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# Projections of Water Use in Electricity and Hydrogen Production to 2050, under the 2020 Future Energy and CCC Scenarios - Regional Analysis


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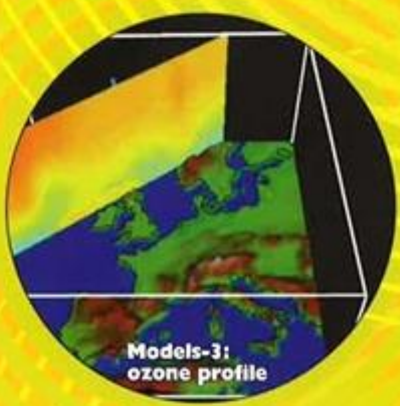
RWE Generation UK


ENV/677/2021

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**by**

## A Moores

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# List of Abbreviations

| | |
|---|---|
| AMR | Advanced Modular Reactor |
| BAT | Best Available Technique |
| BECCS | Bio-energy with carbon capture and storage |
| BEIS | Department for Business, Energy & Industrial Strategy |
| BREF | BAT Reference (Document) |
| CCC | Climate Change Committee |
| CCC20 | The UK's path to Net Zero scenarios – released by Climate Change Committee, see reference CCC (2020a) |
| CCGT | Combined Cycle Gas Turbine |
| CCUS | Carbon Capture Utilization and Storage |
| CT | Consumer Transformation – a specific scenario in FES20 |
| DEFRA | Department for Environment, Food & Rural Affairs |
| DUKES | Digest of UK Energy Statistics |
| ESO | Electricity System Operator |
| EWP | Energy White Paper |
| FES19 | Future Energy Scenarios (2019 edition) – released by National Grid, see reference NG-ESO (2019) |
| FES20 | Future Energy Scenarios (2020 edition) – released by National Grid, see reference NG-ESO (2020) |
| GHG | Greenhouse Gas |
| HOF | Hands off flow |
| HOL | Hands off level |
| HRSG | Heat Recovery Steam Generator |
| HW | Headwinds – a specific scenario in CCC20 |
| JEP | Joint Environmental Programme |
| LW | Leading the Way – a specific scenario in FES20 |
| NHH | Non Household |
| NHHD | Non Household Demand |
| NSIP | Nationally Significant Infrastructure Projects |
| NWRF | National Water Resource Framework |
| PEM | Proton Exchange Membrane (for hydrogen production by electrolysis) |
| PWS | Public Water Supply |
| SMR | Steam Methane Reduction (for hydrogen production) |
| SP | Steady Progression – a specific scenario in FES20 |
| ST | System Transformation – a specific scenario in FES20 |
| TDG | Technical Development Group (within WRE) |
| TEC | Transmission Entry Capacity |
| TW | Tailwinds – a specific scenario in CCC20 |
| WE | Widespread Engagement – a specific scenario in CCC20 |
| WI | Widespread Innovation– a specific scenario in CCC20 |
| WRE | Water Resources East |
| WReN | Water Resources North |
| WRW | Water Resources West |
| WRZ | Water Resources Zone |

## Summary

The study is aimed at illustrating the potential development and uncertainty of power sector future water use in the period to 2050. It is an addendum to the recently released report by JEP (2021) which modelled water use by the power sector under a number of energy scenarios released by National Grid ESO and the Climate Change Committee during 2020. Whereas JEP (2020 & 2021) focused on water use at GB scale and in the East of England, this study has applied the same modelling process to consumptive freshwater use in electricity generation and for hydrogen production within water resource regions. It is intended that this report be read in conjunction with JEP (2021) which provides details of the model, the derivation of the energy scenarios and the water use rates. However, for ease of use some text, from JEP (2021), providing an overview of the modelling process and context for the work has been included.

The UK faces a variety of water resource challenges in the coming decades, particularly in the south and east of England resulting from a combination of pressures such as Climate Change, population growth, land use change, and stakeholder aspiration to explore various level of ambition for environmental protection. This has led to a new Abstraction Plan (DEFRA, 2017), which aims to reform the way in which water resource is managed and spawned much new water resource focused activity at national, regional, water company and individual catchment level. Central to these initiatives is that a more collaborative multi-sector approach is needed to provide an appropriate balance between environmental protection, a resilient Public Water Supply and resilient water-dependent industry including for example power and energy provision and agriculture, in an affordable and cost-effective way.

For many years the strategic planning of the water resource needs of the water industry has been carried out in a transparent way with highly evolved approaches to selecting supply and demand options to best meet estimates of future demand. However, in water-dependent sectors that are not subject to the economic regulatory oversight that Ofwat provides in Public Water Supply, no such approaches are possible. Thus, there is no plan for sectors such as the power sector or for agriculture which can be translated into potential future water need. Moreover, the requirements of Competition law preclude collaboration between individual actors within such sectors and therefore rule out the preparation of such plans by the sector itself. However, there is ready public access to authoritative information on quantification of actual water use in UK power plant operating in today’s commercial power market.

For many power/energy plant the dominant water demand will be for cooling purposes which would not be of potable quality. However, all thermal power plant require high quality water (e.g. for steam generation) and hydrogen production plant will require high quality water as a feedstock. A given installation may source high quality water from either a potable supply or from direct abstraction, depending on the cost, quality and reliability of each feasible option. JEP (2021) modelled this high quality water demand and noted that the volumes may be of a scale significant in PWS terms if sourced from PWS non-household demand. This study has also modelled high quality water use on a regional scale. It is worth noting that demand for high quality water is also exerted during the construction period of a new plant (which, for large power plant, can extend over several years). This additional component, which might be of local significance at project level, has not been considered in the present report.

The work of JEP (2021) was concerned with the potential development and uncertainty of power sector future water use, in the period to 2050. The following energy scenarios and supporting material, recently released in the public domain, are used in JEP (2021) report and this addendum:

- 2020 Future Energy Scenarios (FES20), released by National Grid ESO in July 2020;
- UK’s path to Net Zero scenarios, released by the Climate Change Committee in December 2020 (in the framework of the Sixth Carbon Budget) (CCC20); and

– ‘Modelling 2050: Electricity System Analysis’ published by the Department for Business, Energy & Industrial Strategy (BEIS), also in December 2020.

Neither the National Grid ESO nor the Committee for Climate Change ranked the scenarios they produced. In this report, as in JEP (2021), there is therefore no judgement or ranking of the individual FES20 and CCC20 scenarios. Nor should the order in which the results are presented be construed as a ranking of the work of the National Grid ESO and Climate Change Committee. The scenarios are used to present two authorities views on plausible pathways for the energy (electricity and hydrogen) sector to UK net zero by 2050.

Consistently with JEP (2021), we take the power (synonymously energy) sector to include use of plant producing electricity, plant providing capacity to produce electricity and plant providing grid services in the electricity market. We also take it to include plant producing hydrogen either for use subsequently to produce electricity or for supply to decarbonise other hard-to-electrify sectors (e.g. long-range transport, space heating, etc.). Thus, in this study the definition of the power sector itself is future facing.

The objective of the report is to interpret potential water demand consequences of the plausible future trajectories to a UK net zero 2050 developed as FES20 & CCC20 and there is no attempt to judge or rank the scenarios. This will then allow parties active in UK water resource planning initiatives an appreciation, expressed quantitatively, of the potential power sector future demand for water and water resource, in particular freshwater in regions other than those addressed by JEP (2021). The focus of our quantitative reporting is freshwater consumed (not returned to surface waters, e.g. through evaporation), where consumption is regarded for the purposes of this report to be on an installation basis.

To capture different aspects of the electricity market, two different metrics are used in this report:

- long-term water consumption (exemplified by annual demand, quantified generally in $Mm^3pa$)
- short-term water consumption (exemplified by maximum daily demand, quantified generally in Ml/d)

The latter is estimated under the assumption that all available dispatchable capacity may be required to run at full load to meet the country’s needs at times of ’system stress events’ to provide security of national power supply and daily demand might therefore be significantly higher than the average daily demand based on the annual consumption.

The modelling approach of JEP (2021) only uses public domain information and has inputs from other participants in the sector consistent with Competition Law requirements. Closure of existing plant and choices of new plant types and locations are made within a Monte Carlo framework, informed by the characteristics of sites historically or currently associated with the power sector, and making use of simple ‘rules’ - whilst all the time being fully consistent with the plant mix provided by the scenario under analysis.

Whilst the rules used have only limited intelligence when applied at individual plant/location level this approach is well-suited to illustrating potential uncertainty ranges without favouring any particular plant type, location or company. In reality the location of future plant and closure decisions on existing plant will be determined by individual owner/operator choices based on their perception of the risk and reward of project options available to them in the UK and in their wider portfolios.

In the model, it has also been assumed that a plant might be fitted with CCUS (Carbon Capture Utilisation and Storage), in the future, if ‘sufficiently close’ to one of the industrial clusters identified by Government as well suited to early CCUS deployment. As ‘closeness’ within the modelling is based on ‘straight line’ distance only, the rule strongly simplifies the likely operator actual decision process, which will be based on the pipeline infrastructure and the pipeline corridors needed to transport carbon to where it can be utilized and stored, the availability of and access to which may depend on government policy decisions outside direct operator influence. Better criteria or at least a sensitivity study on how to represent ‘CCUS connectivity’ might be worthwhile in future. Similar considerations could apply in future in relation to developing hydrogen infrastructure (i.e. production, storage, transport and offtaker locations).

Furthermore, given the nature of the work undertaken in interpreting the potential water use consequences of uncertain approaches to meeting an uncertain future demand for energy, the resulting numeric values should be used with care. Thus, although the underlying modelling has been carried out rigorously and consistently with the assumptions made, results are quoted in representative rounded form and any reported result should however be regarded as indicative, rather than as a specific forecast.

There is considerable uncertainty in future energy sector potential water need at regional geographic scale. This is due to the uncertainty in the overall approach to the objective of carbon net-zero by 2050 within the generation and other sectors. Whilst a carbon net-zero position is the UK legal position as of 2020, there is the possibility that decarbonisation may prove to occur faster or slower than 2050. This modelling study has used eight scenarios from FES20 & CCC20 each of which has a different balance of energy plant over the years until 2050. These differences in generation and energy production between scenarios at a UK scale are reflected in the freshwater consumption at UK and regional scales. There is also uncertainty that arises from the model’s sampling from the range of water consumptions observed at actual power plant.

Some uncertainty in the outcomes arises because the model uses a rule set to convert the energy mix of each of the eight Net Zero pathway scenarios used into an electricity and hydrogen production fleet. This process of defining a future energy production fleet is repeated a large number of times to sample the potential outcomes that satisfy the Net Zero pathway. The rules allow SMR hydrogen production, BEECS and CCUS fitted CCGTs only for a set of sites considered close enough to one of the five CCUS industrial hubs. This limits the potential cooling water demand in regions where sites are distant from one of the five clusters because some future generation options required by a scenario are unavailable. In addition as SMR production of hydrogen has a large freshwater demand any increase in the number of CCUS clusters will result in greater demand within a region. WRSE is an example of a region where consideration of SMR production away from the five CCUS hubs has been considered (Project Cavendish ENA (2020)).

Within a region the uncertainty will tend to be greater than at GB scale (JEP 2021) as a sub set of the total GB options are available with fewer potential sites at which the energy production required by the scenario can occur.

The rule set also only considers the water use at a site that is directly attributable to energy production. Some operators may have in place or have plans for multi-use of existing site licenses for uses such as water sharing or supplies to third parties. Examples of third party uses could include use in industrial processes such as data centres or for drinking water supplies. The rule set does not cover these cases and therefore the circumstances and hence water use at a specific site should be confirmed for water resource planning purposes.

For all regions the model predicts an initial reduction in freshwater consumption followed by an increase after 2025 to 2030 as hydrogen production ramps up. In general the range of use post 2035 often exceeds that in the 2018 baseline year for the current modelling study. The range of 2050 consumption in the current modelling is also often greater than the baseline in the 2010 baseline used in earlier modelling by Gasparino (2012) particularly when compared to the 2010 baseline without coal fired generation.

The model has been used to predict freshwater consumption by energy producers. For thermal power plant this is for cooling purposes. In practise thermal power plant also require a source of high quality water. This can be derived from a river or a non-household water supply or potentially a desalination plant at a coastal or estuarine site. If the water is taken from a non-household supply it is likely to be an additional, indirect, freshwater consumptive use at the site. For regions where the model has no freshwater cooled sites this could be the dominant freshwater use by thermal plant.

The freshwater consumption for each region is summarised below.

## 1.1 Summary of the Regional Water Use Results

### 1.1.1 Summary Freshwater consumption WRE

- Freshwater consumption for energy production in both FES20 & CCC20 reduces until 2025 to 2030 after which it increases
- Consumption for energy production & electricity generation under FES20 & CCC20 can be greater than 2018 & 2010 baselines
- FES20 has BECCS, CCGTs and hydrogen at 2050
- CCC20 has BECCS, CCGT (with and without CCUS) and hydrogen at 2050
- FES20 Annual energy use: median up to 62Mm$^3$/y, 95%ile up to 153Mm$^3$/y
- FES20 Annual electricity use: median up to 11Mm3/y, 95%ile up to 69Mm$^3$/y
- FES20 Daily energy use: median up to 214Ml/d, 95%ile up to 455Ml/d
- FES20 Daily electricity use: median up to 62Ml/d, 95%ile up to 240Ml/d
- CCC20 Annual energy use: median up to 46Mm$^3$/y, 95%ile up to 91Mm$^3$/y
- CCC20 Annual electricity use: median up to 20Mm3/y, 95%ile up to 54Mm$^3$/y
- CCC20 Daily energy use: median up to 237Ml/d, 95%ile up to 437Ml/d
- CCC20 Daily electricity use: median up to 160Ml/d, 95%ile up to 349Ml/d
- High Quality Water: Electricity production 95%ile up to 5Mm$^3$/y

### 1.1.2 Summary Freshwater consumption WReN

- Freshwater consumption for energy production in both FES20 & CCC20 reduces until 2025 to 2030 after which it increases
- Consumption for energy & electricity production under FES20 & CCC20 can be greater than the 2018 & 2010 baselines
- FES20 has BECCS, CCGTs, nuclear and hydrogen at 2050
- FES20 Annual energy use: median up to 108Mm$^3$/y, 95%ile up to 201Mm$^3$/y
- FES20 Annual electricity use: median up to 29Mm3/y, 95%ile up to 76Mm$^3$/y
- FES20 Daily energy use: median up to 330Ml/d, 95%ile up to 610Ml/d
- FES20 Daily electricity use: median up to 115Ml/d, 95%ile up to 310Ml/d
- CCC20 Annual energy use: median up to 63Mm$^3$/y, 95%ile up to 116Mm$^3$/y
- CCC20 Annual electricity use: median up to 23Mm3/y, 95%ile up to 63Mm$^3$/y
- CCC20 Daily energy use: median up to 256Ml/d, 95%ile up to 480Ml/d
- CCC20 Daily electricity use: median up to 148Ml/d, 95%ile up to 354Ml/d
- High Quality Water: Electricity production 95%ile up to 7Mm$^3$/y

### 1.1.3 Summary Freshwater consumption WRSE

- Freshwater consumption for energy production in both FES20 & CCC20 reduces until 2025 to 2030 after which it increases

- Consumption for energy production under FES20 & CCC20 can be greater than both 2010 (without coal) & 2018 (with coal) baselines.
- The range of daily maximum consumption for electricity production is equal or greater than the 2018 (with) and 2010 (without coal) baselines
- Development of hydrogen (as in Project Cavendish) could increase use
- With only a single freshwater generation site the model will be sensitive to site specific developments
- FES20 Annual energy use: median up to 6Mm$^3$/y, 95%ile up to 13Mm$^3$/y
- FES20 Annual electricity use: median up to 2Mm3/y, 95%ile up to 3Mm$^3$/y
- FES20 Daily energy use: median up to 20Ml/d, 95%ile up to 36Ml/d
- FES20 Daily electricity use: median up to 19Ml/d, 95%ile up to 34Ml/d
- CCC20 Annual energy use: median up to 5Mm$^3$/y, 95%ile up to 13Mm$^3$/y
- CCC20 Annual electricity use:  95%ile up to 0.5Mm$^3$/y
- CCC20 Daily energy use: median up to 17Ml/d, 95%ile up to 44Ml/d
- CCC20 Daily electricity use: 95%ile up to 25Ml/d
- High Quality Water: Electricity production 95%ile up to 1.3Mm$^3$/y

### 1.1.4 Summary Freshwater consumption WRW

- Freshwater consumption for energy production in both FES20 & CCC20 reduces until 2025 to 2030 after which it increases
- Consumption for energy & electricity production under FES20 & CCC20 can be greater than both the 2010 and 2018 baselines
- FES20 has BECCS, CCGT and hydrogen production at 2050 consuming freshwater
- CCC20 has BECCS, CCGT (with and without CCUS) and hydrogen production at 2050 consuming freshwater
- FES20 Annual energy use: median up to 48Mm3/y, 95%ile up to 131Mm$^3$/y
- FES20 Annual electricity use: median up to 4Mm3/y, 95%ile up to 55Mm$^3$/y
- FES20 Daily energy use: median up to 168Ml/d, 95%ile up to 424Ml/d
- FES20 Daily electricity use: median up to 42Ml/d, 95%ile up to 219Ml/d
- CCC20 Annual energy use: median up to 28Mm$^3$/y, 95%ile up to 72Mm$^3$/y
- CCC20 Annual electricity use:  median up to 7Mm$^3$/y, 95%ile up to 38Mm$^3$/y
- CCC20 Daily energy use: median up to 178Ml/d, 95%ile up to 351Ml/d
- CCC20 Daily electricity use: median up to 123Ml/d, 95%ile up to 298Ml/d
- High Quality Water: Electricity production 95%ile up to 5.7Mm$^3$/y

### 1.1.5 Summary Freshwater consumption WCWR

- No current freshwater cooled sites therefore 2050 consumption is greater than baseline
- Both CCC20 & FES20 only have hydrogen production at 2050 consuming freshwater for cooling
- FES20 use for energy production in 2050: median up to 9Mm$^3$/y, 95%ile up to 22Mm$^3$/y
- FES20 daily use for energy production: median up to 25Ml/d, 95%ile up to 63Ml/d
- CCC20 use for energy production in 2050: median up to 8Mm$^3$/y, 95%ile up to 21Mm$^3$/y
- CCC20 daily use for energy production: median up to 23Ml/d, 95%ile up to 58Ml/d
- High Quality Water: Electricity production 95%ile up to 1.3Mm$^3$/y

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## 2 Introduction

The UK faces a variety of water resource challenges in the coming decades, particularly in the south and east of England resulting from a combination of pressures such as Climate Change, population growth, land use change, and stakeholder aspiration to explore various level of ambition for environmental protection. This has led to a new Abstraction Plan (DEFRA, 2017), which aims to reform the way in which water resource is managed and spawned much new water resource focused activity at national, regional, water company and individual catchment level (e.g., EA, 2020). Central to these initiatives is that a more collaborative multi-sector approach is needed to provide appropriate environmental protection, a resilient Public Water Supply and resilient water-dependent industry including for example power and energy provision and agriculture, in an affordable and cost-effective way.

For many years the strategic planning of the water resource needs of the water industry has been carried out in a transparent way with highly evolved approaches to selecting supply and demand options to best meet estimates of future need. However, in water-dependent sectors that are not subject to the economic regulatory oversight that Ofwat provides in Public Water Supply, no such approaches are possible. Thus, there is no plan for sectors such as the power sector or for agriculture which can be translated into potential future water need. Moreover, the requirements of Competition law preclude collaboration between individual actors within such sectors and therefore rules out the preparation of such plans by the sector itself. However, there is ready public access to authoritative information on quantification of actual water use in UK power plant (e.g., Booth and Edwards, 2019) operating in today's commercial power market.

This report is an addendum to the work of JEP (2021) which modelled potential water use by the energy sector to 2050. In the absence of a sector plan JEP made use of the future plant mixes and generation loads reported in the latest edition of the Future Energy Scenarios (FES20) developed by National Grid ESO (NG-ESO, 2020) and net zero future pathways to 2050 released by the Climate Change Committee (CCC, 2020a). The water need implied by the energy mix under each of the scenarios was then modelled.

The objective of JEP (2021) and therefore the present study is to allow parties active in UK water resource planning initiatives an appreciation, expressed quantitatively, of the potential power sector future demand for water and water resource, in particular freshwater. It makes use solely of public domain information and with inputs from other participants in the sector consistent with Competition Law requirements. The model assumes as input a list of sites where future plant might be located. The capacity that might be deployed at each of these sites reflects:

- the installed plant capacity (for sites presently operational or that have been active in the past);
- the planned plant capacity (for sites listed as Nationally Significant Infrastructure Projects).

Choices of new plant types and locations and choices of closure of existing plant are made within a Monte Carlo framework making use of simple 'rules' whilst all the time being fully consistent with a plant mix scenario provided by FES20 or CCC20. Whilst the rules used have only limited intelligence when applied at individual plant/location level this approach is well-suited to illustrating potential uncertainty ranges without favouring any particular plant type, location or company.

The focus of our quantitative reporting is freshwater consumed (not returned to surface waters, e.g. through evaporation) where consumption is regarded for the purposes of this report on an installation basis.

Although, for water resource planning purposes, the focus is freshwater it is necessary to consider the potential for location of plant accessing salt water since relevant plant are not restricted by their technical requirements to be located at a specific quality of water supply. Main steam cycle wet cooling systems can operate with either freshwater or saltwater and the water for smaller volume but nonetheless essential use of high quality water (e.g., heat recovery steam generator make up water) can be sourced from water of any quality (at the cost of differing levels of water treatment) with overall costs and reliability being typical main considerations. The location of future plant and closure decisions on existing plant will be determined by individual owner/operator choices based on their perception of the risk and reward of project options available to them in the UK and in their wider portfolios. This choice will always include ‘do nothing’ since there is no obligation on any party to build future power plant of any type. Moreover, the risk reward perception may also be conditioned by wider regulatory policy. It is often advocated that, as a climate change adaption strategy, the power sector can ‘move to the coast’ freeing up scarce freshwater resource for sectors which do not have such an adaptation strategy available. However, this does not take into account the reality of project development in which there can be considerable advantages in developing freshwater sites and considerable problems in developing saltwater ones. JEP (2021) includes some sensitivity studies exploring the potential consequences of policy backdrops which might favour, or hamper use of the freshwater or saltwater environments.

