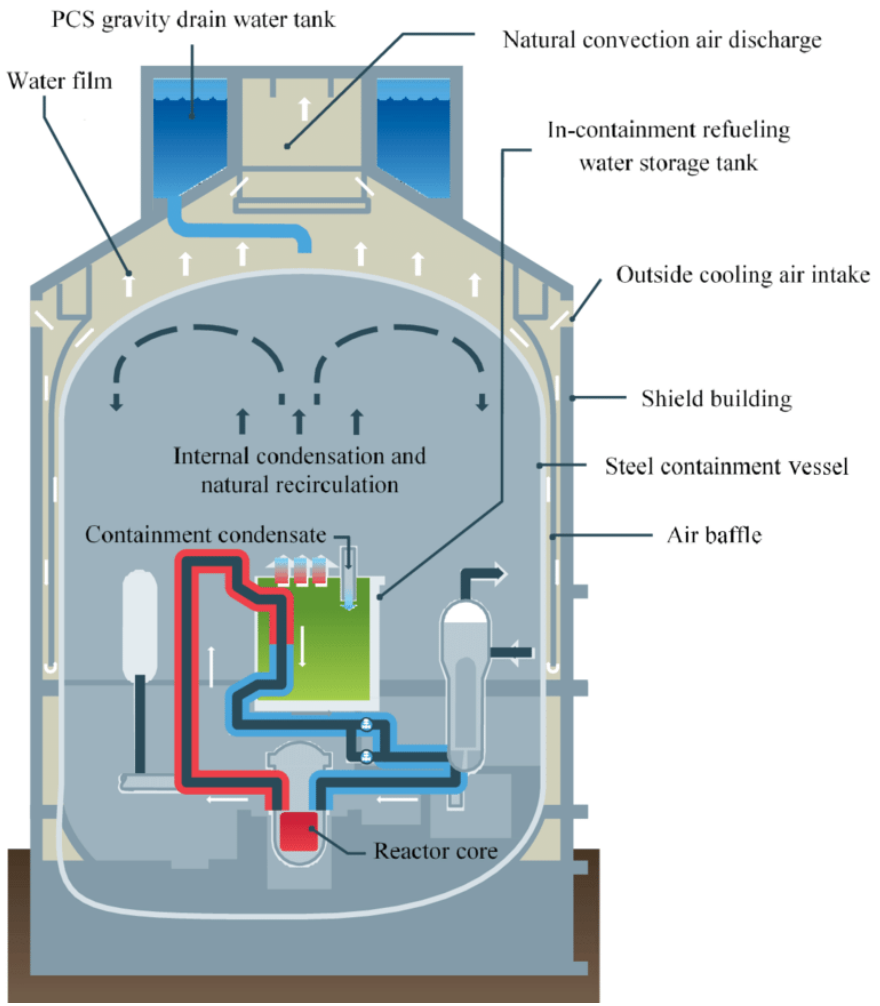
**Passive Safety Systems in nuclear reactors only require natural forces to operate and therefore do not rely on either on-site or offsite power**

- Passive safety systems use forces such as gravity, natural circulation and compressed gas to ensure the safe shut down of the reactor can be achieved in the event of an emergency.
- Rising steam produced from boiling cooling water condenses when it comes into contact with the cool steel surface of the containment vessel.
- This water is then **naturally re-circulated** by gravity back into the reactor containment where it can act as a coolant again.
- This simplified system has the ability to continue operating and cooling the core indefinitely.
- The latest currently available nuclear reactors are the generation 3+ reactors (shown right), such as the AP 1000 pressurised water reactor (PWR).

***Natural re-circulation of cooling water could reduce total water consumption in carbon capture applications***

*The suitability and applicability of passive water saving measures for carbon capture and other industrial cooling applications requires further investigation*

**AP1000 generation 3+ nuclear reactor passive cooling safety systems**



# Water can be produced as a by-product in certain direct air capture configurations

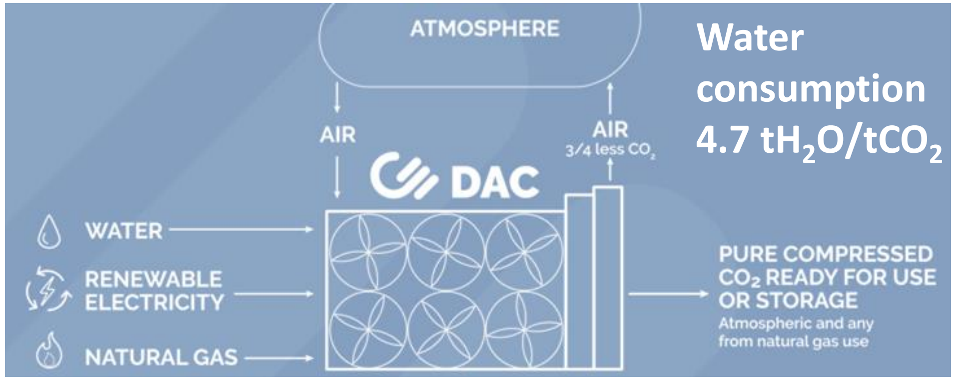
**Water loss in direct air capture primarily occurs during the sorbent-air contacting process**