Throughout the work both the long-term water use (exemplified by annual demand) and short-term (exemplified by daily demand) has been considered. This reflects aspects of the highly dynamic electricity and energy markets which respond to short-term variations in supply and demand driven by weather, work-day patterns, changing plant availability as well as longer term variations (e.g., associated with seasons). Together these lead to variation in individual plant operation within day, and day to day, as the plant respond to market requirements. Thus, the requirement for water on a given day may be very significantly different to the annual average requirement and may differ significantly from day to day. In particular, plant contracted in the capacity market will generally require their full licenced water right in order to generate at full load if called upon to do so. In the model the long term (annual use) is set by the annual generation required by each scenario. The daily water use is calculated assuming all generation plant are called on to operate at full capacity for 24hours. This is taken to represent a so called system stress event which can occur when other forms of generation are unavailable. The maximum daily generation demand (and hence water use) is likely to be greater than the daily average implied by the annual demand. Hydrogen production is assumed to operate differently because it can be stored, and production is constant throughout the year. For hydrogen the daily water demand is derived from the annual use.

Given the nature of the work undertaken in interpreting the potential water use consequences of uncertain approaches to meeting an uncertain future demand for energy, the resulting numeric values should be used with care. Thus, although the underlying modelling has been carried out rigorously and consistently with the assumptions made, results are quoted in representative rounded form. In a region with few existing and potential generation sites or where there is less variety in the type of generation the modelling assumptions will have a relatively stronger influence on the results than in regions whose sites have more generation options available. An example of this are those regions where it is assumed that carbon capture is not available as carbon capture fitted gas or biomass plant have different generation profiles in the scenarios to unabated generators. The modelling should not be used to inform a view about future need at an individual site level.

# 3 Assessment Methodology

Full details of the model and the development of the energy scenarios are given in JEP (2021) with an overview (reproduced from that report) provided here for convenience. The aim of the model is to illustrate the potential future water requirements by energy (electricity & hydrogen) producers involved in pursuing and adapting to a carbon neutral energy system by 2050 in line with the Energy Scenarios provided by respected third parties.

For this purpose, a list of the operational power plant as of 2018 was collated, as well as a list (based on sites listed as Nationally Significant Infrastructure Project or historical information) of available, but not operational, sites (which might potentially become operational in the future). However, since the drivers for future plant location differ in some regards from those in the past, there is always the possibility that some future plant will be sited in locations not historically or currently associated with the power sector. In compiling the 'longlist' of potential sites a degree of peer review was sought by giving Energy UK members the opportunity to comment on the viability or otherwise of sites. Where comment was received this has affected the presence or otherwise of a site on the 'available' site list.

For each of these sites the following is specified: fuel, capacity, location and Water Resource Region, kind of abstracted water (fresh river, fresh tidal, saltwater estuary or saltwater coast), type of cooling (once-through, towers or dry cooling)[1] and the year of commissioning.

The model relies then on the specification at national level of a future energy scenario to project the pathways of future capacity and generation associated with different types of plant. The following classes of water-relying plant have been used: coal-fired, biomass-fired (with or without Carbon Capture Utilisation and Storage – CCUS), gas-fired (Combined Cycle Gas Turbines – CCGT, including plant fitting CCUS and plant converted to burn hydrogen instead of natural gas), nuclear and hydrogen production (by electrolysis or steam methane reforming).

For each of the examined energy scenarios, the water requirements are then estimated using the following three main steps:

(i) Build the 'initial condition' (based on the list of operational plant): GB generating fleet at the start of the simulation (assumed to be 2019)

(ii) Use a 'set of rules' (Monte Carlo approach) to iteratively determine the future evolution of the 'initial fleet' (from 2019 to 2050). The 'set of rules' governs the opening of new plant capacity (based on the list of operational plant) or the closure of existing ones - to guarantee that the makeup of the GB generation fleet reflects the one specified, for each class of generators, in the energy scenario under investigation. As the fleet evolves in time, generation is gradually shifted towards new plant, so that the solution for 2050 is mainly determined by the specified 'set of rules' and tends to retain little memory of the specified initial condition. However, in intervening times there is significant influence of the location and plant types of the initial fleet.

(iii) Quantify future water requirements, using pre-specified ranges (in units of $m^3$/MWh or $m^3$/Kg for hydrogen) for water gross usage and water consumption (different rates are used for different cooling systems and different classes of generators).

For simplicity, the capacity choice and water use are modelled without consideration of any operational constraint (e.g. in relation to occurrence of abstraction licence HOF, HOL, temperature constraints on discharge, planned or unplanned outages, etc.) associated with different classes of generators.

A more detailed description of the modelling approach is provided in Appendix B of JEP (2021).

[1] The type of cooling can also be expressed in probabilistic terms for those 'available' sites for which the likely project development preference for choice of cooling system is not clear cut.

Two complementary metrics are used to report the water gross usage and consumption calculated by the model:

- The annual total (conventionally reported by the model in units of: $Mm^3pa$)
- The daily maximum (conventionally reported by the model in units of: Ml/d)

It is worth noting that the two metrics are intended to capture different aspects of the electricity market (and therefore are not just the result of a straightforward unit conversion):

- to calculate the annual total, the modelling assumes that, once operational, each power station delivers its energy [TWh] contribution to the energy scenario national TWh for its class, proportional to its installed capacity [GW];

to calculate the maximum daily uses, the modelling assumes that security of supply might force all installed dispatchable capacity that are reliant on water to be running at full load (for more than 24 hours in a row), to meet the country's needs at times of so-called 'system stress events' (e.g. under those rare weather patterns, which cause high demand and minimal wind power generation in the UK and Continental Europe, see e.g. Dawkins, 2019). Under these rare circumstances, daily generation by dispatchable plant is given by multiplying the installed capacity [GW] by 24 hours). The approach is different for hydrogen as it is assumed that hydrogen can be stored and therefore the daily use is constant throughout the year. The hydrogen maximum daily use equals the daily average use.

### 3.1 Types of uncertainty considered by the model

Three main sources of uncertainty are considered by the model:

(i) Uncertainties inherent in the pace and breadth of changes in the future energy landscape. Approached by:
   - running the same model under alternative sets of plausible energy scenarios, produced by respected third parties;

(ii) Uncertainties inherent in the characteristics of the future fleet (such as locations, cooling options of future plant). Approached by:
   - expressing the 'set of rules' in probabilistic terms and generating, in a typical Monte Carlo fashion, a large number of replications (consistent with the probability distributions specified by the implemented 'set of rules');
   - JEP (2021) also tested the impacts of using a number of alternative, but plausible, 'sets of rules'. This might, for example, be used to analyse the consequences of different policies (such as to prioritise the choice of available stations that are at coastal locations, the linkage to particular CCUS clusters, any strategic water resource decisions emerging in the National Water Resource Framework, etc.).

(ii) the uncertainty inherent in the assumed rates of water use. Approached by:
   - expressing the water rates as probability distributions and using a Monte Carlo approach.

### 3.2 Energy Scenarios considered by the model

JEP (2021) provide full details of the energy scenarios used in the modelling but for ease of use an overview is provided below.

There is no power sector plan or national decarbonisation plan. In practice plant operators would be expected to act on the basis of their perception of the risks and opportunities of action or inaction in the context of their overall portfolio position. For many, this would include consideration of their company positions outside the UK. There is no duty on any party to develop a power plant. In the absence of such plans, and in the absence of sector collaboration to produce such plans (which would be prohibited under competition law requirements) to provide insight on alternative plausible future developments for capacity and generation, from here to 2050 - we have made use:

- the *Future Energy Scenarios* (FES20) released by National Grid ESO in July 2020 (source: NG-ESO, 2020);
- the *UK's path to Net Zero* (CCC20) released by Climate Change Committee in December 2020 (source: CCC, 2020a);

Whilst a carbon net-zero[2] position is the UK legal position as of 2020, there is the possibility that decarbonisation may prove to occur faster or slower than 2050:

- Two of the four FES20 (Consumer Transformation and System Transformation) are consistent with an achievement of net zero in 2050;
- The other two illustrate a faster (Leading the Way) and a slower (Steady Progression) decarbonisation timescale. These are interpreted by NG-ESO as '*fastest'* and the '*slowest credible decarbonisation*' pathway and representative of those scenarios that do not meet the net zero target in 2050.

The CCC20 scenarios - see CCC (2020a) and JEP (2021) for more details – consist of four explorative and a balanced scenario:

- in the **Headwinds (HW** in the text & figures that follow**)** scenario: people change their behaviour and new technologies develop, but we do not see widespread behavioural shifts or innovations that significantly reduce the cost of green technologies ahead of our current projections. This scenario is more reliant on the use of large hydrogen and carbon capture and storage (CCS) infrastructure to achieve Net Zero;
- the **Widespread Engagement (WE)** scenario is more optimistic than Headwinds on developments regarding societal and behavioural changes (people and businesses are willing to make more changes to their behaviour). This reduces demand for the most high-carbon activities and increases the uptake of some climate mitigation measures.
- the **Widespread Innovation (WI)** scenario is more optimistic than Headwinds on developments regarding improvements in technology costs and performance (greater success in reducing costs of low-carbon technologies). This allows more widespread electrification, a more resource and energy efficient economy, and more cost-effective technologies to remove $CO_2$ from the atmosphere.
- **Tailwinds (TW),** the last exploratory scenario, assumes instead that a considerable success on both innovation and societal/behavioural change can be achieved, and goes beyond the 'Balanced Net Zero Pathway' to achieve Net Zero before 2050.
- A fifth scenario the '**Balanced Net Zero Pathway**' that reaches net zero by 2050 was then construed as a 'recommended pathway' being a scenario where progress is driven through the 2020s, while creating options in a way that seeks to keep the exploratory scenarios open. JEP modelled the four underlying scenarios.

Only the four exploratory CCC20 scenarios are considered in the present report.

In order to estimate the power sector future water use associated with the scenarios, time series for the projected capacity, electricity generation and hydrogen production (in the period to 2050, at yearly time step) are needed by the water use model. These are derived (see JEP (2021 for details) from information available in the data supporting the energy scenarios.

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[2] In June 2019, the UK Government amended the Climate Change Act from 80% to 100% GHG reduced emissions – or Net Zero – by 2050. 'Net' means balancing any residual emissions with an equal quantity of carbon dioxide removals from the atmosphere, as long as this takes place in the UK.

As discussed in detail below the model includes a range of energy production technologies including different thermal (combustion and nuclear) electricity generation as well as hydrogen production. The model does not include the use of water for hydroelectric generation. Although such generation is non consumptive there is a link to water resource planning via the need to retain adequate river flow.

The scenarios consider several technologies some details of which are given below:

### 3.2.1 Carbon Capture, Utilization, and Storage (CCUS)

The deployment of CCUS in industry, with bioenergy (for GHG removal from the atmosphere) and very likely for hydrogen and electricity production, is viewed by the Climate Change Committee as a necessity, not an option (CCC, 2019). This would require the development of a major $CO_2$ transport and storage infrastructure at several CCUS clusters and, possibly, with some $CO_2$ transported by ships or heavy goods vehicles. CCC suggest $CO_2$ infrastructure development should start as early as possible and will need clusters in all areas with large industrial emission.

The Government has set a target to commission the first CCUS facility by the mid-2020s, BEIS (2019). The Energy White Paper (EWP, 2020) pledges to *support the deployment of CCUS in 4 industrial clusters including at least one power CCUS project, to be operational by 2030 and to put in place the commercial frameworks required to help stimulate the market to deliver a future pipeline of CCUS projects*. CCC call for more than two CCUS clusters, at least one including hydrogen production, to be operating by 2030 with the first operational by 2026.

Five industrial clusters: Teesside, Humberside (now 'Zero Carbon Humber'), Merseyside, South Wales and North East Scotland – have been identified by Government as well suited to early CCUS deployment.

In the model, it has been assumed that a plant might be fitted with CCUS, in the future, if 'sufficiently close' to one of these five clusters (JEP 2021, Appendix B.3). As it is based on 'straight line' distance only, the rule strongly simplifies the likely operator actual decision process, which will be based on the pipeline infrastructure and the pipeline corridors needed to transport carbon to where it can be utilized and stored. It should therefore be regarded as illustrative only.

### 3.2.2 Combined Cycle Gas Turbines (CCGT)

CCGTs have a future role in providing a flexible and efficient source of electricity (especially when the renewable output is low), system stability and balancing services (which facilitates the cost-effective integration of low-carbon generation, such as renewables and nuclear) and in improving the system diversity and, consequently, security of supply. Currently, the consequences in the decarbonisation pathways for CCGT are either through managed load, potentially leading to closure or the fitting of (or replacement by a new plant with) CCUS. Another credible pathway is through adapting an existing CCGT initially to combust a blend of methane and hydrogen and ultimately to combust exclusively hydrogen. This could be done at either a whole plant or individual unit level, noting that a commercial power plant often consists of a number of units which could be adapted differently if desired.

Under FES20, conventional natural gas-fired CCGTs (non-CCUS fitted) might still be contributing to security of supply in 2050, under the 'Steady Progression' scenario. In the scenarios consistent with net zero by 2050 ('System Transformation', and 'Consumer Transformation'), the current fleet of methane-fired CCGTs is converted or replaced to transform by 2050 into a fleet of hydrogen-fired CCGTs. No contributions from this plant are projected under the 'Leading the Way' scenario.

It is interesting that (as a result of higher cost and presence of residual carbon emissions from post-combustion CCUS technology) none of the FES20 projects a future for CCUS-fitted CCGTs. This is in contrast with FES19, the Climate Change Committee's and Imperial college's scenarios analysed in JEP (2020), as well as the scenarios most recently released by the Climate Change Committee (CCC20) (see JEP 2021, Appendix F), which were more inclined towards a CCUS-fitted future for CCGTs. The most recent analysis by the Department for Business, Energy & Industrial Strategy (BEIS, 2020) also supports the conclusions that 'low system cost' solutions at low carbon intensities can only be achieved, for all the technology cost scenarios investigated in the report, with a substantial deployment of gas-CCUS and nuclear capacity.

Hydrogen-based generation enables decarbonisation of traditional gas plant technologies and can provide flexibility while making efficient use of the hydrogen infrastructure. The advantages of a hydrogen-based approach include making use of existing sites with their existing infrastructure connections and avoiding the need for construction and operation of a carbon dioxide pipeline. Such an approach may be particularly attractive for plant envisaging modest and low load but inevitably much would turn on site-specific and owner-specific considerations including their wider portfolio positions and appreciation of risk and reward. In particular this approach might well result in greater use of inland freshwater sites, compared to a CCUS deployment scenario favouring large-scale estuarine or seaside sites linked to a coastal carbon-sequestering pipeline network or offering opportunity for transport to storage sites by ship. The electricity system analysis undertaken in BEIS (2020) also supports the conclusions that moderate levels of low-carbon hydrogen-fired generation could replace unabated gas-fired generation and reduce the requirement for new nuclear and gas CCUS in low carbon systems, reducing the total system costs of the transition to a low carbon electricity system.

Moreover, CCC20 identifies scenarios in which SMR functions as a transition technology for hydrogen production which is phased out prior to 2050 in favour of electrolysis. If this were to become 'accepted' some operators may prefer to focus on non-SMR hydrogen production from the outset and this could include favouring freshwater sites. Provision of renewable electricity to such sites would be more efficiently provided through contractual means rather than necessitating direct-wire connections.

### 3.2.3 Biomass

When using biomass, the highest savings of Greenhouse Gases are achieved with high $CO_2$ sequestration rates and displacement of high-carbon alternatives. One option for doing this is to burn woody biomass to generate electricity (while capturing and storing its carbon emissions - BECCS). Several other routes are however also conceivable, such as its use in industry, timber frame & wood panel construction or hydrogen production. A '*best use of bioenergy*' analysis was originally undertaken by the Climate Change Committee in CCC (2018). This has been successively updated and extended (in the framework of the Sixth Carbon Budget analysis, see CCC, 2020a and 2020b). The CCC results (see Figure 6.5 and Figure 6.6, in CCC, 2020b) show that the '*best uses*' of biomass in 2035 already align well with those in 2050. They also show that uses of biomass in construction, industry, power and hydrogen production are likely to result in similarly high total levels of carbon abatement. There is still therefore significant uncertainty on the '*best use*' of bioenergy resources to deliver net zero[3]. The Government will publish a *new Biomass Strategy* by 2022 to assess the contribution of biomass technology to its goals as well as sustainability standards.

### 3.2.4 Nuclear & Small Modular Reactors

To date, nuclear power plant in the UK have been relatively few in number and large in capacity and have been sited in estuarine and coastal locations. Nuclear plant is the subject of a specific National

[3] In this respect, it is worth noting that BEIS didn't consider the 'optimal' deployment of BECCS in their analysis (see Appendix in F.2). Following BEIS: *this is because the amount of biomass that will be available, and the sector in which it is most efficiently used to meet net zero are both uncertain and under review as part of the work to develop a biomass strategy*.

Policy Statement (DECC EN-6, 2011) a revision to which in relation to siting criteria has recently been consulted upon for plant with capacity >1GWe.

In recent years there have been developments in nuclear technology which has led to consideration of the possibility of introduction of small modular nuclear reactors (generally 500MWe equivalent or less, designed with modular technology using module factory fabrication). There may be the possibility that these could be deployed at locations other than those which to date have been considered for nuclear power plant, in particular increasing the potential for them to be sited to make use of freshwater for cooling.

The Energy White Paper (EWP, 2020) confirms the Government's view that nuclear energy, complementing a renewable energy mix, is required to meet the UK's commitment to decarbonisation. The White Paper provides an 'in principle' commitment to large-scale nuclear and an overview of existing funding and programmes for advanced nuclear technologies. As part of the Government's Ten Point Plan, additional large-scale nuclear power plants and the development of the next generation of nuclear technologies - Small Modular Reactors and Advanced Modular Reactors (AMRs) - are embedded in the Government's vision for the UK's low carbon future. The Energy White Paper also picks out the potential role for AMRs with high operating temperatures in providing a cost effective solution to hydrogen production, helping to unlock hydrogen as a low cost, low carbon alternative fuel.

FES20 recognise that today's nuclear power sector mostly consists of reactors due to reach end of life in the 2020s and these have to be replaced by a new generation of nuclear plant. In the 'ST' scenario, the ambition to decarbonise with more centralised technologies leads to a focus on large-scale nuclear generation, while in the 'CT' scenario, despite the focus on decentralised generation, National Grid ESO still see nuclear as transmission connected, but with greater uptake of small modular reactors. The other two FES20 ('SP' and 'LW') have lower levels of nuclear capacity.

For the purposes of this study we have not explicitly factored this into nuclear plant siting rules and therefore introduction of riverine Advanced Nuclear Technologies[4] is a factor which could lead to increased freshwater use compared to that considered in our study. One might reconsider this aspect if more details on the projected role and function of Advanced Nuclear Technologies (subject to demonstration, and social and political acceptance) become available.

#### 3.2.5 Hydrogen Production

Given the importance of the contribution of large scale hydrogen production - via Proton Exchange Membrane (PEM) electrolysis and/or Steam Methane Reforming (SMR) - to a Net Zero energy system, especially in industry, and the importance of CCUS to its production by SMR, CCC call for hydrogen production to start at scale by 2030, at each of the industrial CCUS clusters. The recent Energy White Paper (EWP, 2020) also places a focus on existing industrial clusters and the Government envisages *support for the delivery of four low-carbon clusters by 2030 and at least one fully net zero cluster by 2040.* A dedicated *Hydrogen Strategy* is expected in early 2021, targeting 5 GW of low-carbon hydrogen production capacity by 2030 and a ten-fold increase by 2050. This level will require a number of production technologies, including methane reformation with CCUS, biomass gasification with CCUS and electrolytic hydrogen using renewable or nuclear generated electricity. Clean hydrogen will be produced at scale by the mid-2020s, with 1 GW production capacity by 2025. Also in the 2020s the safety, security, cost and potential for emissions reduction of clean hydrogen will be assessed, to scale up even further in the 2030s. Government supports an early deployment that will help the UK to capture increasing international demand for hydrogen goods and services.

[4] defined as Small Modular Reactors which are smaller versions of today's technology, and Advanced Modular Reactors which adopt next generation technologies.

The production of Hydrogen (by electrolysis, SMR and/or other means) would add additional water requirements to the sector[5], which have been estimated on the basis of the annual amounts of produced Hydrogen and appropriate rates for water uses (see JEP 2021, Appendix **Error! Reference source not found.** for details).

In the model, the $H_2$-producing plant is assumed:

- for electrolysis - to be spatially distributed (analogously to the electricity-generating plant);
- for SMR - to be located 'linked' to one of the CCUS industrial clusters, to allow, under a Net Zero future, the capture and storage of the carbon released in the hydrogen production process.

Again, this basic approach to modelling the deployment of future hydrogen plant should be regarded as illustrative only.

### 3.2.6 Hydrogen and CCUS infrastructure

A recent publication by Imperial College (Sunny, 2020) investigates the regional infrastructure (hydrogen and CCUS) needed, in Great Britain, to 'optimise' the transition from the present (carbon intensive) natural gas-based heating sector to a hydrogen-based one. The study used mathematical optimisation to develop a detailed spatial-temporal description of the deployment of all network elements, and to identify the key factors in the synergistic design of the nation-wide $H_2$ and $CO_2$ infrastructure. The main results show that optimal regions for siting $H_2$ production are characterised by proximity to: 1) underground $H_2$ storage, 2) high demands for $H_2$, 3) geological storage for $CO_2$. More specifically, while - as it might be expected - the CCUS and $H_2$ producing plant are initially deployed in the proximity of the (coastal located) CCUS industrial clusters, and infrastructure is initially developed to allow their interconnection, on a longer time scale the 'optimal' infrastructure tends to extend to inland (and therefore to freshwater dependent) locations. The reason for this can be understood by considering Imperial College's assumptions, the system costs for the deployment of the CCUS and $H_2$ infrastructure tend, in the long term, to be dominated by the storage infrastructure (in particular $H_2$ storage, as this allows an increase in the annual load of the deployed hydrogen producing plant and, consequently, a decrease in the number of plants needed to be deployed to satisfy the future demand for hydrogen). Spatial vicinity to demand centres and storage sites tends therefore to become one of the dominant driving forces to select the 'cost optimal' locations for siting a plant. The infrastructure development envisaged in Sunny (2020) would have more CCUS nodes inland and hence could allow more dispersed SMR production than is currently modelled under the assumption of JEP (2021) (where CCUS plant are constrained to be 'in the vicinity' of one of the industrial CCUS clusters presently identified by Government and located in coastal zones).

The recently published UK Strategy for industrial decarbonisation (UK Gov 2021) also assumed a more widely distributed network of CCUS industrial clusters would be required. The UK Gov (2021) modelling assumed a minimum of nine clusters. These included two $CO_2$ injection points within the WRSE region (Southampton and Medway, where the captured $CO_2$ is shipped for offshore storage) that were not previously considered and are not assumed in the current water use model.

## 3.3 Deployment strategies

Even when future generation levels are constrained to reproduce the values specified under a single energy scenario, there will still be a considerable variability in the potential future water needs of the sector that is intrinsically linked to uncertainties in the locations and cooling options adopted by the fleet supplying the generation levels projected by the scenario under investigation. These

[5] It is worth noting that this would be paired with a (partial) displacement of the traditional (gaseous and solid hydrocarbons-based) refining sector, the consequences of which have not been quantified in the present report.

uncertainties might be expected to be higher, the higher the resolution (e.g. higher at regional than national level, or higher for freshwater than total water).

The generating fleet of the future will evolve as a result of a wide range of commercial choices made by individual operators over time, informed by their own views on future market and policy drivers, their risk perception and their attitude to risk (with individual operators that might opt for different deployment strategies and roles). To address these issues, and its intrinsic uncertainty, the model has been developed allowing for some flexibility in the criteria followed to select the plant to be deployed. This is done by ranking all available sites (in accordance with a prescribed set of rules) and sequentially selecting the top ranked plant until the generation capability prescribed by the energy scenario (used as input by the model) at the given time is reached. The set of rules, implemented in a stochastic Monte Carlo programming framework, is inherently non-deterministic and there is therefore a certain degree of randomness associated with the ranking of the available plant. The consequence of this is that, for each available plant, there is only a certain probability (determined by the implemented 'deployment rules') of being actually deployed. Different plant will therefore be sampled in the different Monte Carlo replications.

Alternative options for the 'deployment rules' (portraying alternative dynamics in future market and policy drivers) have been developed and implemented in the modelling reported by JEP (2021) who undertook an analysis of the sensitivity of the model to these assumptions. They found that for a range of seven rules which varied between favouring freshwater to favouring saltwater sites as well as changing the number of CCUS clusters that for GB as a whole there was a 60% difference in the freshwater consumption between the highest and lowest within a single scenario. At the east of England scale there was a twofold difference in the predicted freshwater consumption in 2050 between the rules that resulted in the highest and lowest values. For simplicity this extra source of uncertainty is not analysed in the present report.

## 3.4 Allocation of Potential sites to Water Resource Regions

The sole difference between JEP (2021) and the present report is the spatial aggregation used for the presentation of the modelling results. The present study has aggregated sites to a Water Resource Region. JEP (2021) focussed on GB and East of England. The definition of the East of England area and its sub regions had been agreed with interested parties but they do not align with current Water Resource Regions. For the present study the existing and potential sites were each individually allocated to the appropriate Water Resource Region using a GIS system (see Figure 1 below for an illustration of sites and the regional boundaries). The latest Resource Region definition maps (V5) provided by the Environment Agency[6] were used in the allocation process. Where a site was close to the region boundary a manual check was made to confirm the assigned grid reference and the region assignment.

[6] Pers, comm. 5/11/2019

**Figure 1: Water Resource Regions and generation sites used in the model**

It is worth noting that with the region boundaries running across and along some water bodies there are some rivers shared between regions. The Trent, for example, flows through Water Resource West and then into Water Resource East while downstream of Gainsborough the east bank is Water Resource East with the west being Water Resource North.

### 3.5 Water consumption rates

As with JEP (2021) this report has considered both the use of freshwater in cooling and the use of high quality water, which may be derived from freshwater, in energy generation.

#### 3.5.1 Cooling Water consumption rates

The approach taken in JEP (2021) and hence this study uses energy scenarios and deployment rules to model the main characteristics of future electricity generation and hydrogen production. The scenarios are used to define an annual value for the amount of installed capacity (in GW) and generated electricity (in TWh) and the amount of hydrogen (expressed in kilotonne $H_2$) for the UK as a whole. The model then uses a rule set to assign the energy production required by the scenario to individual sites.

In a further step, the values of annual generation are converted into the corresponding annual water consumptive uses (expressed in $Mm^3$) using appropriate rates[7]. The adopted rates depend on the (station-specific) cooling system (once-through, wet or hybrid towers or dry cooling) and are derived through 'random extraction' from probability distributions that are consistent with those derived by JEP on the basis of reported data, in recent years (Booth & Edwards, 2019) or from the literature. The rates of water use are not treated in a deterministic way, but are defined through 'ranges of uncertainty', specified by a minimum, a 'central' ('most likely' outcome) and a maximum value. More details on the assumed rates and their derivation are reported in JEP (2021), Appendix C.

Maximum daily water uses are also estimated by the model, using the same rates, but in doing this:

- for each site where electricity is produced they are estimated under the assumption that (for the 24 hours of interest) the site will be running at its full capacity,
- for the sites where hydrogen is produced no difference is instead assumed to occur between daily maximum and daily averaged water uses as, contrary to electricity, hydrogen can provide potential long-term (seasonal) storage capabilities and, consequently, its production would not have to ramp up during short term stresses. Under this simplifying assumption, the daily maximum water uses are estimated by simply re-scaling the annual ones.

It is important to note that:

- Thermal power plant use water for several different purposes (see, for example, Booth and Edwards, 2019). The amount of water used can differ significantly between plant of different types and playing different roles within the market. Future plant will be required to become 'flexible operators' as they will have a key role in balancing the grid in order to ensure a secure electricity supply. In some circumstances this will adversely affect specific water consumption ($Mm^3$/TWh), as a result of greater incidence of starting and stopping and/or part loading of the plant.
- For simplicity in the modelling it is assumed that all the water consumption occurring for plant located at saltwater sites is saltwater. However, whilst consumptive use in tower-cooled cooling systems at saltwater sites will invariably be saltwater, other, smaller volume 'high quality' uses (e.g., Heat Recovery Steam Generator (HRSG) make up), may be derived from freshwater sources including public water supply (PWS), or groundwater or through third party supply (e.g. industrial water). This high quality water is covered in section 3.5.2 below. The details will vary from site to site depending on cost, quality, and reliability considerations, taking into account the possibility of sourcing high quality water supplies from saltwater using desalination plant.
- At riverine locations main plant cooling water will invariably be sourced from surface water through direct abstraction. The plant may source water for smaller volume high quality uses (such as Heat Recovery Steam Generator (HRSG) make up) either from public water supply (PWS) or through direct abstraction from surface or groundwater or through third party supply (e.g. industrial water). The details will vary from site to site depending on cost, quality, and reliability considerations. Generally air-cooled plant would be expected to make use of third party or PWS source of supply rather than direct–abstraction.

[7] For the various classes of electricity generators the water use rates are expressed in units of $Mm^3$/TWh, while - for the two classes related to hydrogen production (electrolysis or Steam Methane Reforming) - they are in units of $Mm^3/ktH_2$

To date, PWS for use at power plant will have been accounted for in Water Company Non Household (NHH) Demand. However, with:

- the potential development of hydrogen production facilities using SMR in which significant volumes of water are used both for cooling and as a chemical feedstock;
- increasing focus on resilience of water-dependent activity

it may be useful to distinguish in future between dependence on direct abstraction (by source of supply) and dependence on PWS (NHH Demand).

#### 3.5.2 High Quality Water Consumption

Whilst not generally material in volume terms for a given power plant, the sector's demand for high quality water may be relevant for future water company planning purposes. For example, a project could lead to additional significant NHH demand in a remote location within a Water Company supply zone. Moreover, there may be multi-sector collaborative opportunity, for example, through a desalination project potentially sized to serve both power plant need - avoiding indirect NHH demand on PWS - and Water Company need through contributing to general PWS. In particular future CCUS clusters and the industry they might attract could exert a significant PWS-NHH demand unless sourced through desalination or other supply routes. Whether or not a Water Company has made adequate provision for such an NHH demand and the quality and resilience of locally available third-party water options (e.g. industrial water re-use within clusters) may be material factors in the project developer choice.

In a region without significant freshwater cooled generation plant the high quality water demand could be the dominant, although indirect, freshwater demand by the energy sector until the development of hydrogen production.

High Quality water will also be required during the construction of any new build power project. Construction of a large generating station can take several years and in addition to use in construction (concrete for example) a high quality supply will also be required for domestic services to the workforce which can number in the thousands.

Predictions of high quality water use for operational energy production at 2050 have been included for each region in the present study. These use the consumption rates listed in Table 14 Appendix C of JEP 2021.

For the electricity generating sites the high quality water is an additional water use to the modelled freshwater consumption. For hydrogen production however, the freshwater consumption results include both cooling and water used a feedstock.

# 4 Results

Although it is presently impossible to predict the exact mix of technologies and behaviours that will best achieve GHG-Net Zero, credible decarbonisation pathways involve widespread electrification and the necessity of increases in electricity generation capacity, both renewable and low carbon, as well as introduction of large-scale hydrogen production capacity.

FES20 provide four alternative pathways for the projected deployed capacity and level of generation. The CCC20 also provides four scenarios (plus a balanced pathway between all options that has not been used in this study). The freshwater consumption implied by these scenarios has been modelled from a baseline of 2018 to 2050 for each of the Water Resource Regions.

In the following the modelled freshwater consumption for energy production (electricity and hydrogen) is presented first for the FES20 scenarios and then the CCC20 scenarios. As noted previously there is no implied ranking in the order in which the FES20 & CCC20 scenarios are presented.

The format is the same for both sets of scenarios. Firstly, the freshwater consumption for combustion generation predicted by the JEP (2021) model over the pathways to 2050 are plotted. This is then followed by the consumption by nuclear generators (if the region has suitable sites) and in hydrogen production. The final pathway plots show the combined freshwater consumption for each scenario. In addition to the water consumption pathways the annual and daily use at 2050 are plotted
Finally, the annual high quality water consumed in electricity generation and hydrogen production in 2050 are presented.

Before making use of the results provided below, in for example water resource planning, it is important to consider whether the results will provide all the required information. The model has been developed to explore the water use implications of the GB's future energy use. As noted above the model uses a rule set to convert the energy mix of each of the eight Net Zero pathway scenarios used into an electricity and hydrogen production fleet. This process of defining a future energy production fleet is repeated a large number of times to sample the potential outcomes that satisfy the Net Zero pathway. The rule set is an important consideration in terms of the model output. As an example, the rules allow SMR hydrogen production only for a set of sites considered close enough to one of five CCUS hubs. As SMR production of hydrogen has a large freshwater demand any changes to the number of CCUS clusters could result in greater demand within a region. WRSE is an example of a region where consideration of SMR production away from the five CCUS hubs has been considered (Project Cavendish ENA (2020)). The study by Imperial College (Sunny et al 2020) on cost optimisation of hydrogen selected a more dispersed set of SMR sites. London being a large potential demand node attracted hydrogen production in Sunny's modelling with production sites within WRSE. Having additional CCUS clusters would also facilitate the development of BECCS and gas fired generation fitted with CCUS both of which would increase the potential water use within a region.

A further example of the evolving position on the number and location of CCUS and hydrogen infrastructure is the recently published UK decarbonisation strategy document (UK Gov 2021). This reported on modelling of what were termed plausible pathways that industry might follow to reach net zero by 2050. These pathways assumed either nine CCUS/hydrogen clusters or a national network where all industrial sites are able to adopt CCUS or hydrogen fuels. The modelling then considered the costs and degree of decarbonisation possible. Whilst the UK Gov (2021) was not focussed on the energy sector the work illustrates drivers towards a greater number of clusters than the five assumed in the present water use model. A wider distribution of CCUS could increase water use in those regions currently assumed to be too remote from a cluster for the energy sector to adopt CCUS and SMR hydrogen production. It is worth noting that the UK Gov (2021) strategy report includes two $CO_2$ injection points within the WRSE region (Southampton and Medway, where the captured $CO_2$ is shipped for offshore storage) that were not previously considered and are not assumed in the current water use model.

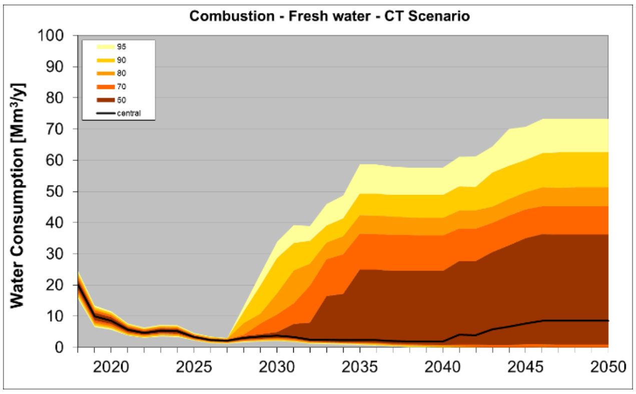
The rule set also only considers the water use at a site that is directly attributable to energy production. Some operators may have in place or have plans for multi-use of existing site licenses for uses such as water sharing or supplies to third parties. Examples of third party uses could include use in industrial processes such as data centres or for drinking water supplies. The rule set does not cover these cases and therefore the circumstances and hence water use at a specific site should be confirmed for water resource planning purposes. The assumptions made in the model for individual sites will be more important for those regions where there are few freshwater sites in the assumed fleet.

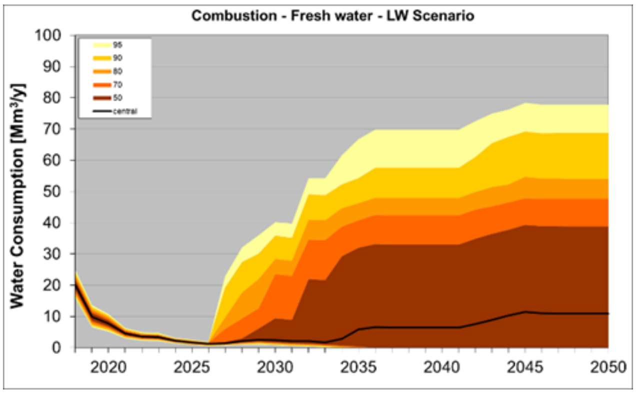
Finally, the present modelling study has not attempted to allocate demand to a river, but rather potential water use is quantified at a water resource regional scale. Where a river is shared between regions modelling at a river scale may be more appropriate than combining the results at regional scale because outcomes on a regional basis are spatially correlated and not independent (this is apparent if we consider the hypothetical case where there were two regions sharing a river. In the extreme the model could allocate all generation required by the scenario to either one of the two regions. The maximum demand on the river would not be the sum of the individual regional maxima as that case could not occur.)

## 4.1 Modelled Freshwater Consumption: pathways to 2050 Water Resource East (WRE)

The Water Resource East (WRE) region is in the eastern part of England and includes a relatively large number of existing and potential generation sites. In WRE potential hydrogen production sites are close enough to a CCUS cluster (JEP 2021) for the model to include SMR as well as Proton Exchange Membrane (PEM) electrolysis as a hydrogen production method. The region includes a number of existing or potential freshwater cooled generation sites. The river Trent which has been and continues to be important for electricity generation flows through the region.

The freshwater consumption by combustion plant under the four FES20 scenarios is plotted below:



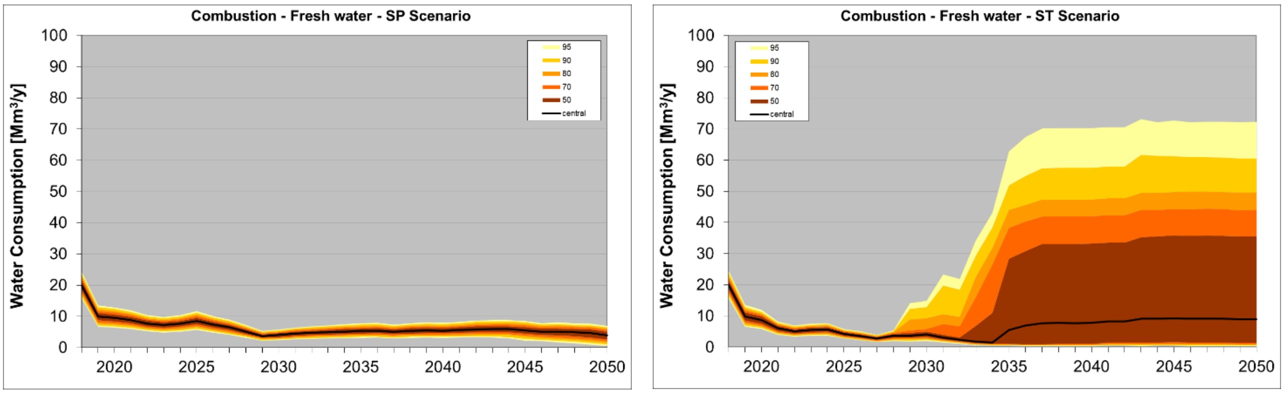
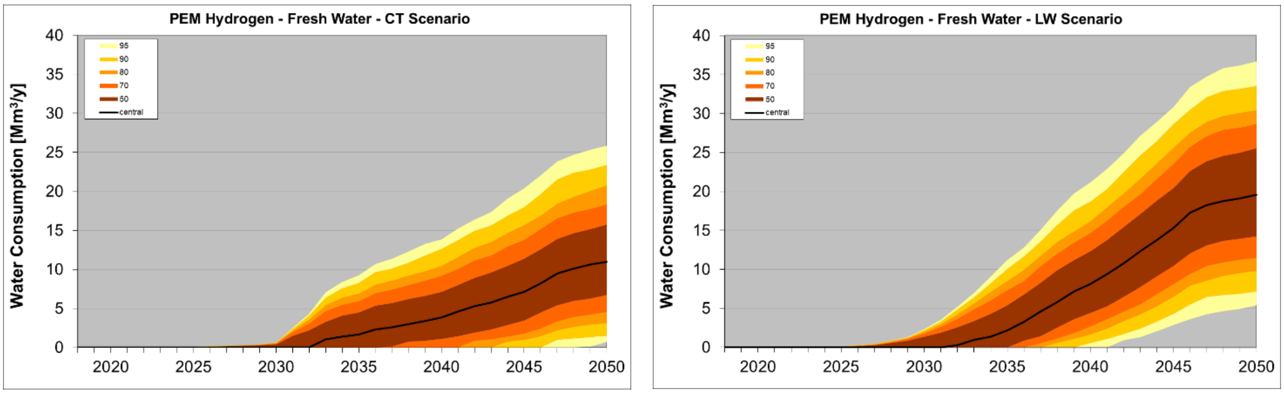



**Figure 2: WRE: annual freshwater consumption by generation by combustion plant (coal + biomass + gas- and hydrogen-fired CCGTs), as projected under each of the four FES20 (CT: top left; LW: top right; ST: bottom right and SP: bottom left; ). Uncertainty is illustrated by showing confidence intervals around the Monte Carlo modelled central value (median). The outer uncertainty envelope illustrates the 95th percentile of the sampled values (see Appendix D of JEP (2021) for more details).**

The model predicts a reduction in freshwater consumption from the 2018 baseline under all four FES20 scenarios until between 2025 and 2030 at combustion power plant. Thereafter there is an increase in consumptive use for all but the SP scenario. For scenarios LW, CT & ST post 2035 the range of use at a given year is well in excess of that in the 2018 baseline.

None of the potential freshwater nuclear sites considered by the model lies within the WRE boundary. Production of hydrogen in WRE by electrolysis is required under all four FES20 scenarios and also by SMR for the CT & ST scenarios. The freshwater consumptive use for hydrogen production is plotted in the following figure.