- Most water use is contained in closed-loop systems, whereby water is continuously recycled in both solid and solution-based direct air capture processes.
- Cooling water is required to condense out water vapor from the calcination flue gas. This water is largely recirculated and does not contribute significantly to the overall water consumption.
- In addition, water is required for the synthesis of the solid sorbents. Considering the short sorbent lifetimes, water consumption for this purpose could be substantial.
- The water loss in high temperature aqueous solution DAC systems could be between 0-50 $tH_2O/tCO_2$ captured, depending on the temperature and humidity of the ambient air and concentration of the solution.
- The new Carbon Engineering design needs 4.7 $tH_2O/tCO_2$ captured, at ambient conditions of 64% relative humidity and 20ºC. In the Humber, average yearly temperatures and humidity is likely to be significantly lower, resulting in a small increase in water consumption.

**Low temperature DAC systems can capture water as a by-product**

- Climeworks technology can capture 0.8-2 $tH_2O/tCO_2$ as a by-product.
- From an energy point of view, it is generally the goal to capture as little water as possible, however, low temperature DAC systems could potentially provide water needed for industrial processes.

**Carbon Engineering – High Temperature direct air capture**




**Water consumption 4.7 $tH_2O/tCO_2$**

**Low Temperature direct air capture system (e.g. Climeworks)**

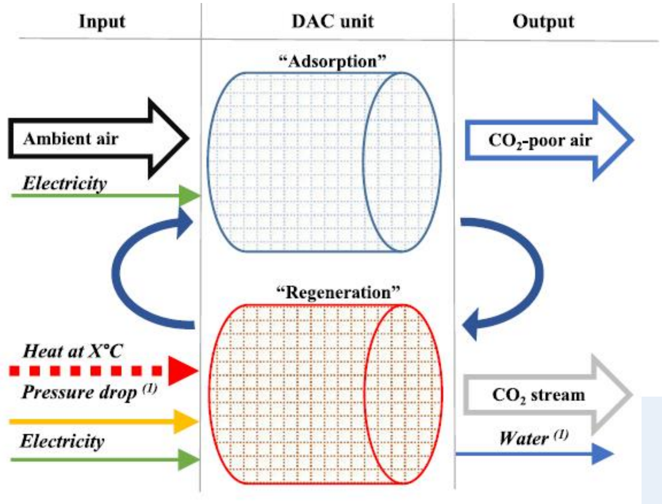



Fig. 3. Example of a low temperature solution DAC system.
(1) Conditional (depends on the system).

*By-product water production can be utilised to meet industrial demands*

**Water production 0.8-2 $tH_2O/tCO_2$**

[1]Carbon Engineering – Our Technology [2]Fasihi et al 2019 - Techno-economic assessment of CO2 direct air capture plants
[3]National Academies 2019 - Negative Emissions Technologies and Reliable Sequestration

# Producing water as a by-product of hydrogen consumption is largely unexplored and requires further analysis

**Most applications for hydrogen require it to be combusted or utilised in a fuel cell which converts it into energy and water**

- While most water can be recovered, it is not generally returned to the original body of water and it is therefore consumed.

**Harvesting water from hydrogen fuel cells should be considered as a by-product of their operation[1]**

- Hydrogen fuel cells are based on a simple chemical reaction in which oxygen oxidizes hydrogen to produce water:

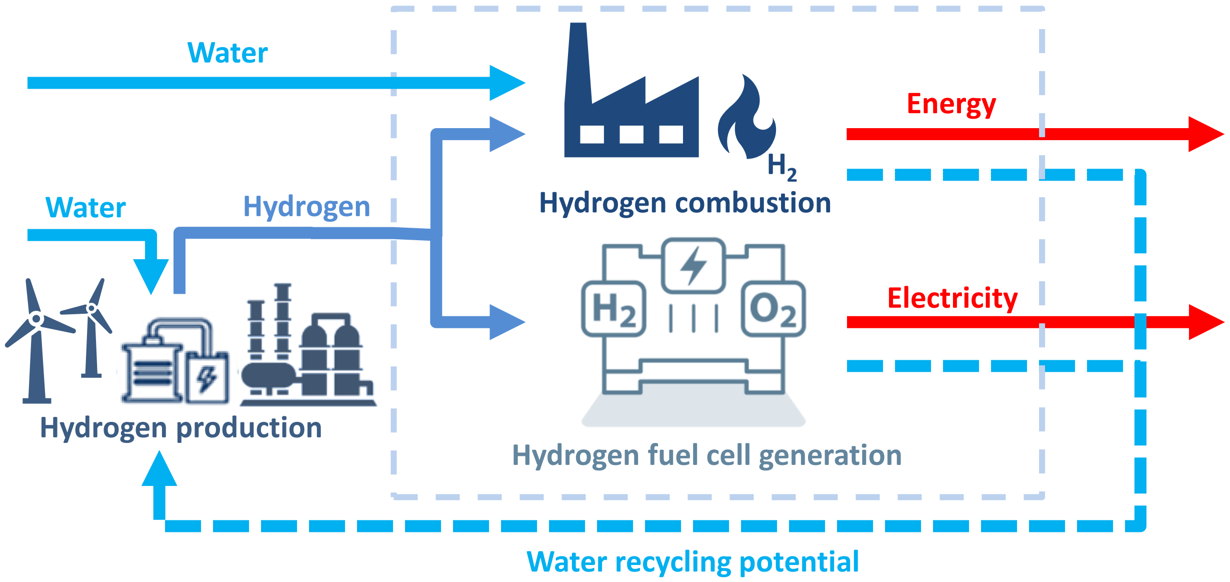
$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

- Typically, the water leaving the fuel cell exits as **both a liquid and vapor**, depending on the operating current, temperature and level of gas reactant humidification in the fuel cell.
- Many membranes are now self-humidifying or use reclaimed fuel cell product water, which eliminates external water supplies as a source and potential contaminant.
- The transport of hydrogen may simultaneously enable the production of by-product water onsite where hydrogen is utilised in water stressed areas.

***Today, limited focus has been placed on producing water as a by-product of hydrogen consumption***

***Water vapour is a greenhouse gas**, however, large increases in anthropogenic water vapour emissions are currently considered to have negligible warming impacts on the climate[3].*

**The hydrogen cycle with water recycling**




***Water demand for cooling will be required by hydrogen fuelled power generation***

**Renewable electricity generation has a significantly lower water footprint than low-carbon hydrogen production over its lifetime[2]**

- Electrification could be favoured over hydrogen fuel switching pathways in high stress water regions.
- Analysis of the water requirements of electrification will be required in the future.

[1]Hristovski et al 2009 - Producing drinking water from hydrogen fuel cells
[2]ACS Energy Letters 2021 - Does the Green Hydrogen Economy Have a Water Problem?
[3]Sherwood et al 2018, The global warming potential of near-surface emitted water vapour [3]Global warming potential (GWP) of $CO_2$ = 1, GWP of water vapour = (-0.001 to +0.0005)

# Contents

# Overview of core decarbonisation scenario narratives developed

## Scenario A: CCUS commitment

***Hydrogen and CCS infrastructure slanted scenario, with less emphasis on electrification and resource & energy efficiency.***

- There is a UK wide **push on carbon capture & hydrogen technology** innovations and adoption incentives, however supply chain issues may not be resolved.
- There may be **good support for CCS enabled hydrogen** projects due to clear communication or technology demonstrations, and/or higher electricity costs may reduce preference for electrolytic hydrogen.
- Current Humber decarbonisation plans are able to go ahead **broadly in alignment with current expectations**, with possibility of some changes to timelines.

## Scenario B: Innovations & incentives

***Ambitious scenario with strong UK technology progress and adoption of wider efficiency measures.***

- There is a UK wide **push on development across all decarbonisation technologies,** including technology innovation and supply chain development.
- Engagement of the wider industry and public on resource and energy efficiency, with **greater carbon pricing incentives**.
- Innovations and/or lower electricity costs and/or public acceptance result in **predominantly electrolysis** based future hydrogen production projects.
- Current Humber decarbonisation plans are able to go ahead **broadly in alignment with current expectations**.

## Scenario C: Barriers with limited enablers

***Hesitation or lower engagement scenario, where initial progress on infrastructure projects is delayed and overall progress is likely reduced.***

- There is **not a strong developmental push** towards any particular technology innovation pathway, with a focus instead on energy and resource efficiency measures.
- Barriers resulting from technology uncertainties, policy or regulatory factors, and/or public engagement result in initial **delays to large-scale infrastructure** deployment in the Humber.
- Overall Humber plans go ahead but with some significant delays and some sites **changing decarbonisation strategies**.