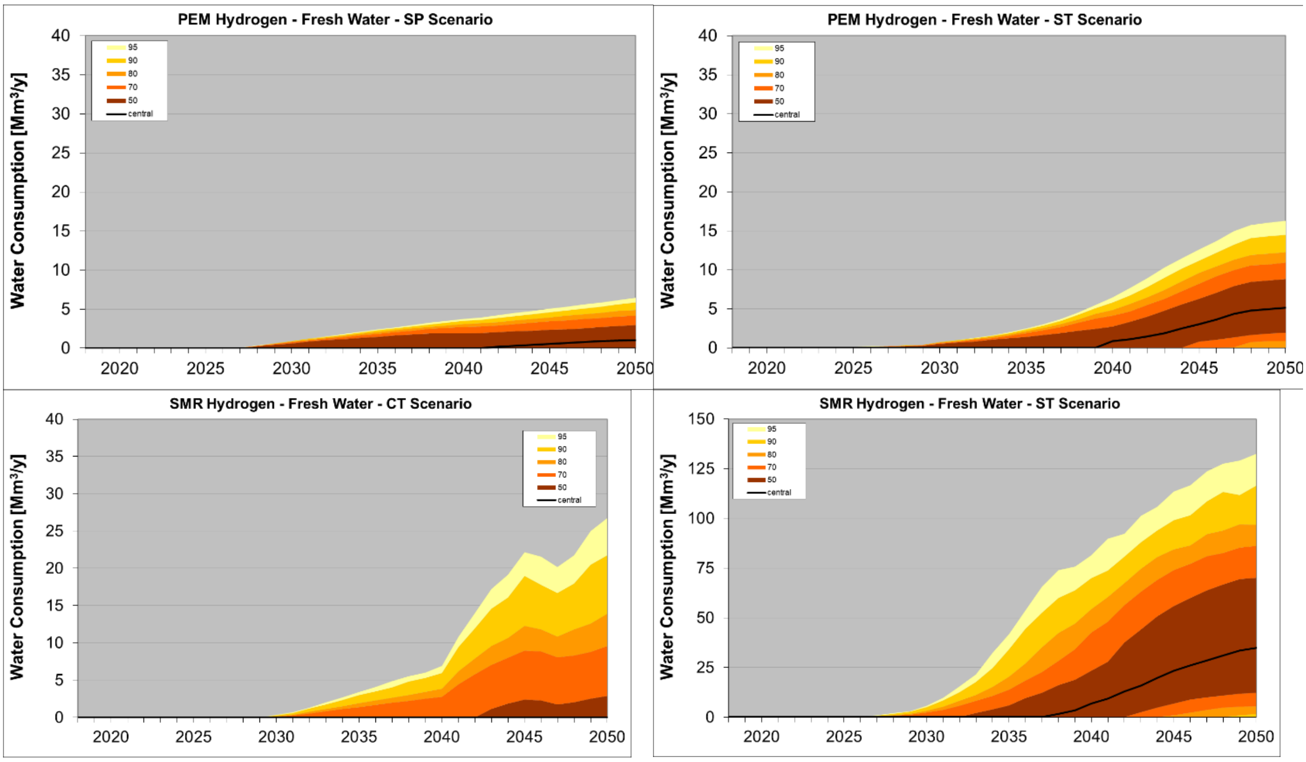
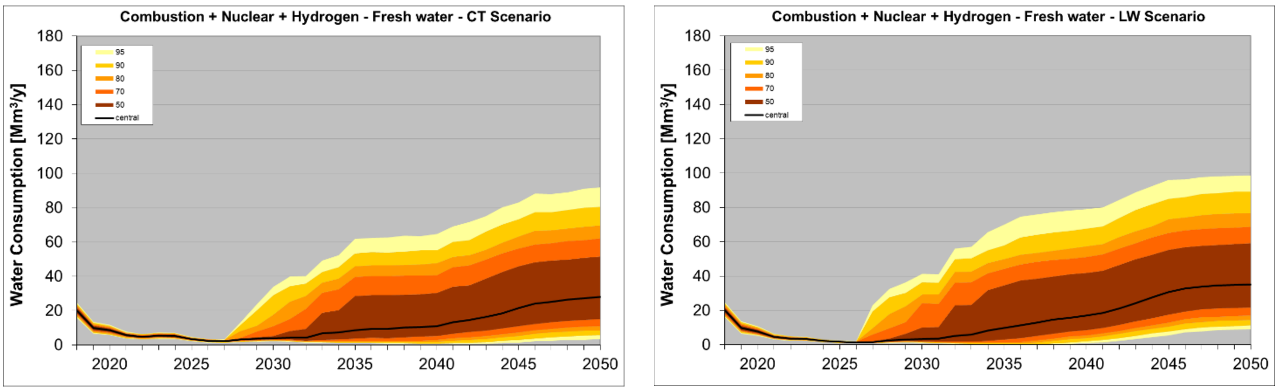
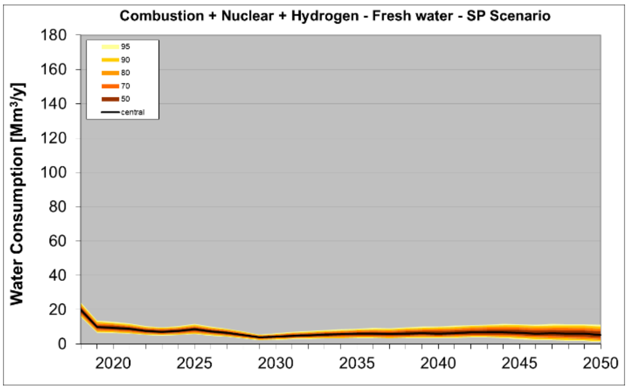



**Figure 3: same as Figure 2, but for the freshwater annually consumed to produce hydrogen by electrolysis (top and middle charts) and steam methane reforming (bottom charts: in this case the results are only illustrated for CT and ST, i.e. the two FES20 with non -zero SMR hydrogen production – note change of scale for SMR ST).**

Depending on the scenario significant freshwater consumption for hydrogen production begins between 2025 and 2030 and increases over the period until 2050.

The total freshwater consumptive use for energy production in the WRE region under the FES20 scenarios follows:





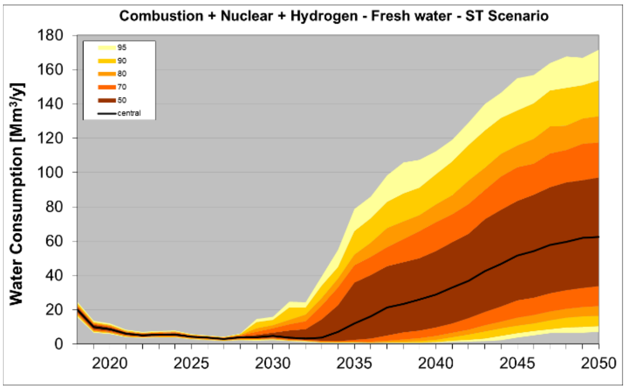



**Figure 4: same as Figure 2, but also including annual freshwater consumption by hydrogen production (electrolysis and steam methane reforming).**

The total freshwater consumption in electricity and hydrogen production within the WRE region under the FES20 scenarios all show an initial relatively rapid reduction from baseline volumes over the first two years of the simulation. Volumes then reduce slowly until a minimum in the period 2025 to 2030 and thereafter volumes increase. The rate of increase varies between scenarios for all except one (SP, the only FES20 not consistent with net zero) the range of use at a given year post 2035 is well in excess of that in the 2018 baseline.

The total annual freshwater consumption projected in 2050 is plotted below, for the four scenarios, illustrating the contributions of the different considered technologies (CCGT, BECCS, hydrogen etc):

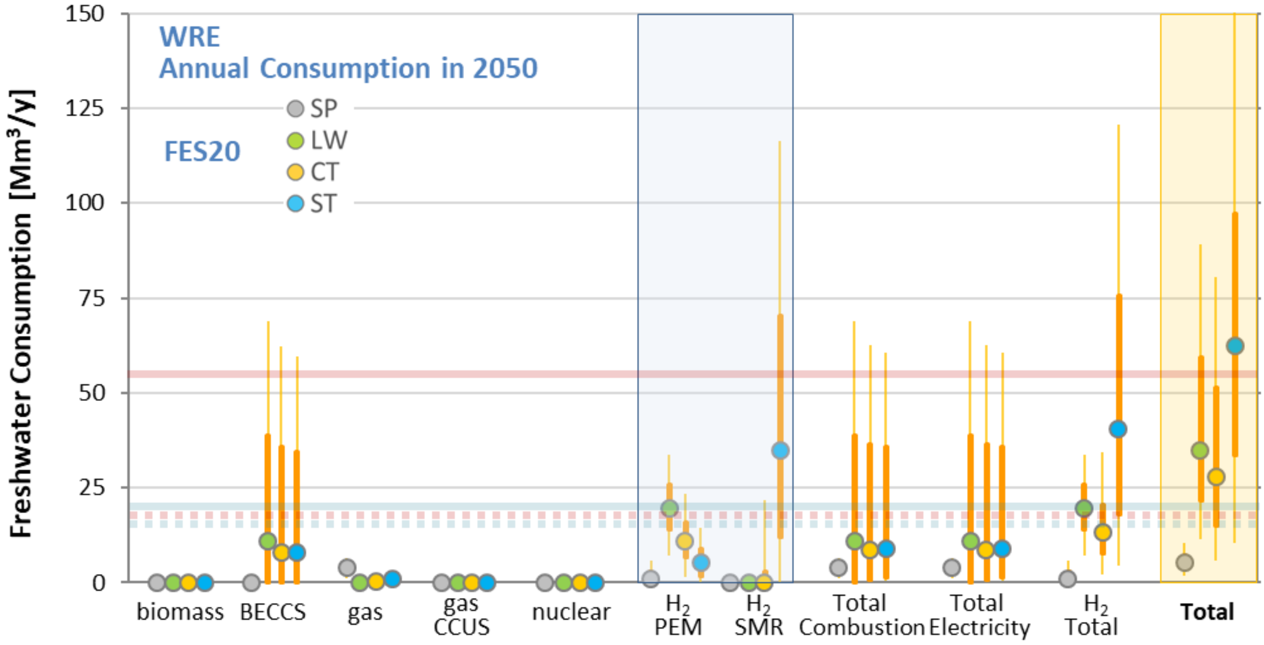



**Figure 5: WRE annual freshwater consumption by power producers in 2050, modelled using FES20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the 25$^{th}$-75$^{th}$ (boxes) and 5$^{th}$-95$^{th}$ (whiskers) percentile ranges. To place these values into context, the chart also reports (horizontal solid blue line) the freshwater consumption estimated by the model for the reference year 2018 (and if contributions from coal-fired plant are omitted, as these plants are being rapidly phased-out, consumption reduces to the one marked by the dotted blue line). Equivalent results, as obtained in Gasparino (2012) for the then baseline 2010, are also illustrated (again with the inclusion or exclusion of contributions from coal-fired plant: solid and dotted red lines, respectively)**

The modelled 2050 consumptive use plotted as Figure 5 above shows there to be a requirement for cooling water use in combustion plant, this being predominantly for BECCS sites although for the SP scenario there is some consumption in 2050 by CCGTs. The use of freshwater for hydrogen production is a major element of the total energy sector consumption in 2050 for most of the scenarios.

The median of the predicted freshwater consumptive use for energy production in 2050 is between 5 and 62Mm$^3$/y depending on the scenario used. The 95%ile annual consumption ranges up to 69 m3/y for electricity production and up to 153Mm$^3$/y for electricity and hydrogen combined.

By 2050 the median freshwater consumption in WRE for the energy sector generally exceeds that of the no coal (red dotted) 2010 baseline. The exception is for the FES20 scenario that does not achieve Net Zero by 2050 (SP). The range of consumption for the scenarios that achieve Net Zero by 2050 exceeds the 2010 baseline with coal (red line in Figure 5). Except for the SP scenario the median freshwater consumption for energy production is greater than the 2018 baseline with coal included.

The potential daily consumptive use of freshwater within WRE during system stress events in 2050 is plotted below. As discussed previously these events, which can occur during periods of low output from intermittent generators, may require dispatchable plant to operate at full load for periods of 24 hours or more. In the model the system stress water need is simulated by totalling the demand from all sites that the scenario requires to be in operation. It is assumed that hydrogen can be stored and the daily use for hydrogen production is prorated from the annual use.

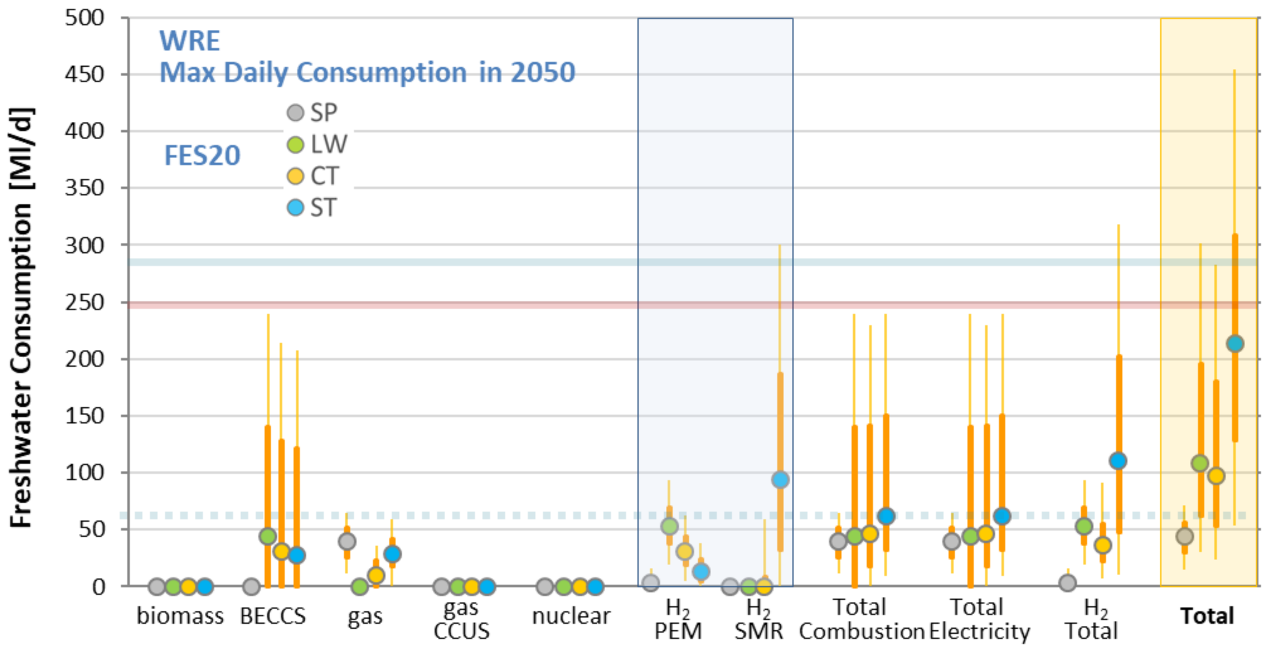



**Figure 6: same as Figure 5, but for the modelled maximum daily freshwater consumption in 2050 in WRE.**

At 2050 the median of the modelled consumptive use in energy production (electricity and hydrogen) varies between 45 and 214Ml/d, with the median daily use for electricity generation being between 40 and 62Ml/d. The 95%ile consumption is up to 240Ml/d for electricity production and up to 455Ml/d for electricity and hydrogen production combined.

The range of daily maximum consumption required for energy production is similar at 2050 to the 2018 baseline with coal and greater than the 2010 baseline with coal generation. The exception is the SP scenario for which the daily maximum is lower than the other scenarios. For the SP scenario the range of consumptive use at 2050 exceeds the 2010 & 2018 baselines without coal generation.

The equivalent modelled consumptive use of freshwater under the CCC20 scenarios follows.

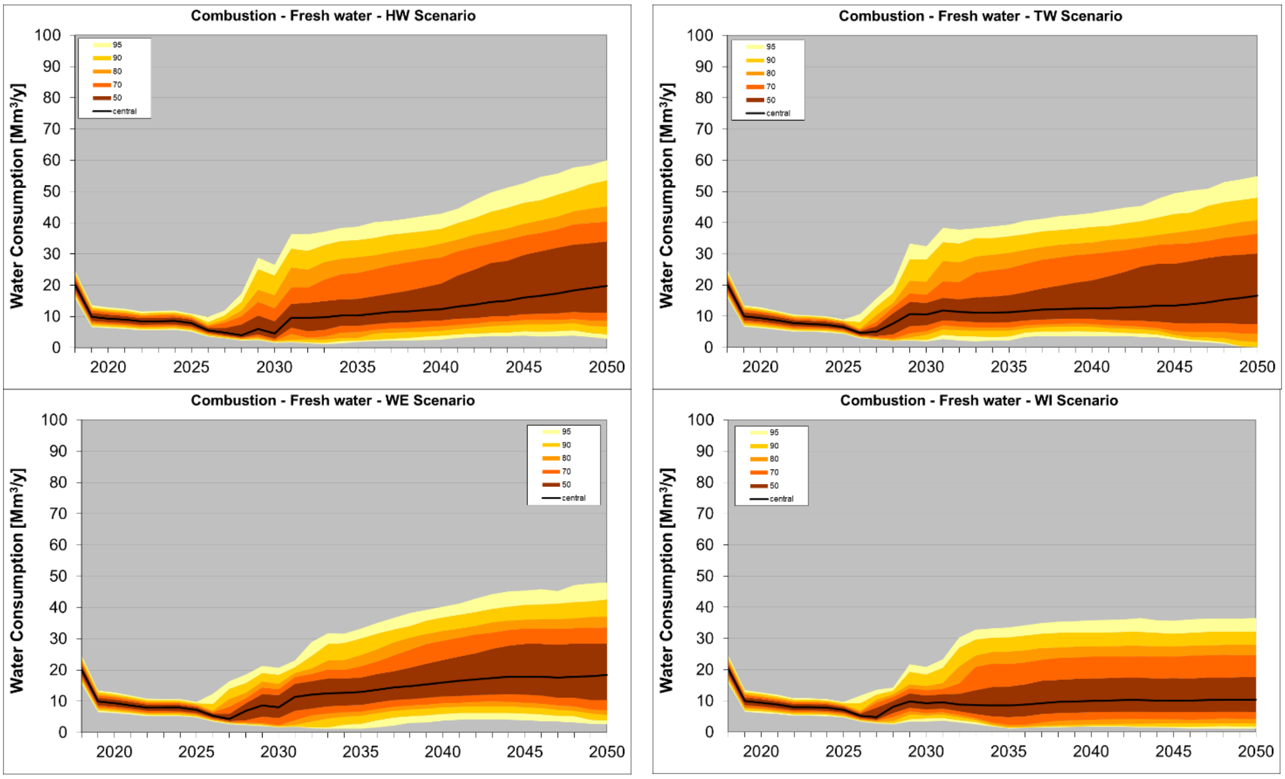



**Figure 7: WRE: annual freshwater consumption by generation by combustion plant (coal + biomass + gas- and hydrogen-fired CCGTs), as projected under each of the four CCC20 (HW: top left; TW: top right; WI: bottom right and WE: bottom left). Uncertainty is illustrated by showing confidence intervals around the Monte Carlo modelled central value (median). The outer uncertainty envelope illustrates the 95th percentile of the sampled values (see Appendix D of JEP (2021) for more details).**

The CCC20 scenarios plotted as Figure 7 above show a similar pattern to those of the FES20 scenarios (Figure 2) with a reduction in consumptive use of freshwater from the baseline (2018) to around 2028 after which the consumptive use increases. Compared to the FES20 scenarios the CCC20 result in slightly lower use of freshwater for combustion generation.

All the CCC20 scenarios used rely on the deployment of both electrolysis and SMR hydrogen production within WRE. The freshwater consumption for hydrogen production is plotted below.

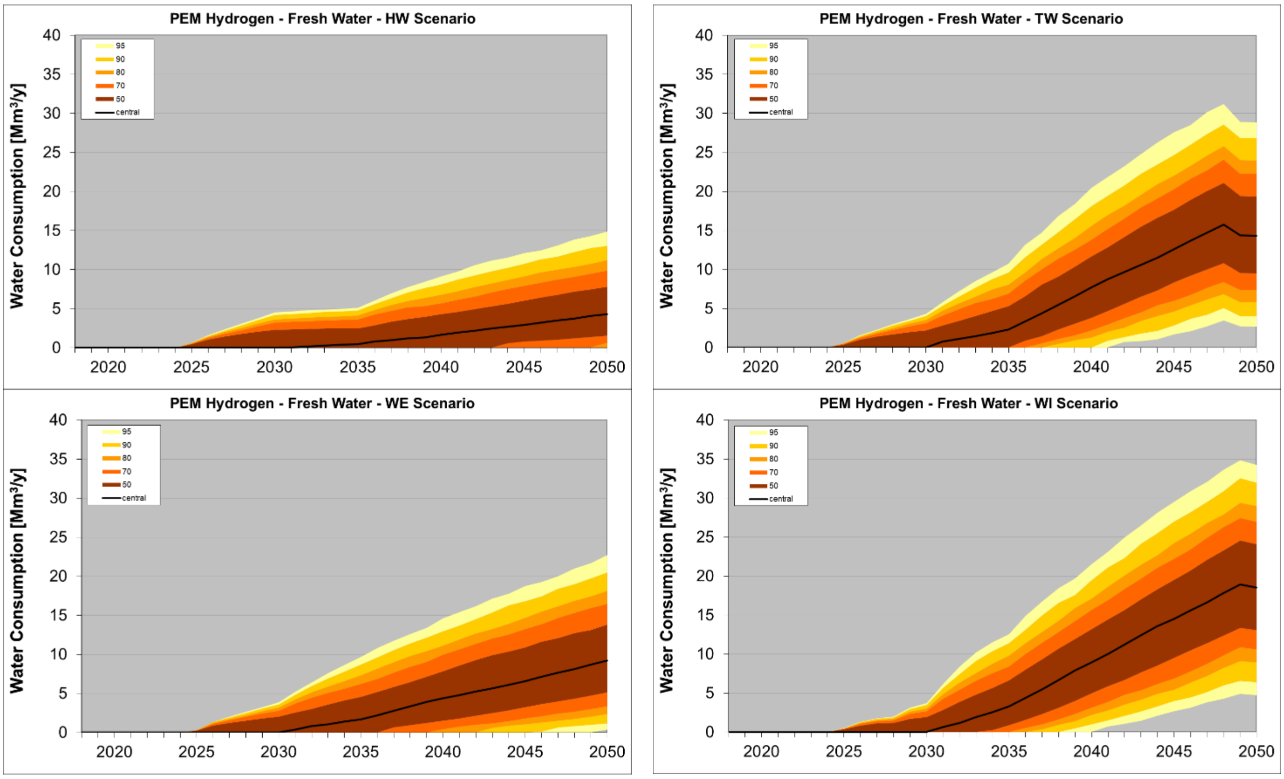
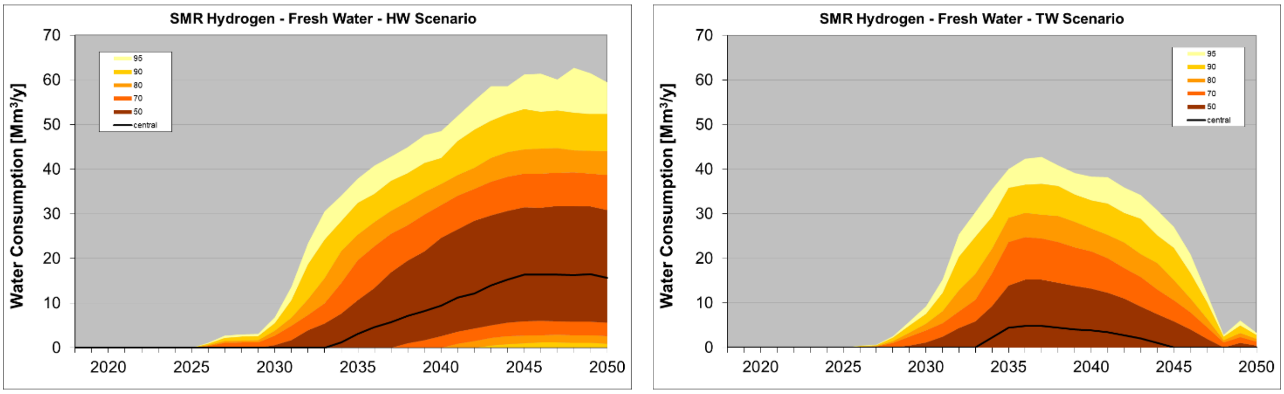



**Figure 8: same as Figure 2, but for the freshwater annually consumed to produce hydrogen by electrolysis for the CCC20 scenarios in WRE.**

The consumptive freshwater use in electrolysis is predicted to increase under all CCC20 scenarios from around 2025 to a maximum annual use just before the end of the simulation (at 2047 for TW and 2029 for WI) or increasing until 2050 (HW & WE).



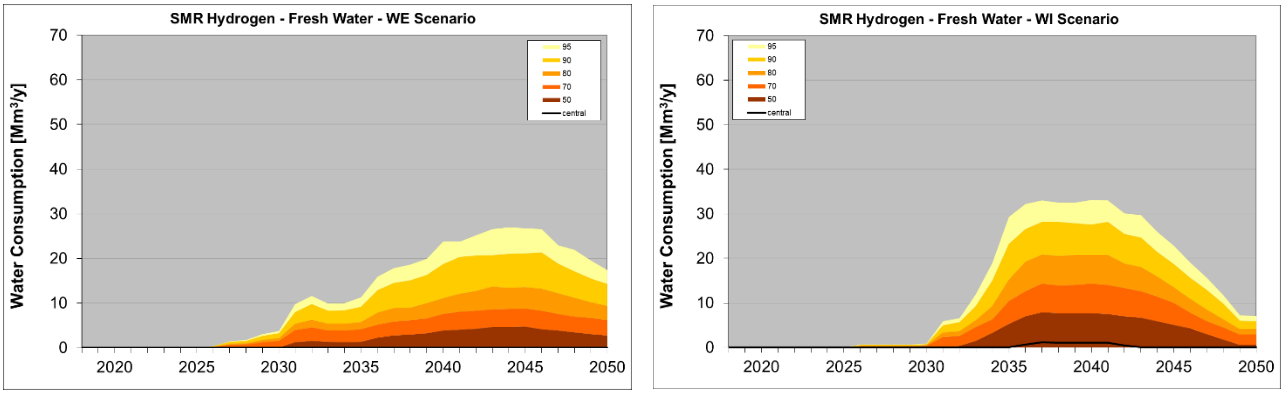



**Figure 9: same as Figure 8, but for the freshwater annually consumed to produce hydrogen by SMR for the CCC20 scenarios in WRE.**

Under the CCC20 scenarios significant consumptive use of freshwater for SMR is predicted to begin from around 2025 with growth tending to increase from 2030. Depending on scenario, SMR ('blue hydrogen') is identified by the CCC as a transitional technology and its use begins to reduce after a peak between 2035 to 2045. The rate of reduction varies so that for TW & WI use has notably reduced in 2050 while for WE & HW the reduction from the peak is less pronounced.

The modelled freshwater demand for energy production (electricity plus hydrogen) follows.

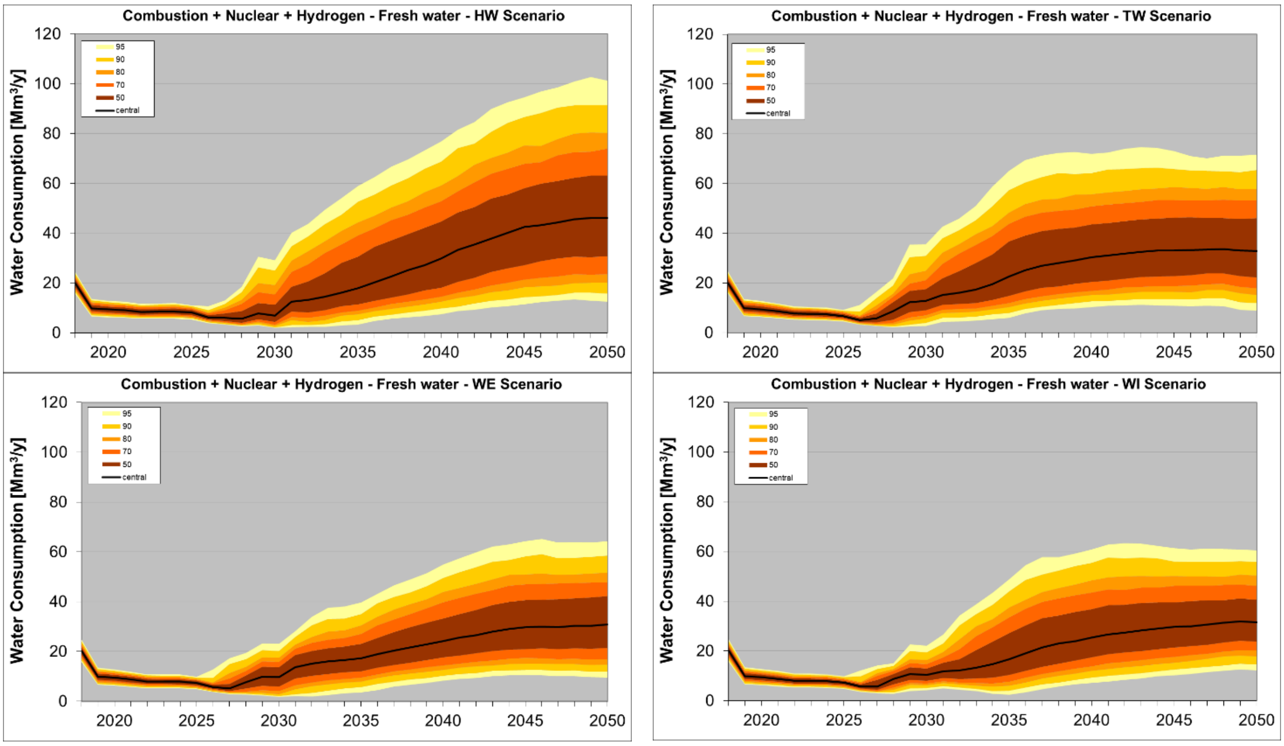



**Figure 10: WRE: total annual freshwater consumption, as projected under the four CCC20 scenarios.**

Under all four CCC20 scenarios after an initial reduction until about 2025 consumptive freshwater use is predicted to increase. The rate of increase varies between scenarios but for all the range of use after 2035 is higher than in the baseline.

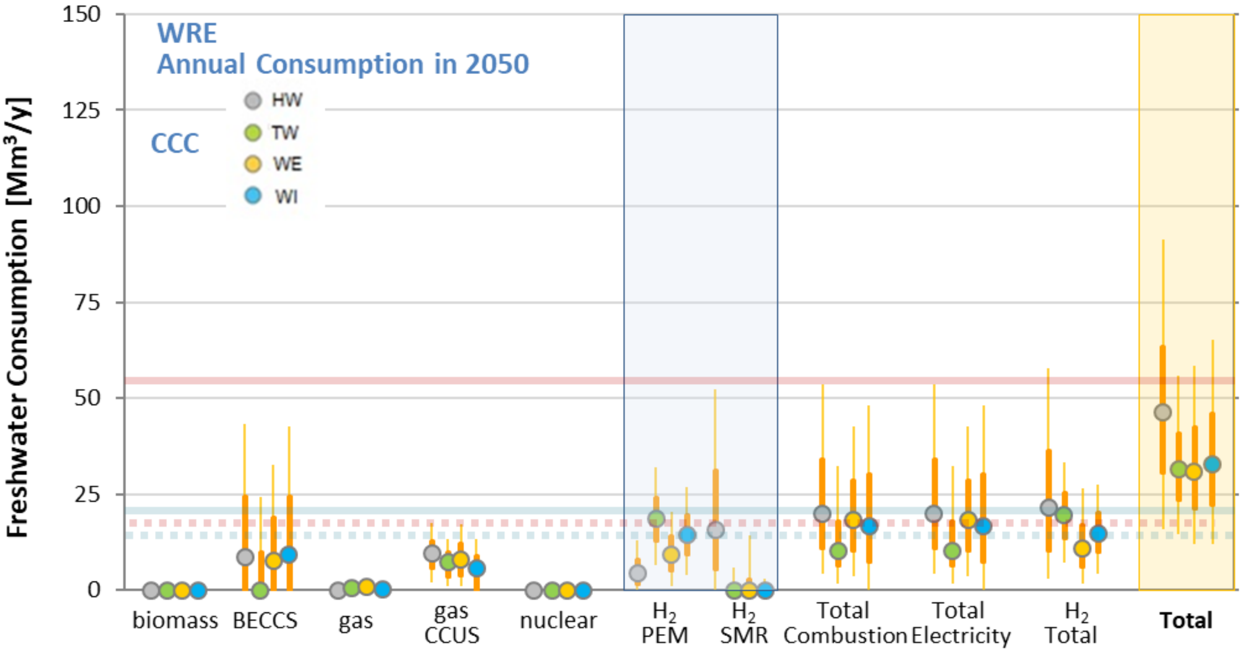



**Figure 11: WRE annual freshwater consumption by power producers in 2050, modelled using CCC20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the 25th-75th (boxes) and 5th-95th (whiskers) percentile ranges. To place these values into context, the chart also reports (horizontal solid blue line) the freshwater consumption estimated by the model for the reference year 2018 (and if contributions from coal-fired plant are omitted, as these plants are being rapidly phased-out, consumption reduces to the one marked by the dotted blue line). Equivalent results, as obtained in Gasparino (2012) for the then baseline 2010, are also illustrated (again with the inclusion or exclusion of contributions from coal-fired plant: solid and dotted red lines, respectively)**

The CCC20 scenarios result in abated biomass and gas plant operating within WRE at 2050 with a median use of between 10 to 20Mm$^3$/y. There is a similar volume of water predicted to be required for hydrogen production. The median total use of freshwater for energy production at 2050 is in the range 31 to 46Mm$^3$/y. The 95%ile consumption by combustion plant ranges to 54Mm$^3$/y and up to 91Mm$^3$/y for electricity and hydrogen production combined.

The median freshwater consumption for energy generation in 2050 under the CCC20 scenarios are all greater than the 2019 baseline with coal and the 2010 baseline without coal. The range of use at 2050 exceeds the 2010 baseline with coal generation included.

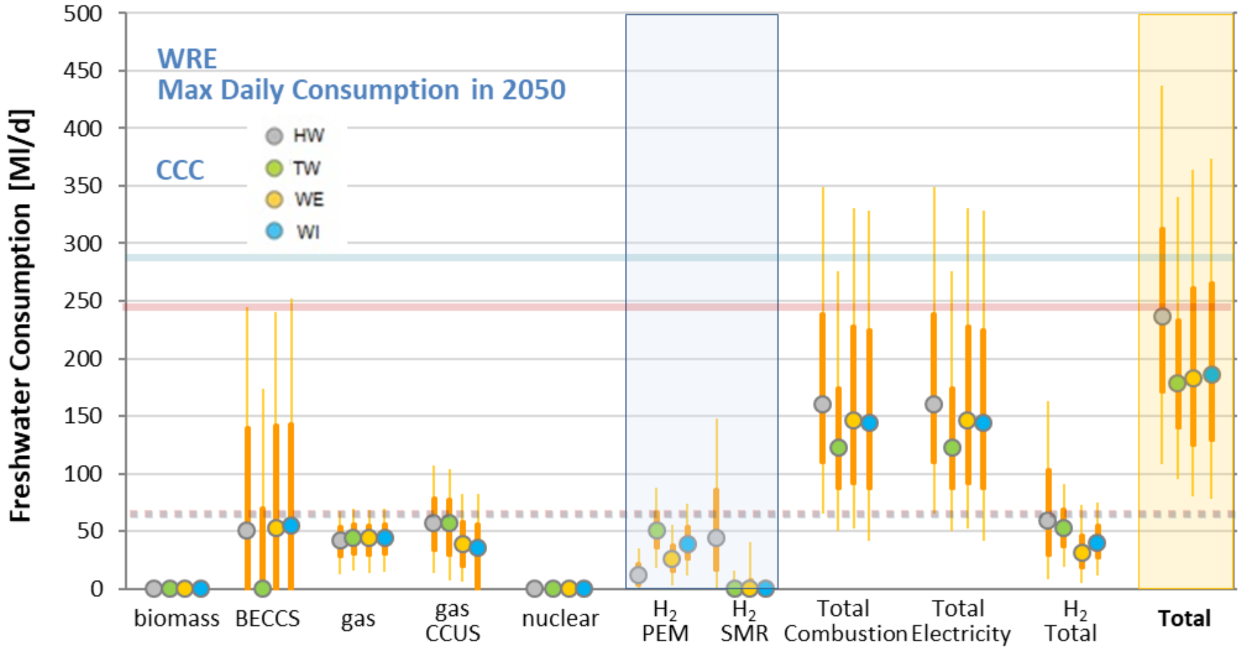


**Figure 12: same as Figure 11, but for the modelled maximum daily freshwater consumption in 2050.**

The median maximum daily use of freshwater predicted for 2050 under the CCC20 scenarios is between 178 to 237Ml/d. The median consumption by the combustion plant is 122 to 160Ml/d with 95%ile consumption of up to 349Ml/d. The 95%ile consumption of the energy sector (electricity plus hydrogen production) is up to 437Ml/d.

The range of maximum daily use at 2050 for energy production exceeds that for 2010 & 2018 with coal included.

### 4.1.1 High Quality Water use in WRE at 2050

The same model used to predict cooling water use has been used to predict high quality water use within the WRE region for the FES20 and CCC20 scenarios. Note that the freshwater consumption results plotted above include the high quality and cooling water use in hydrogen production and therefore the high quality water use in hydrogen production results below are not additive. The high quality water use was not included in the modelling of freshwater use in electricity generation and so the high quality water is an additional consumption to the previous results.

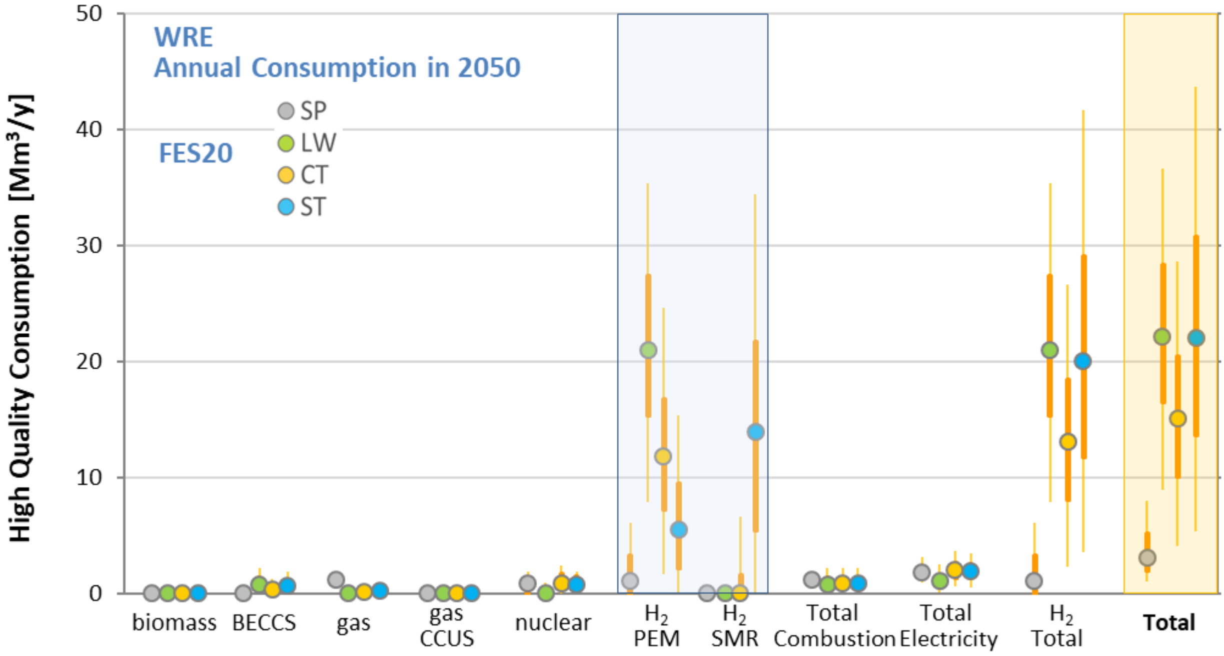



**Figure 13: WRE annual high quality water consumption by power producers in 2050, modelled using FES20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the 25$^{th}$-75$^{th}$ (boxes) and 5$^{th}$-95$^{th}$ (whiskers) percentile ranges.**

The largest volume of high quality water in 2050 under the FES20 scenarios is used within hydrogen production. The median use for electricity production (combustion plus nuclear) is up to 2Mm$^3$/y with 95%ile of 4Mm$^3$/y (while there are not any freshwater cooled nuclear sites within WRE, the coastal nuclear sites that are within the region would require a high quality water supply). The 95%ile high quality water use ranges up to 43Mm$^3$/y for electricity and hydrogen production.

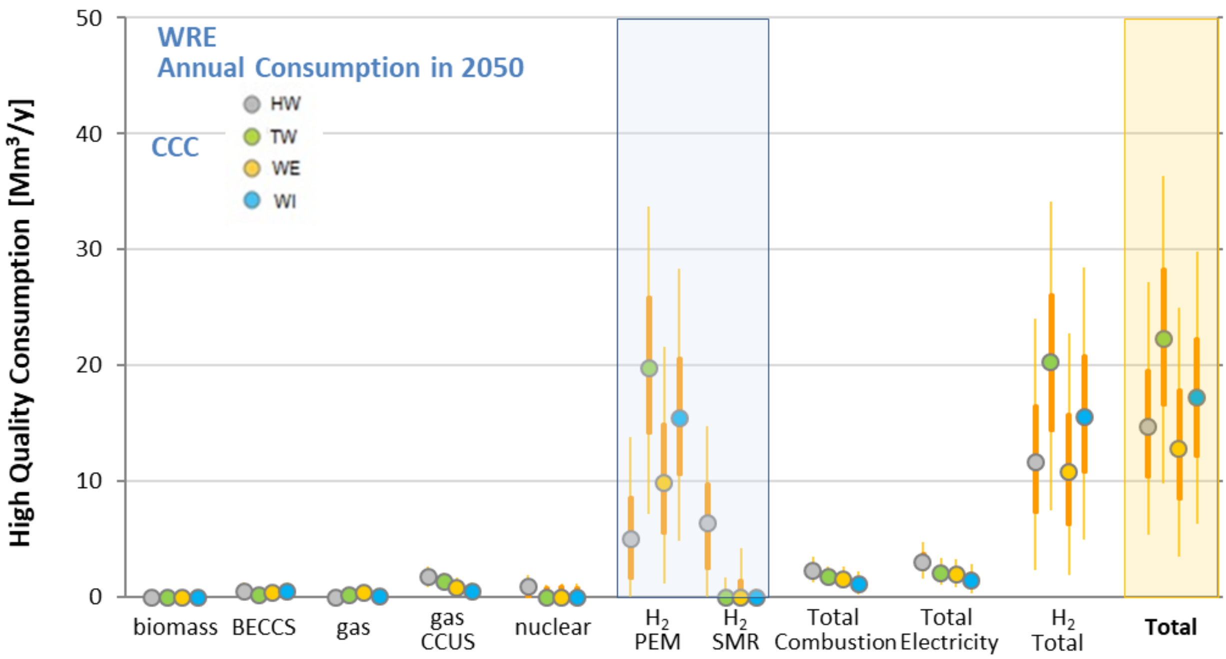



**Figure 14: same as Figure 13, but for the modelled annual high quality water consumption in 2050 under CCC20 scenarios.**

The largest volume of high quality water in 2050 under the CCC20 scenarios is used within hydrogen production. The median use for electricity production (combustion plus nuclear) is up to 3Mm$^3$/y with a 95%ile of up to 5Mm$^3$/y. The 95%ile high quality water use ranges up to 37Mm$^3$/y for the both electricity and hydrogen production.

### 4.1.2 Summary Freshwater consumption WRE

- Freshwater consumption for energy production in both FES20 & CCC20 reduces until 2025 to 2030 after which it increases
- Consumption for energy production & electricity generation under FES20 & CCC20 can be greater than 2018 & 2010 baselines
- FES20 has BECCS, CCGTs and hydrogen at 2050
- CCC20 has BECCS, CCGT (with and without CCUS) and hydrogen at 2050
- FES20 Annual energy use: median up to 62Mm$^3$/y, 95%ile up to 153Mm$^3$/y
- FES20 Annual electricity use: median up to 11Mm3/y, 95%ile up to 69Mm$^3$/y
- FES20 Daily energy use: median up to 214Ml/d, 95%ile up to 455Ml/d
- FES20 Daily electricity use: median up to 62Ml/d, 95%ile up to 240Ml/d
- CCC20 Annual energy use: median up to 46Mm$^3$/y, 95%ile up to 91Mm$^3$/y
- CCC20 Annual electricity use: median up to 20Mm3/y, 95%ile up to 54Mm$^3$/y
- CCC20 Daily energy use: median up to 237Ml/d, 95%ile up to 437Ml/d
- CCC20 Daily electricity use: median up to 160Ml/d, 95%ile up to 349Ml/d
- High Quality Water: Electricity production 95%ile up to 5Mm$^3$/y

## 4.2 Modelled Freshwater Consumption: pathways to 2050 Water Resource North (WReN)

Water Resources North (WReN) (Figure 1) covers the north east of England from Sheffield to the Scottish border. The region shares a border with WRE along part of the tidal Trent and includes the river Aire & Ouse which both have freshwater cooled power plant.