## Scenario D: Alternative solutions

***Scenario slanted towards wider electrification with slightly reduced emphasis on development of CCS & hydrogen infrastructure.***

- There may be **limited support** for continued development of **$CO_2$ transport & storage** and/or **CCS enabled hydrogen** projects, potentially due to lack of public acceptance, higher gas pricing or advances in alternative electrification technologies.
- There is a UK wide **push on electrification** innovations and adoption incentives, however supply chain issues may not be resolved.
- These developments **impact the preferred technology** pathways of sites in the Humber, and may reduce hydrogen demand. Future hydrogen production is **limited to (smaller scale) electrolysis** pathways.

Outputs for '**current plans only**' will also be generated for **simple illustrative and comparative purposes**. Comparisons of the core decarbonisation pathways with this current plans pathway will allow interpretation of the necessary additional costs and impacts beyond the current plans.

# Overview of how the core scenario narratives will be reflected through modelling assumptions

| | **Scenario A:** *Hydrogen and CCS infrastructure slanted scenario, with less emphasis on electrification and resource & energy efficiency.* | **Scenario B:** *Ambitious scenario with strong UK technology progress and adoption of wider efficiency measures.* | **Scenario C:** *Hesitation or lower engagement scenario, where initial progress on infrastructure projects is delayed and overall progress is likely reduced.* | **Scenario D:** *Scenario slanted towards wider electrification with slightly reduced emphasis on development of CCS & hydrogen infrastructure.* |
|---|---|---|---|---|
| Wider UK Influences | **Option 1**<br>High non-industry demands for hydrogen.<br>High amounts of $CO_2$ imports.<br>Higher electricity costs.<br>Strong investment in engineered GGRs. | **Option 2**<br>Lower electricity costs.<br>Higher carbon price.<br>Higher adoption of REEE measures.<br>Investment in engineered GGRs. | **Option 3**<br>Low amounts of $CO_2$ imports.<br>Higher adoption of REEE measures.<br>Delayed investment in engineered GGRs. | **Option 4**<br>Lower electricity costs, higher gas costs.<br>Low non-industry demands for hydrogen.<br>Low amounts of $CO_2$ imports.<br>Limited investment in engineered GGRs. |
| UK Technology Progress | **Option 3**<br>Focus on **carbon capture and hydrogen fuel-switching** technologies.<br>Some constraints on supply chains that **limit rate of adoption**. | **Option 4**<br>More **rapid development** across all technology categories.<br>**Minimal constraints** on supply chains, allowing fast rate of adoption. | **Option 1**<br>Technology developments follow **central estimates** based on current expectations.<br>Some constraints on supply chains that **limit rate of adoption**. | **Option 2**<br>Focus on development of **electrification technologies** and their support.<br>Some constraints on supply chains that **limit rate of adoption**. |
| Hydrogen Production in the Humber | **Option 1**<br>Near-term **projects go ahead** in alignment with current expectations*.<br>The future sees a **mixture of production methods** being deployed. | **Option 2**<br>Near-term **projects go ahead** in alignment with current expectations*.<br>The future sees a preference towards **electrolytic hydrogen**. | **Option 3**<br>Several near-term **projects are delayed**.<br>The future sees a **mixture of production methods** being deployed. | **Option 4**<br>Several near-term **projects are delayed**.<br>The future sees a preference towards **electrolytic hydrogen** projects being deployed. |
| Cluster T&S Network Deployment | **Option 1**<br>Network deployment **goes ahead** in alignment with current expectations*.<br>Storage capacity build out **goes ahead** in alignment with current expectations*. | **Option 1**<br>Network deployment **goes ahead** in alignment with current expectations*.<br>Storage capacity build out **goes ahead** in alignment with current expectations*. | **Option 3**<br>**Initial network** deployment is **delayed** with knock-on **impacts for expansion.**<br>Storage development is **initially delayed** but with no long-term capacity impact. | **Option 2**<br>**Initial network** deployment **goes ahead** but there are barriers to **expansion.**<br>Storage initially **goes ahead** but barriers result in **reduced future storage capacity.** |
| Pre-specified Site Adoptions | **Option 1**<br>**All major projects** adopt their pre-specified technology.<br>Timelines for adoption **align with current expectations***. | **Option 2**<br>**All major projects** adopt their pre-specified technology.<br>Timelines for adoption **are not specified** and are optimised by the model. | **Option 3**<br>Some major projects **adopt an alternative path**, whilst others adopt their pre-specified technology.<br>Timelines for adoption **are not specified.** | **Option 4**<br>**No pre-specification** of major projects with technologies selected by model from a **range of allowed routes**.<br>Timelines for adoption **are not specified.** |

** current expectations to be outlined by Element Energy, these will broadly follow proposed scales and timelines for major projects*

# Lot 1 scenarios – hydrogen and carbon capture demand