The freshwater consumption for combustion generation under the four FES20 scenarios is plotted in Figure 15 below:

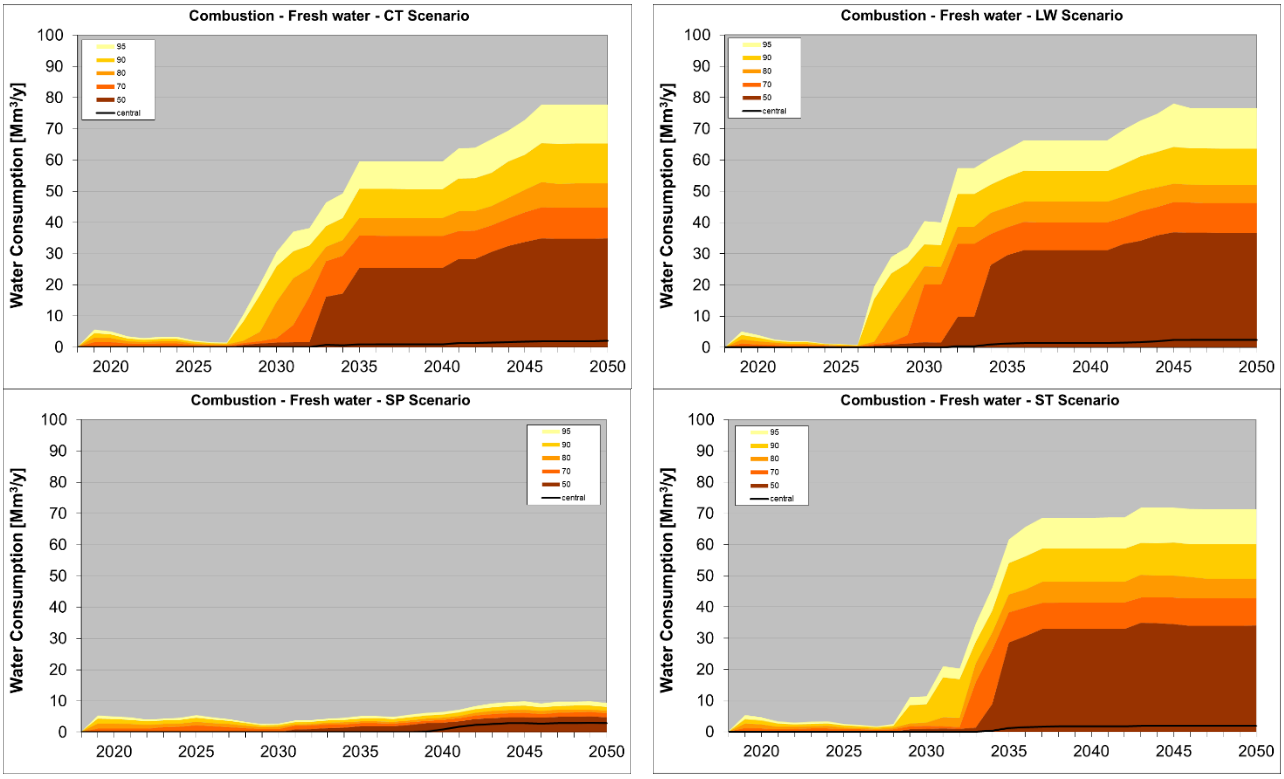



**Figure 15: WReN: annual freshwater consumption by generation by combustion plant (coal + biomass + gas- and hydrogen-fired CCGTs), as projected under each of the four FES20 (SP: bottom left; CT: top left, ST: bottom right and LW: top right). Uncertainty is illustrated by showing confidence intervals around the Monte Carlo modelled central value (median). The outer uncertainty envelope illustrates the 95th percentile of the sampled values (see Appendix D of JEP (2021) for more details).**

The FES20 scenarios show a potential increase in water consumption by combustion plant after 2025 to 2035 with potential need in 2050 being higher than the baseline. The predicted consumptive requirement of combustion plant in 2050 in some cases under the LW, ST & CT scenarios is over 70Mm$^3$/y. The SP scenario (the only FES20 not consistent with net zero) also shows an increase in use over time by combustion generators but of a lower rate of increase than the other scenarios,

The WReN region includes a freshwater location assumed to be suitable as a site for a potential new build nuclear station. The predicted consumption of freshwater for combustion and nuclear generation is plotted below.

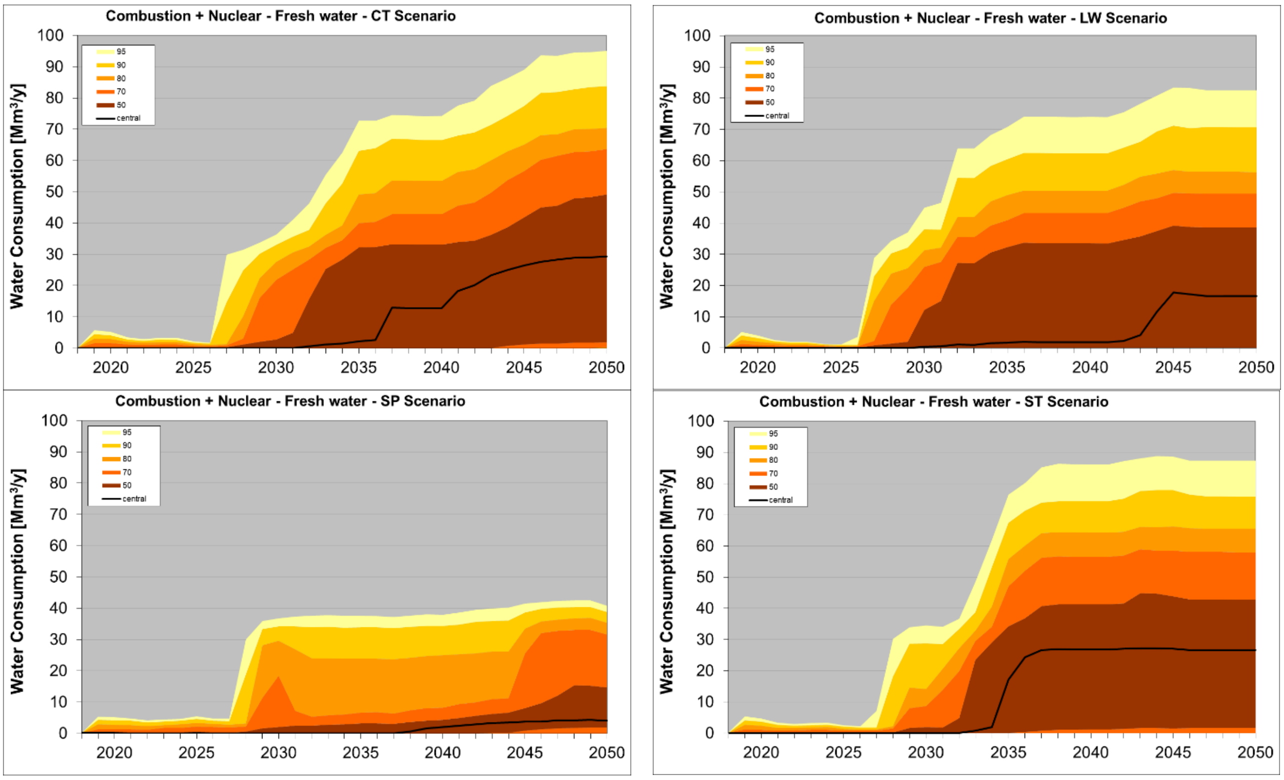



**Figure 16: WReN same as Figure 15, but also including annual freshwater consumption by nuclear plant.**

The inclusion of nuclear generation (Figure 16) increases the predicted freshwater consumption under all scenarios.

The predicted annual consumptive use for hydrogen production by electrolysis and SMR in WReN follows. There is an industrial CCUS cluster close enough for some sites within WReN to be selected by the model for SMR.

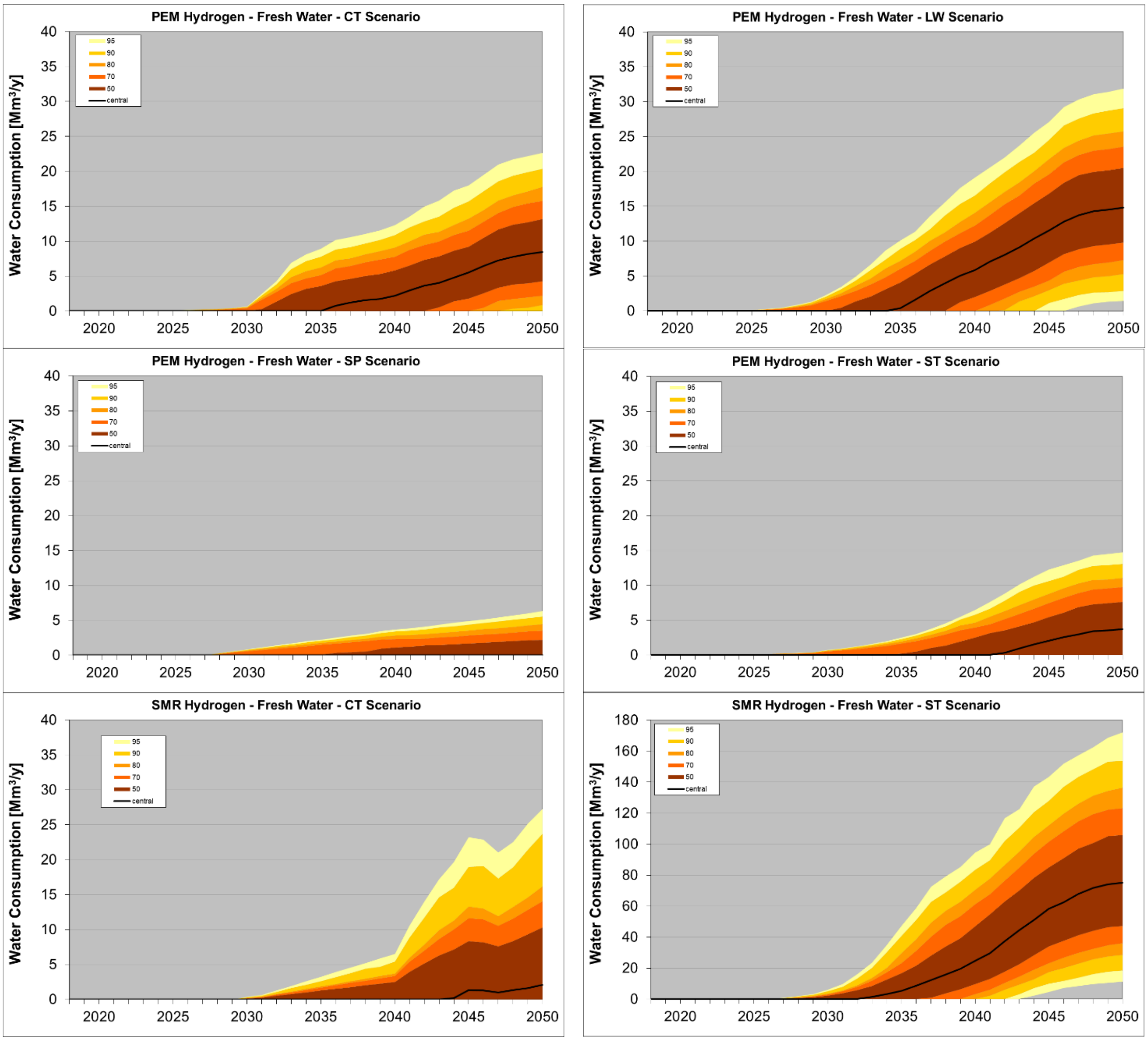



**Figure 17: same as Figure 15, but for the freshwater annually consumed to produce hydrogen by electrolysis (top and middle charts) and steam methane reforming (bottom charts: in this case the results are only illustrated for CT and ST, i.e. the two FES20 with non-zero SMR hydrogen production – note change of scale for SMR ST).**

All the FES scenarios include some PEM (electrolysis) hydrogen production within the WReN region and Steam Methane Reformation is indicated under the CT & ST scenarios. The potential PEM consumption of freshwater ranges to over 30Mm3/y while the maximum predicted use for SMR under the ST scenario it ranges up to 170Mm3/y.

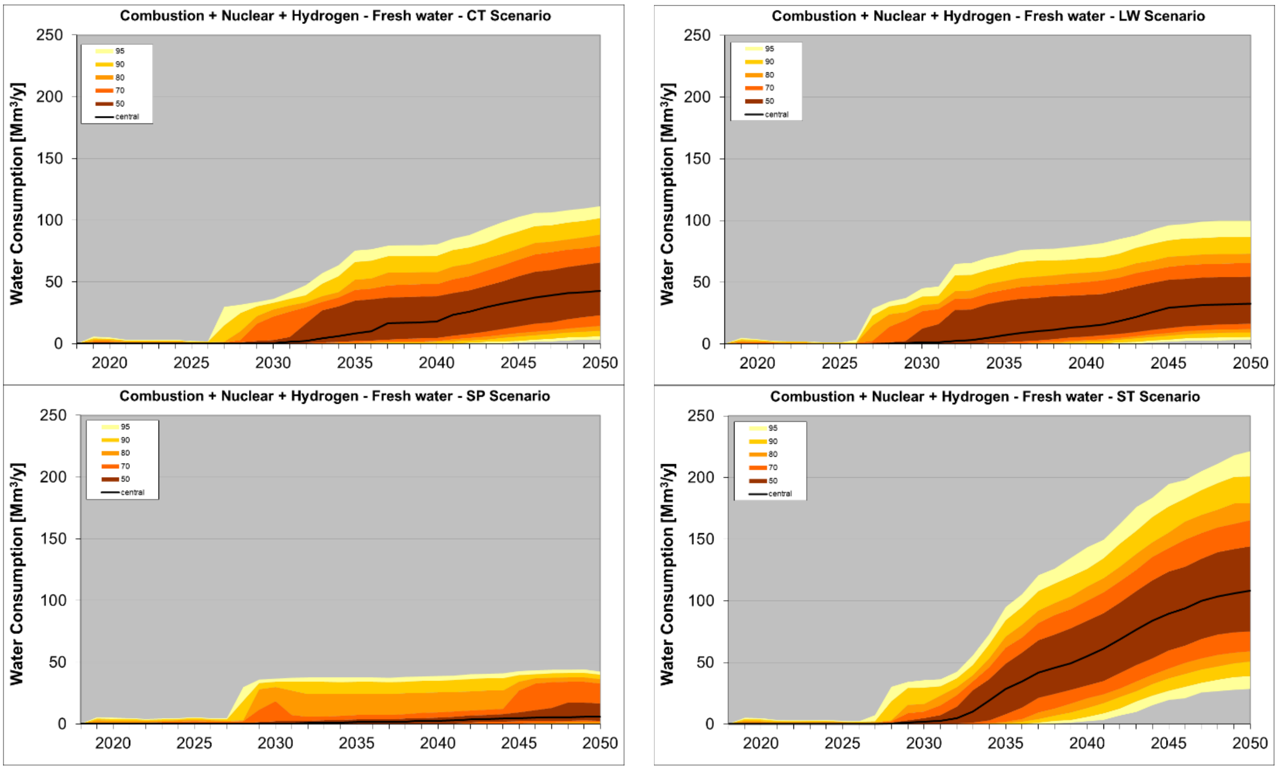



**Figure 18: same as Figure 15, but also including annual freshwater consumption by hydrogen production (electrolysis and steam methane reforming) under FES20 scenarios in WReN.**

For all the scenarios the potential use of freshwater for energy production (generation plus hydrogen) increases after between 2025 to 2030 and while the rates of increase vary between scenarios for all scenarios the use is much greater than the 2018 baseline.

The total predicted annual freshwater consumption in 2050 for energy production and each element of the total (CCGT, BECCS, hydrogen etc) is plotted below for the four scenarios:

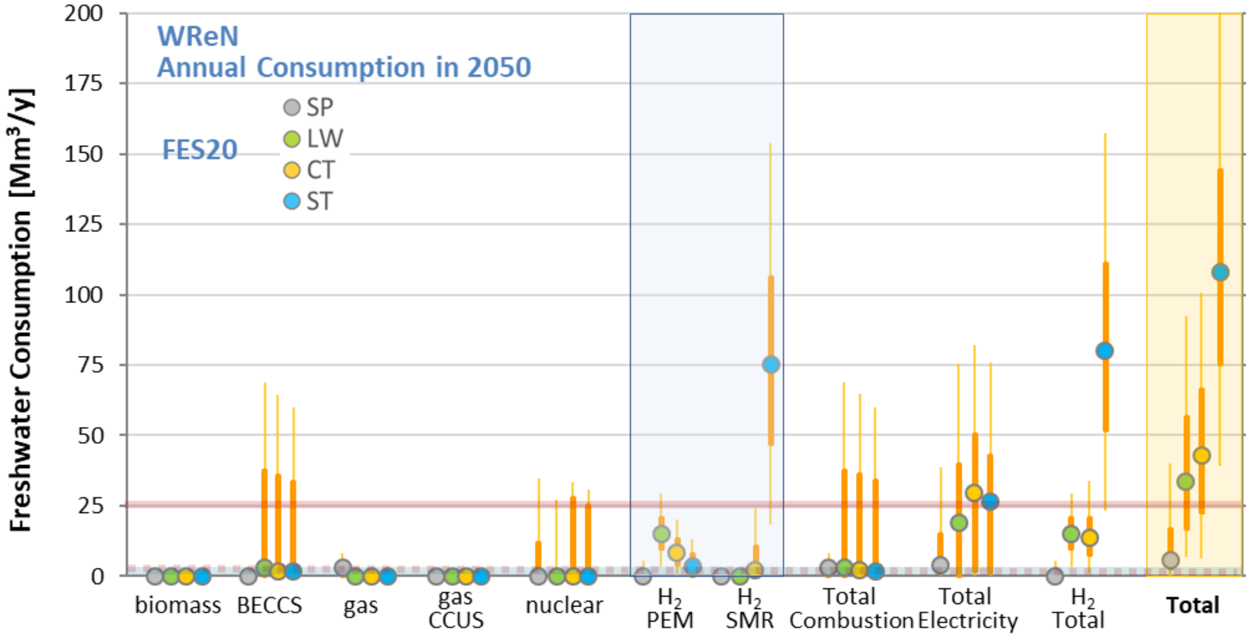



**Figure 19: WReN annual freshwater consumption by power producers in 2050, modelled using FES20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the $25^{th}$-$75^{th}$ (boxes) and $5^{th}$-$95^{th}$ (whiskers) percentile ranges. To place these values into context, the chart also reports (horizontal solid blue line) the freshwater consumption estimated by the model for the reference year 2018 (and if contributions from coal-fired plant are omitted, as these plants are being rapidly phased-out, consumption reduces to the one marked by the dotted blue line). Equivalent results, as obtained in Gasparino (2012) for the then baseline 2010, are also illustrated (again with the inclusion or exclusion of contributions from coal-fired plant: solid and dotted red lines, respectively)**

The median use for total electricity is greater than the sum of the median uses for total combustion and nuclear. This is because of the shape of the distributions, they are both skewed, and the median of the total electricity fleet is not the sum of the combustion and nuclear.

The median total annual freshwater consumption for energy production in WReN at 2050 varies between 6 and 108Mm$^3$/y with between 2 and 29Mm$^3$/y being used in cooling thermal power plant. The 95%ile consumptive use of freshwater ranges up 76Mm$^3$/y for thermal generation (combustion plus nuclear) and 200m$^3$/y for the energy sector (electricity plus hydrogen production) as a whole.

The range of annual freshwater consumption by energy production under all scenarios is greater than the 2010 baseline that included coal generation. Consumptive use in electricity production is also greater than the 2010 coal baseline.

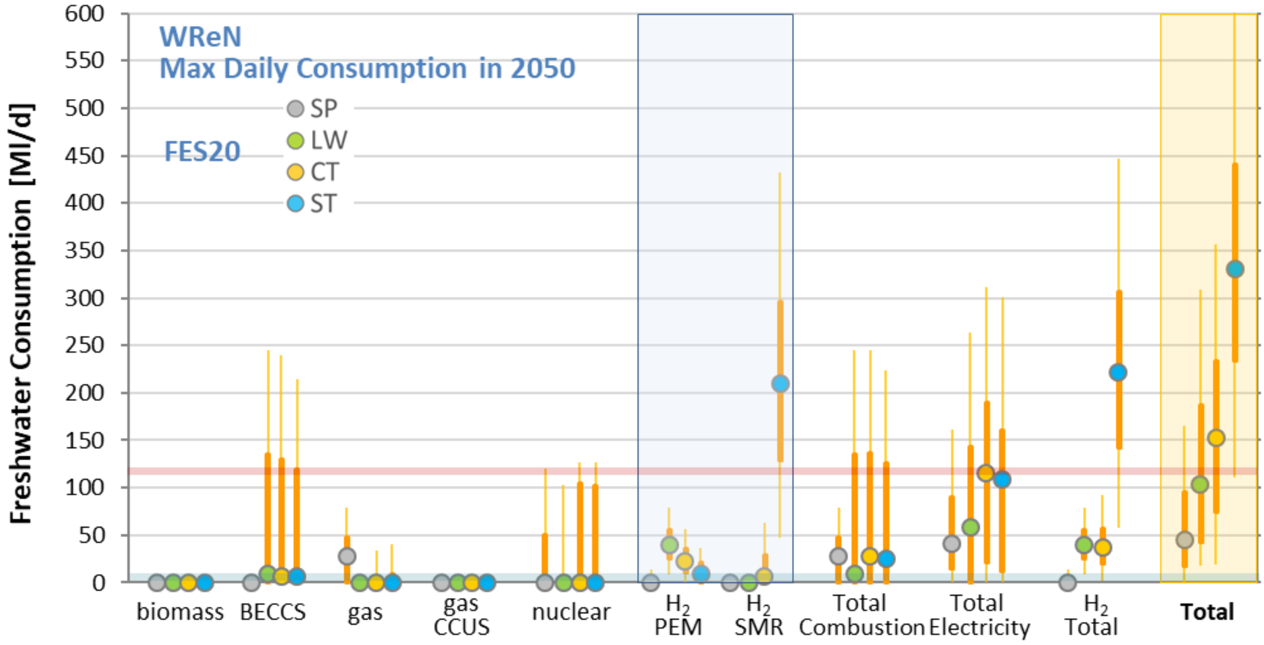



**Figure 20: same as Figure 19, but for the modelled maximum daily freshwater consumption in 2050.**

At 2050 the median of the modelled consumptive use in energy production varies between 44 and 330Ml/d depending on scenario. The median for thermal generation is up to 115Ml/d. The 95%ile consumption by the thermal generators is up to 310Ml/d, with up to 610Ml/d being required by for electricity and hydrogen production combined.

The range of daily maximum freshwater consumption by energy production under all scenarios is greater than the 2010 baseline that included coal generation. Consumptive use in electricity production is also greater than the 2010 coal baseline.

The equivalent modelled consumptive use of freshwater under the CCC20 scenarios follows.

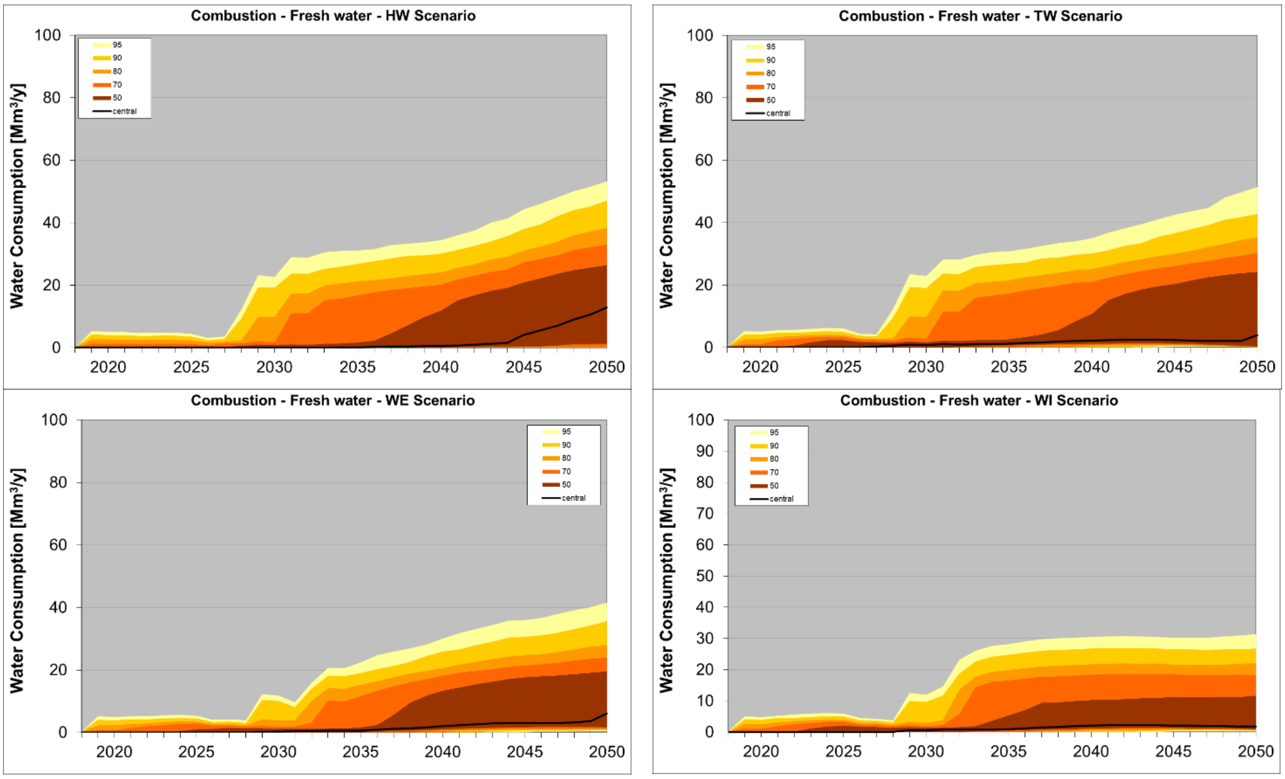



**Figure 21: WReN: annual freshwater consumption by generation by combustion plant (coal + biomass + gas- and hydrogen-fired CCGTs), as projected under each of the four CCC20 (WE: bottom left; HW: top left, WI: bottom right and TW: top right). Uncertainty is illustrated by showing confidence intervals around the Monte Carlo modelled central value (median). The outer uncertainty envelope illustrates the 95th percentile of the sampled values (see Appendix D of JEP (2021) for more details).**

The CCC20 scenarios (Figure 21) show an increase in freshwater consumption by combustion generation plant in WReN beginning from between 2025 to 2035. The predicted freshwater consumption of combustion and nuclear generators follows.

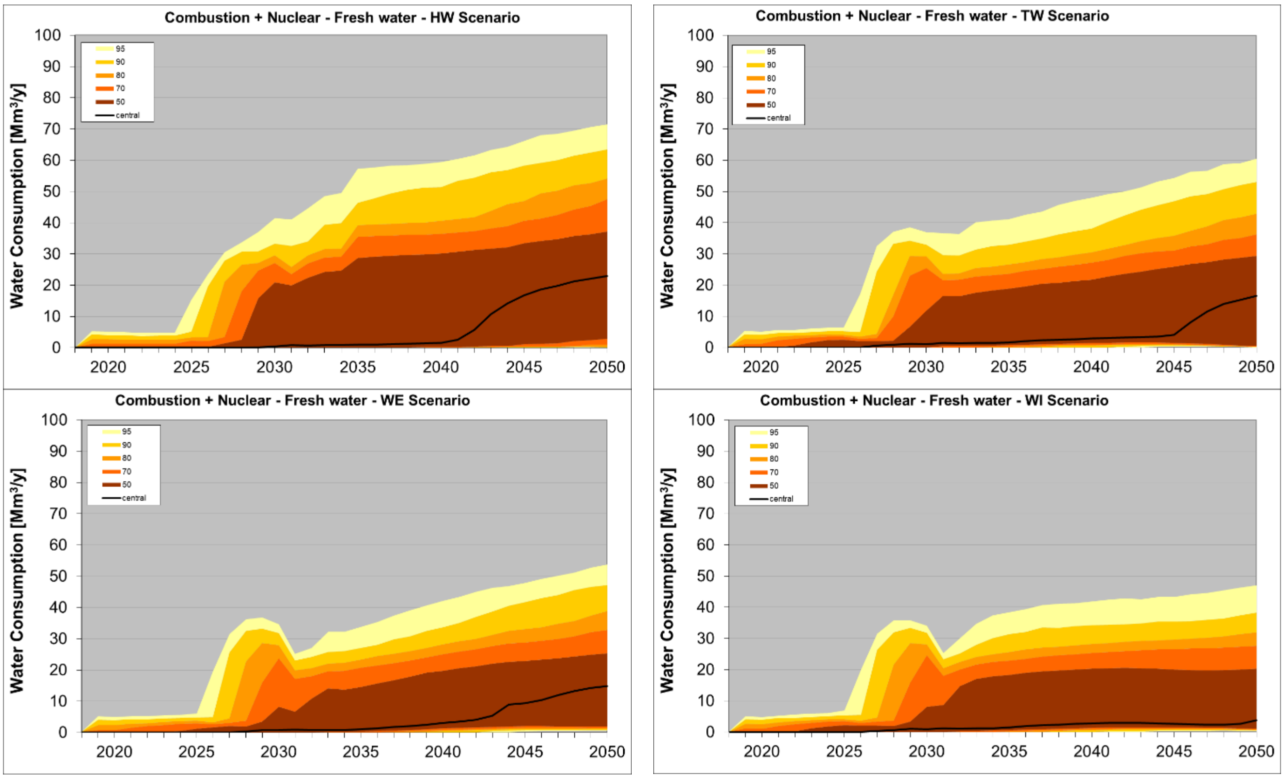



**Figure 22: WReN same as Figure 21, but also including annual freshwater consumption by nuclear plant.**

The predicted uses of freshwater to produce hydrogen under the CCC20 scenarios follows. As with FES20 the presence of a CCUS cluster within the WReN region results in there being SMR as well as electrolysis used to produce hydrogen.

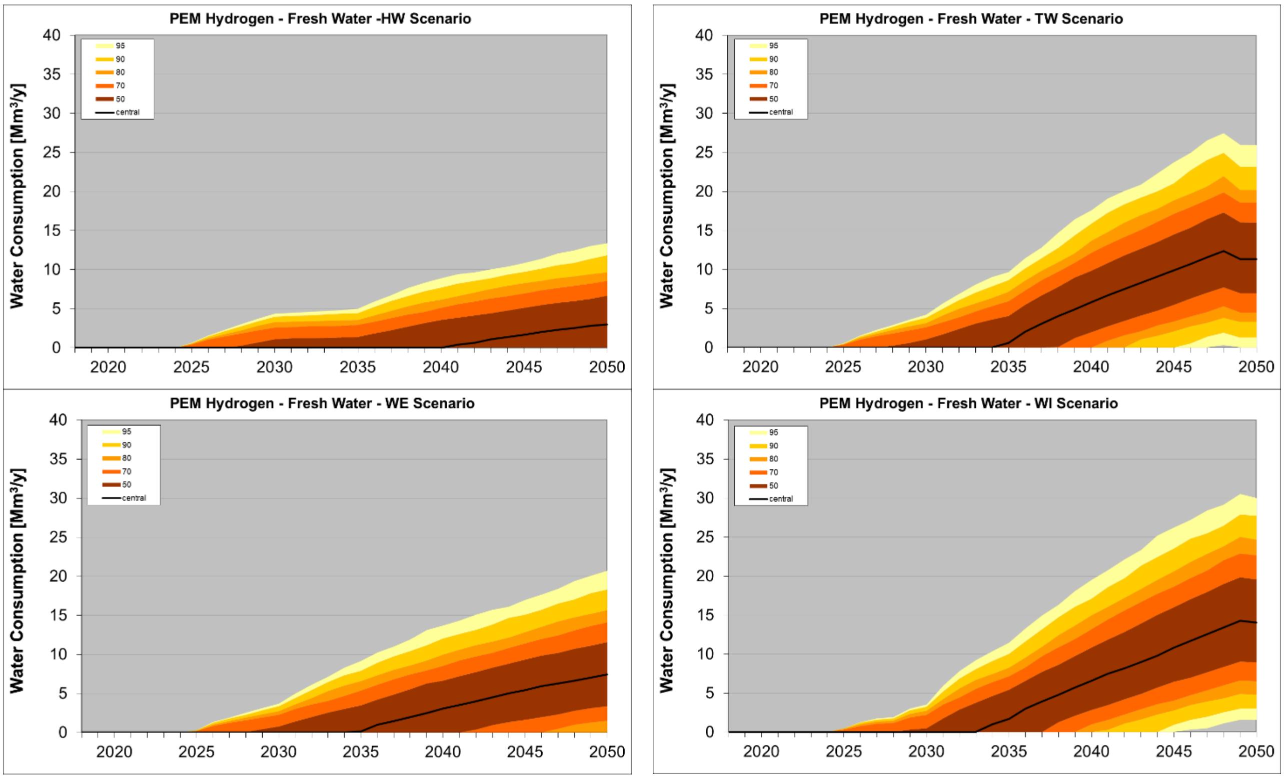



**Figure 23: same as Figure 15, but for the freshwater annually consumed to produce hydrogen by electrolysis for the CCC20 scenarios in WReN.**

In the CCC20 scenario the production of hydrogen by electrolysis takes off around 2025 to 2030 and either continues to increase (HW & WE) or reaches a peak around 2048 (TW & WI).

The predicted freshwater consumption for hydrogen production by Steam Methane Reformation is plotted below:

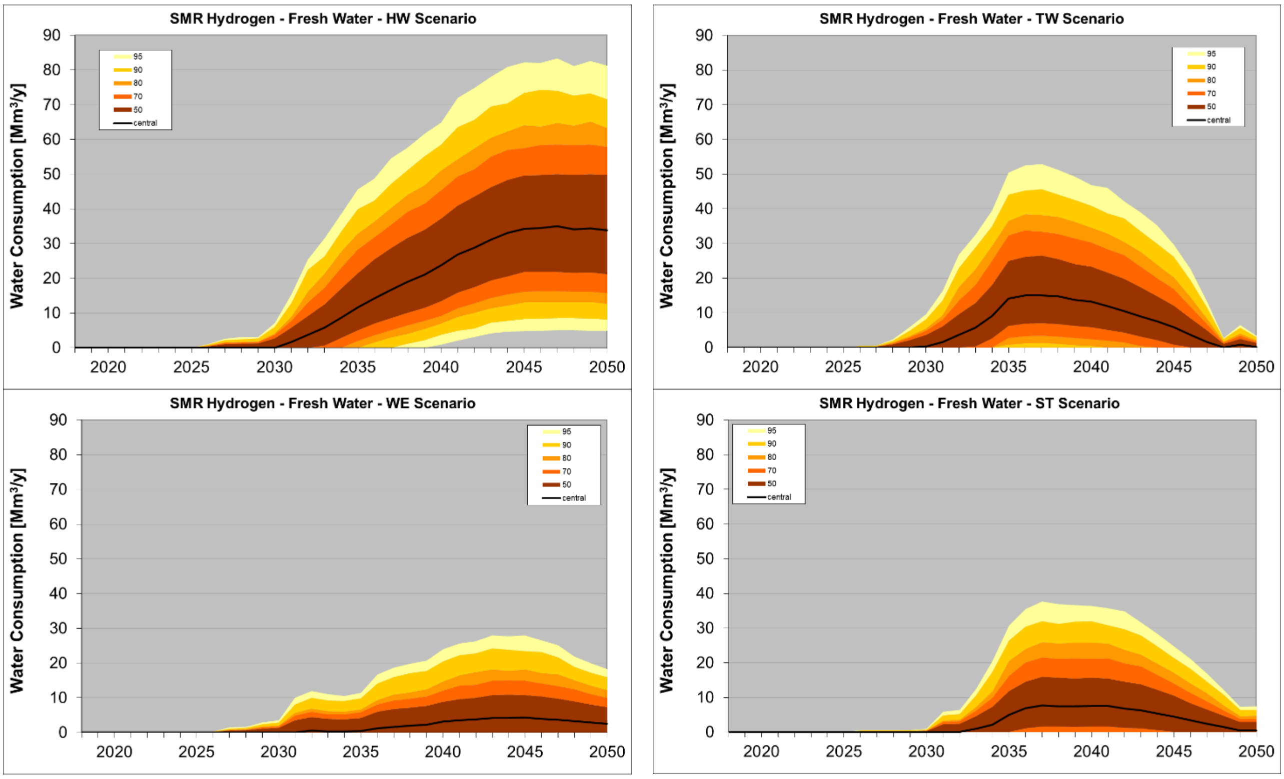



**Figure 24: same as Figure 23, but for the freshwater annually consumed to produce hydrogen by SMR for the CCC20 scenarios in WReN.**

Except for the HW scenario (where consumption is steady after reaching a peak in 2045) the consumption of freshwater for SMR production of hydrogen is predicted to begin in the period 2025 to 2030 and reach a peak between 2035 and 2045 before reducing in the period to 2050.

The total consumption of freshwater for energy production (electricity and hydrogen) is plotted below:

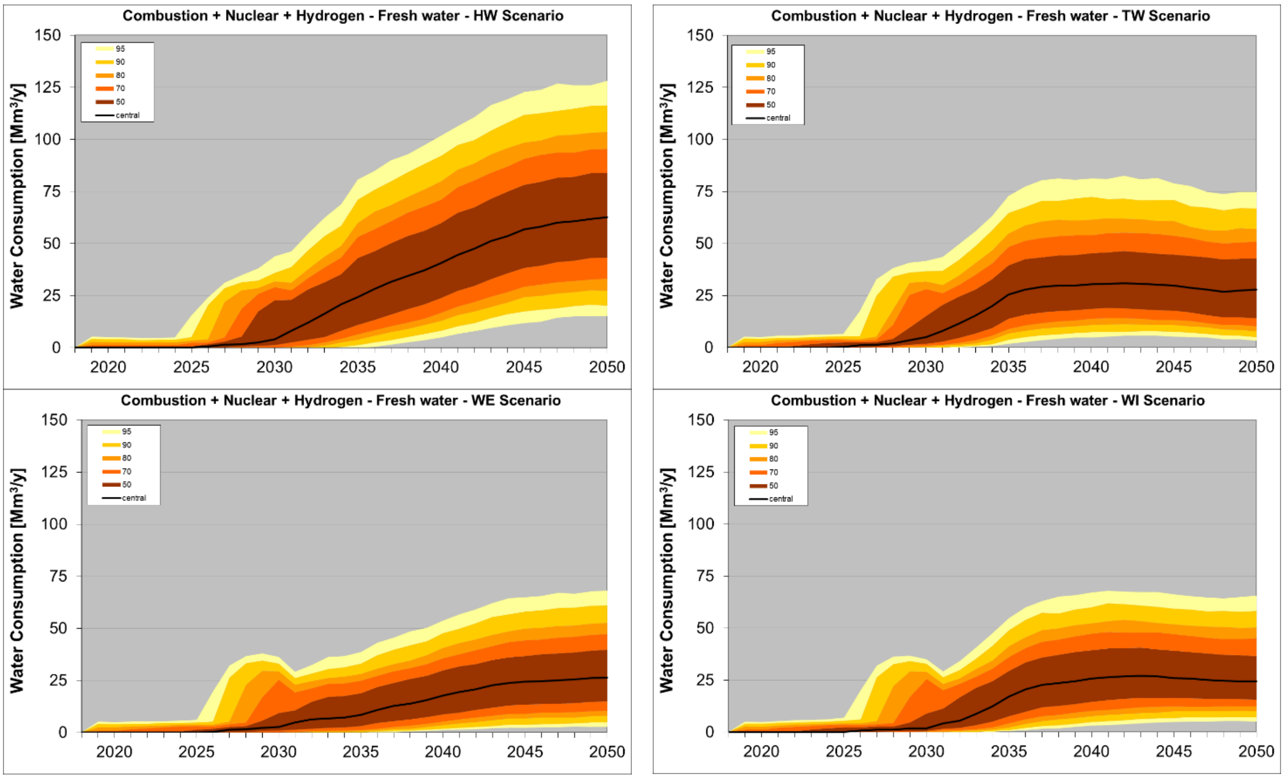



**Figure 25: WReN: annual freshwater consumption for energy production by generation plant plus hydrogen production, as projected under each of the four CCC20 (WE bottom left, HW top left, WI bottom right, TW top right) scenarios.**

For all of the CCC20 scenarios the consumption of freshwater within WReN is predicted to be greater in 2050 than in the baseline with the need for water increasing from between 2025 and 2030.

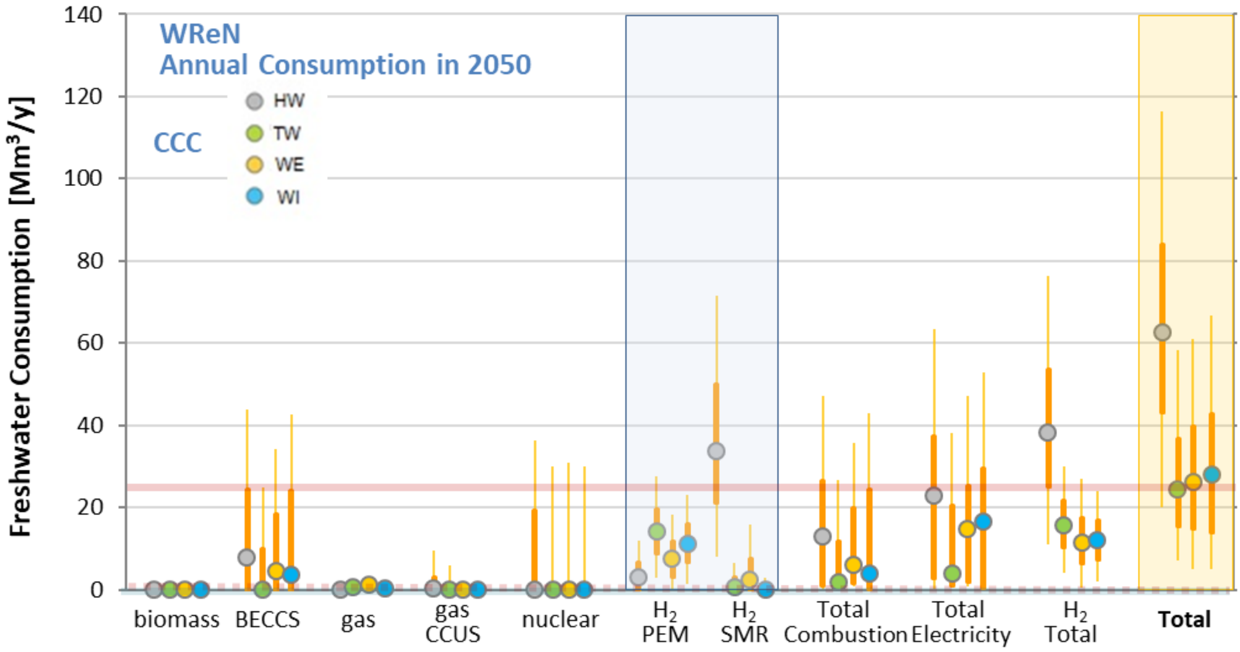



**Figure 26: As Figure 19 but for CCC20 scenarios**

On an annual basis the production of hydrogen is the largest consumptive water use for energy production predicted by the model for WRSE in 2050, this being for the HW scenario. For the WE & WI scenarios more water is required for electricity generation than for hydrogen.

The median total annual freshwater consumption for energy production in WReN at 2050 varies between 25 and 63Mm$^3$/y with between 4 and 23Mm$^3$/y being used in cooling thermal power plant. The 95%ile use for electricity production is up to 64Mm$^3$/y with up to 116Mm$^3$/y for the energy sector.

The median annual freshwater consumption for energy use at 2050 is greater than the 2010 (and 2018) baseline that included coal generation. The range of consumptive use at 2050 for electricity production also exceeds the 2010 baseline with coal generation included.

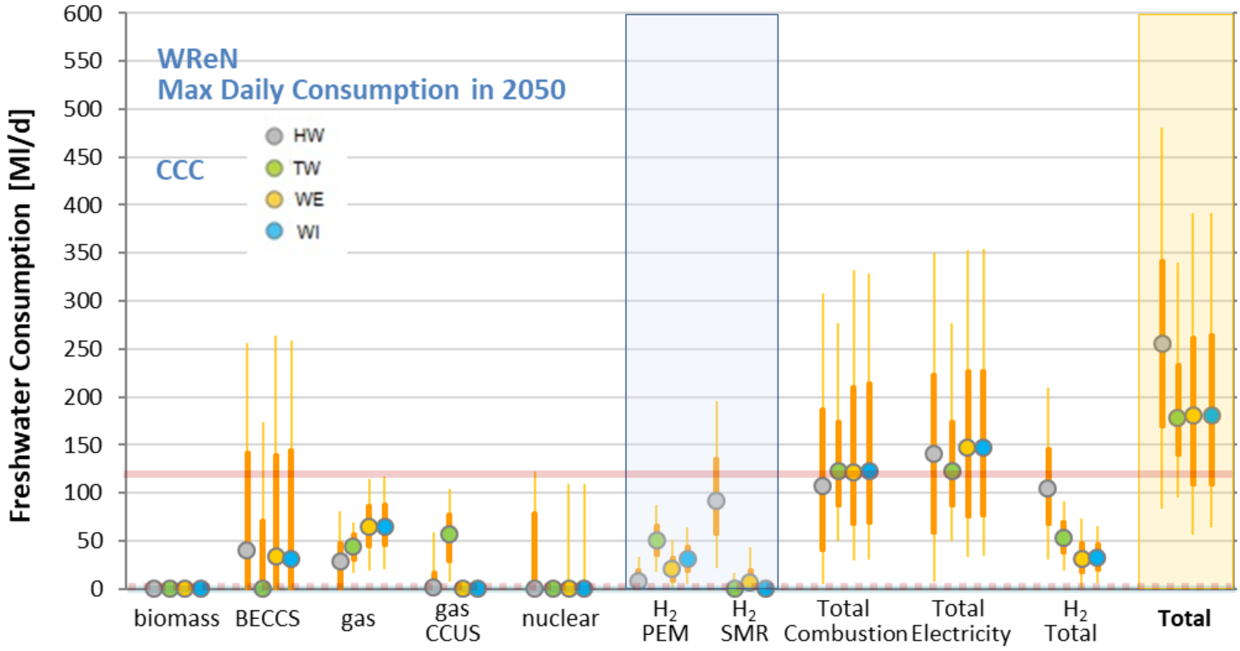



**Figure 27: same as Figure 26, but for the modelled maximum daily freshwater consumption in 2050.**

The median daily maximum freshwater consumption for energy production in WReN at 2050 varies between 181 and 256Mm$^3$/y with between 31 and 148Mm$^3$/y being used in cooling thermal power plant. The 95%ile energy sector (electricity plus hydrogen production) consumption ranges up to 481Ml/d while that for electricity generation is up to 350Ml/d.

The median daily maximum freshwater consumption for energy use at 2050 is greater than the 2010 (and 2018) baseline that included coal generation. The range (and for most scenarios the median) of consumptive use at 2050 for electricity production also exceeds the 2010 baseline with coal generation included.

### 4.2.1 High Quality Water use in WReN at 2050

The same model used to predict cooling water use has been used to predict high quality water use within the WReN region for the FES 20 and CCC20 scenarios. Note that the freshwater consumption results plotted above include the high quality and cooling water use in hydrogen production and therefore the high quality water use in hydrogen production results below are not additive. The high quality water use was not included in the modelling of freshwater use in electricity generation and so the high quality water is an additional consumption to the previous results.

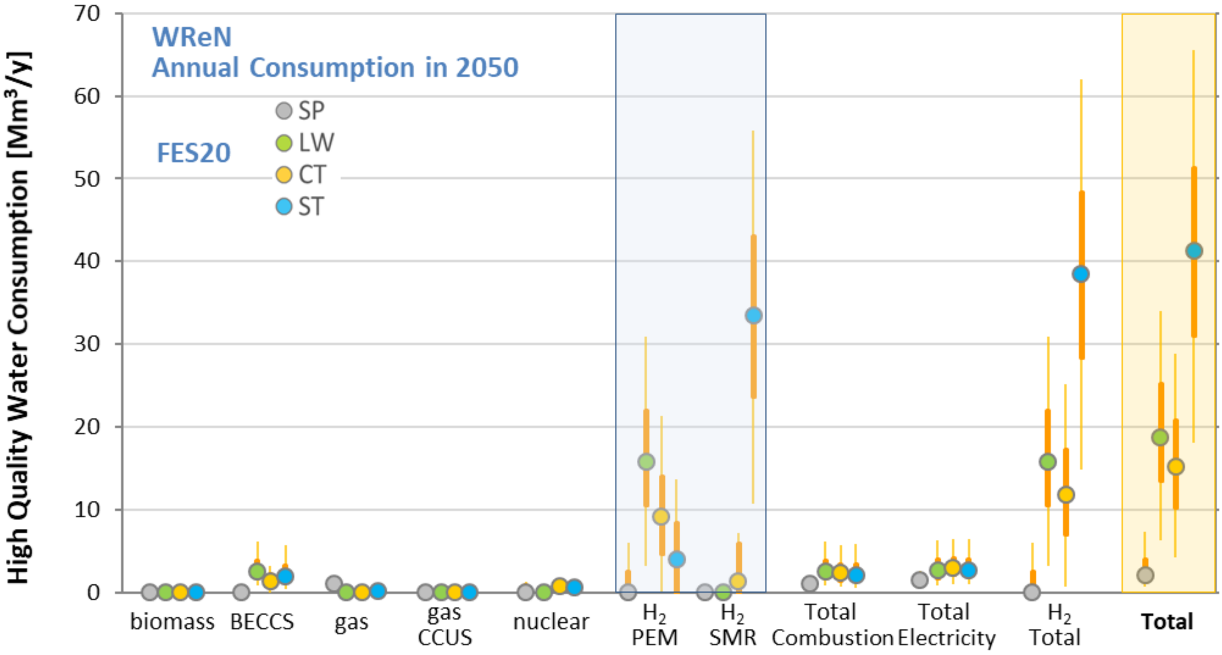



**Figure 28: WReN annual high quality water consumption by power producers in 2050, modelled using CCC20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the $25^{th}$-$75^{th}$ (boxes) and $5^{th}$-$95^{th}$ (whiskers) percentile ranges.**

As for the cooling water use the largest volume of high quality water in 2050 under the FES20 scenarios is used within hydrogen production. The median use for electricity production (combustion plus nuclear) is 1 to 3Mm$^3$/y. The 95%ile high quality water use ranges up to 6.5 for electricity production and up to 66Mm$^3$/y for the energy sector (electricity plus hydrogen production) as a whole.

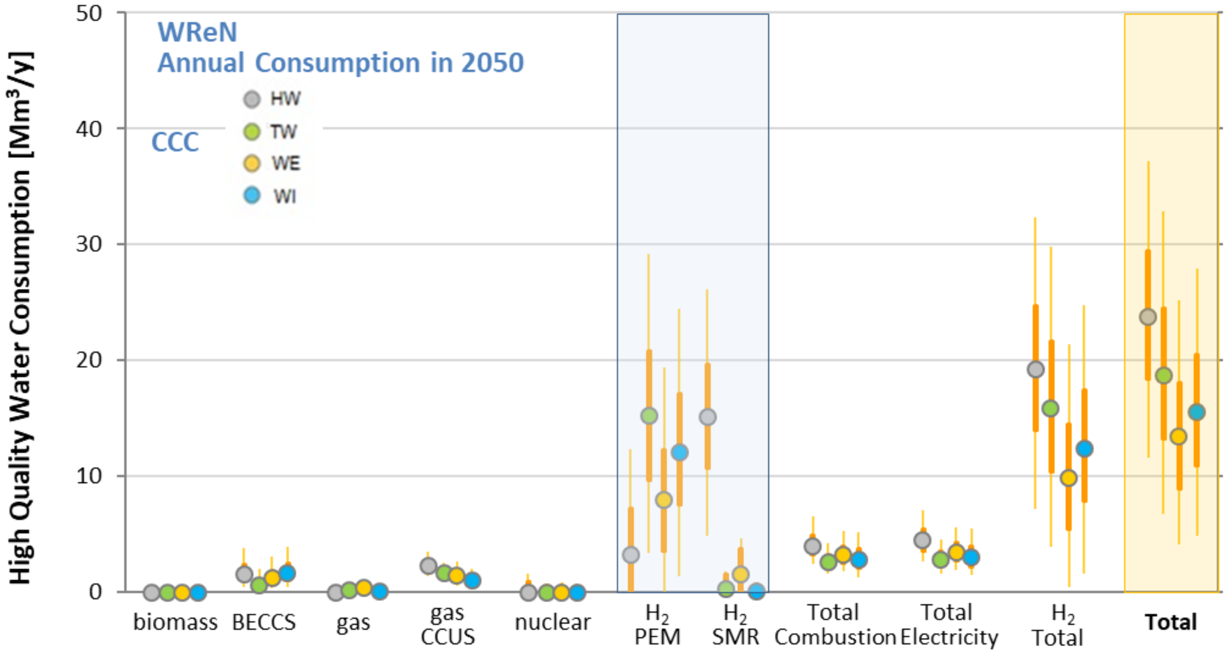



**Figure 29: same as Figure 28, but for the modelled annual high quality water consumption in 2050 under CCC20 scenarios.**

As for the cooling water use the largest volume of high quality water in 2050 under the CCC20 scenarios is used within hydrogen production. The median use for electricity production (combustion plus nuclear) is 3 to 5Mm$^3$/y with a 95%ile of 7Mm$^3$/y. The 95%ile high quality water use ranges up to 37Mm$^3$/y for total energy (electricity plus hydrogen) production.

### 4.2.2 Summary Freshwater consumption WReN

- Freshwater consumption for energy production in both FES20 & CCC20 reduces until 2025 to 2030 after which it increases
- Consumption for energy & electricity production under FES20 & CCC20 can be greater than the 2018 & 2010 baselines
- FES20 has BECCS, CCGTs, nuclear and hydrogen at 2050
- FES20 Annual energy use: median up to 108Mm$^3$/y, 95%ile up to 201Mm$^3$/y
- FES20 Annual electricity use: median up to 29Mm3/y, 95%ile up to 76Mm$^3$/y
- FES20 Daily energy use: median up to 330Ml/d, 95%ile up to 610Ml/d
- FES20 Daily electricity use: median up to 115Ml/d, 95%ile up to 310Ml/d
- CCC20 Annual energy use: median up to 63Mm$^3$/y, 95%ile up to 116Mm$^3$/y
- CCC20 Annual electricity use: median up to 23Mm3/y, 95%ile up to 63Mm$^3$/y
- CCC20 Daily energy use: median up to 256Ml/d, 95%ile up to 480Ml/d
- CCC20 Daily electricity use: median up to 148Ml/d, 95%ile up to 354Ml/d
- High Quality Water: Electricity production 95%ile up to 7Mm$^3$/y

## 4.3 Modelled Freshwater Consumption: pathways to 2050 Water Resource South East (WRSE)

Water Resource South East borders Water Resource East, Water Resource West and West Country Water Resources (Figure 1). WRSE covers the freshwater river Thames and the tidal Thames down to Beckton. Downstream of Beckton the north bank of the Thames is WRE with the south bank being the WRSE region.

Eleven of the sites considered by the model to be ‘available’ for electricity or hydrogen generation fall within this region, but only one of them is freshwater cooled. The WRSE region is not close enough to one of the five CCUS clusters for the model to assign either abated combustion or SMR hydrogen production.

The clusters form part of UK Government strategy to support early innovation in CCUS. How the CCUS and hydrogen network develops will be strongly influenced by market forces and other outcomes and extension beyond these five may be possible. For example it will be noted that the WRSE region includes the Isle of Grain which is the focus of Project Cavendish (ENA 2020). The project explores ways hydrogen could be produced, stored or imported at the Isle of Grain in Kent, to get hydrogen to the South of London. It includes consideration of methods to provide sequestration of $CO_2$ formed during the SMR production of hydrogen[8] and illustrates the potential for SMR hydrogen production to develop away from the CCUS industrial clusters where its deployment is presently constrained by the current assumptions of the model. The potential for a wider distribution of CCUS nodes and SMR than the five coastal clusters currently assumed is discussed in Section 3.2.6 as least cost modelling of hydrogen networks by Imperial College researchers (Sunny at al 2020) showed a benefit from having inland production and CCUS nodes. The modelling showed a cost benefit from having hydrogen production and CCUS near to the London energy demand and within the WRSE region. If such inland CCUS nodes were to be developed it would open the region to a wider mix of energy production including BECCS and SMR and increase the freshwater demand above that shown below.

The recently published UK industrial decarbonisation strategy (UK Gov 2021) assumed at least nine UK clusters with CCUS and hydrogen being available. These included two in the WRSE region (Southampton and Medway, where the captured $CO_2$ is shipped for offshore storage). While the strategy was for industrial decarbonisation (and not the energy sector) any CCUS and hydrogen infrastructure provided as an outcome of the strategy could be accessed by the energy sector.

The modelled annual average freshwater consumption in combustion plant under the four FES20 scenarios are plotted as Figure 30 below:

[8] Final Technical Report: https://www.smarternetworks.org/project/nia_nggt0143/documents

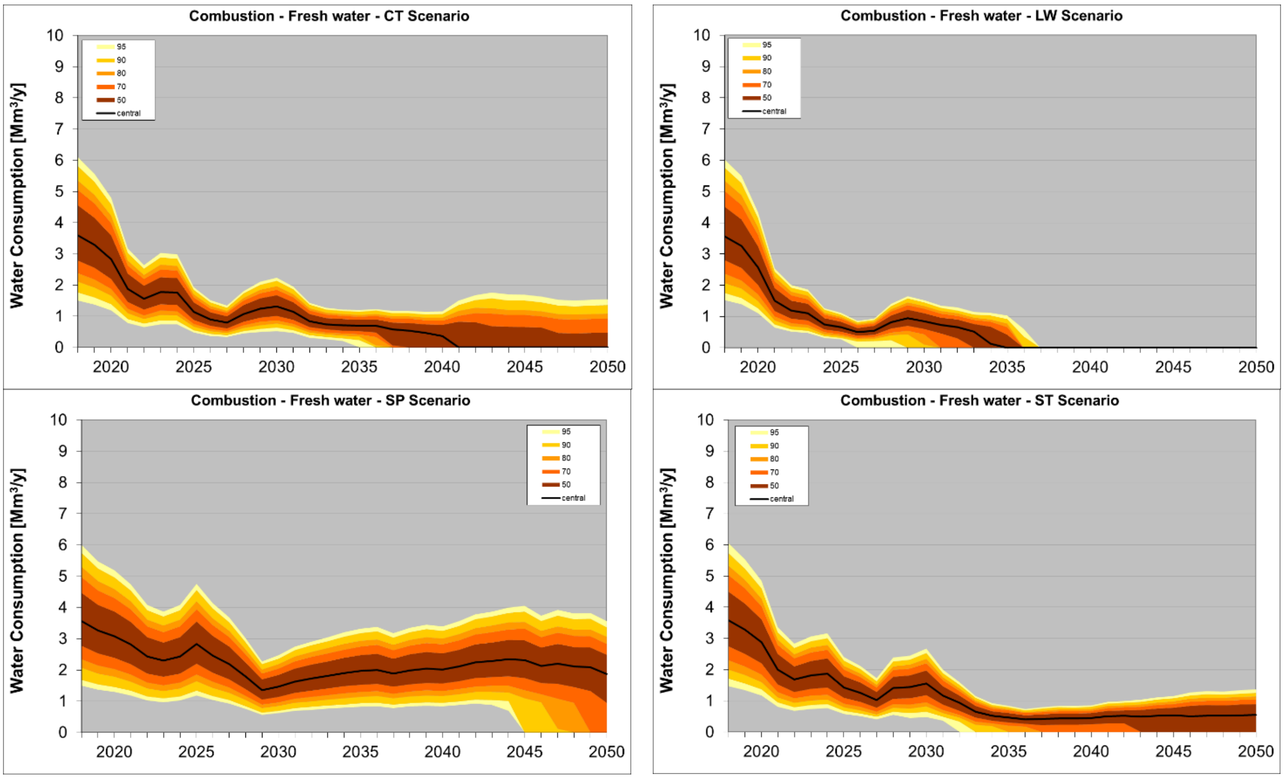



**Figure 30: WRSE: annual freshwater consumption by generation by combustion plant (coal + biomass + gas- and hydrogen-fired CCGTs), as projected under each of the four FES20 (SP: bottom left; CT: top left, ST: bottom right and LW: top right). Uncertainty is illustrated by showing confidence intervals around the Monte Carlo modelled central value (median). The outer uncertainty envelope illustrates the 95th percentile of the sampled values (see Appendix D of JEP (2021) for more details).**

The FES20 scenarios show a reduction in water consumption by combustion plant to 2025 to 2035 and thereafter ongoing need under three of the four scenarios modelled out to the end of the simulation at 2050.

Within the geographic boundary of the WRSE region there are no potential freshwater nuclear sites for the model to select.

The predicted annual consumptive use for hydrogen production follows. All the FES20 scenarios include some PEM hydrogen production within the WRE region but the sites with the WRSE region are not close enough to a CCUS cluster for the model to allocate SMR production.

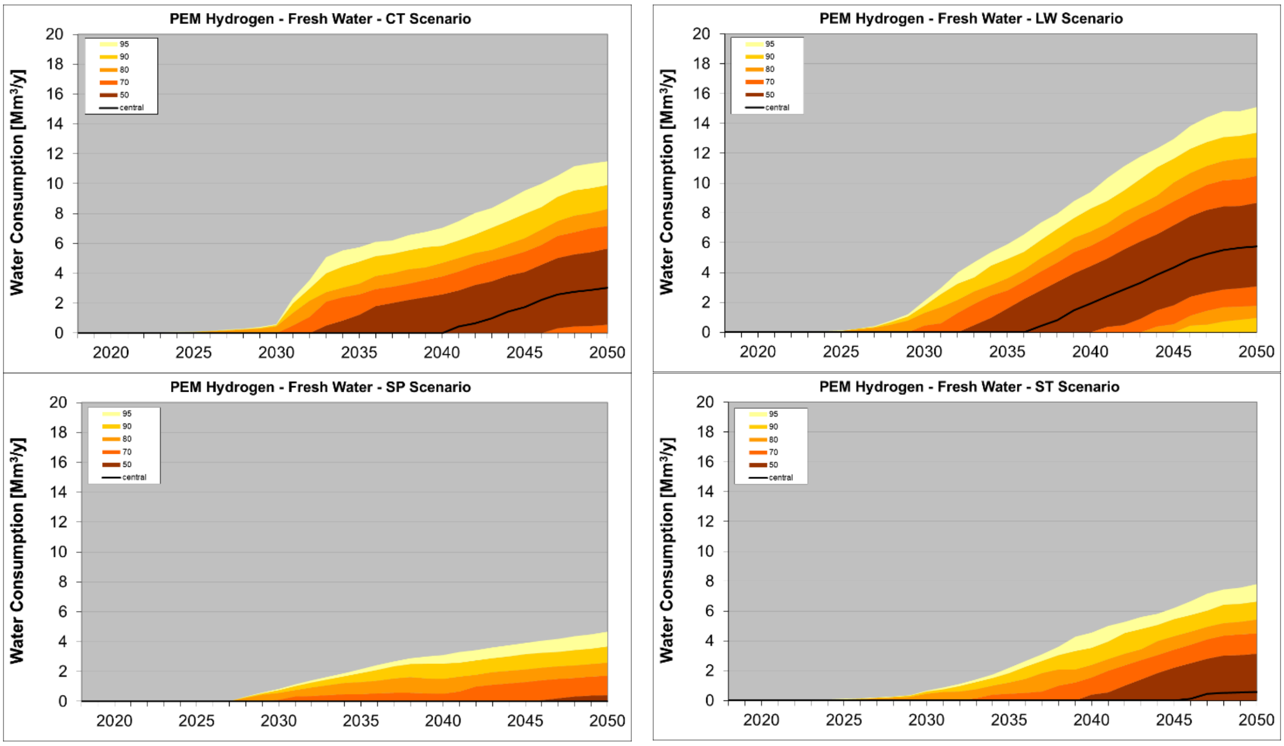



**Figure 31: same as Figure 30, but for the freshwater annually consumed to produce hydrogen by electrolysis in WRSE under FES20.**

In the FES20 scenario the production of hydrogen by electrolysis takes off around 2025 to 2030 and reaches a peak between 2035 to 2045 depending on the scenario.

The predicted total freshwater consumption for energy production (generation plus hydrogen) is plotted below:

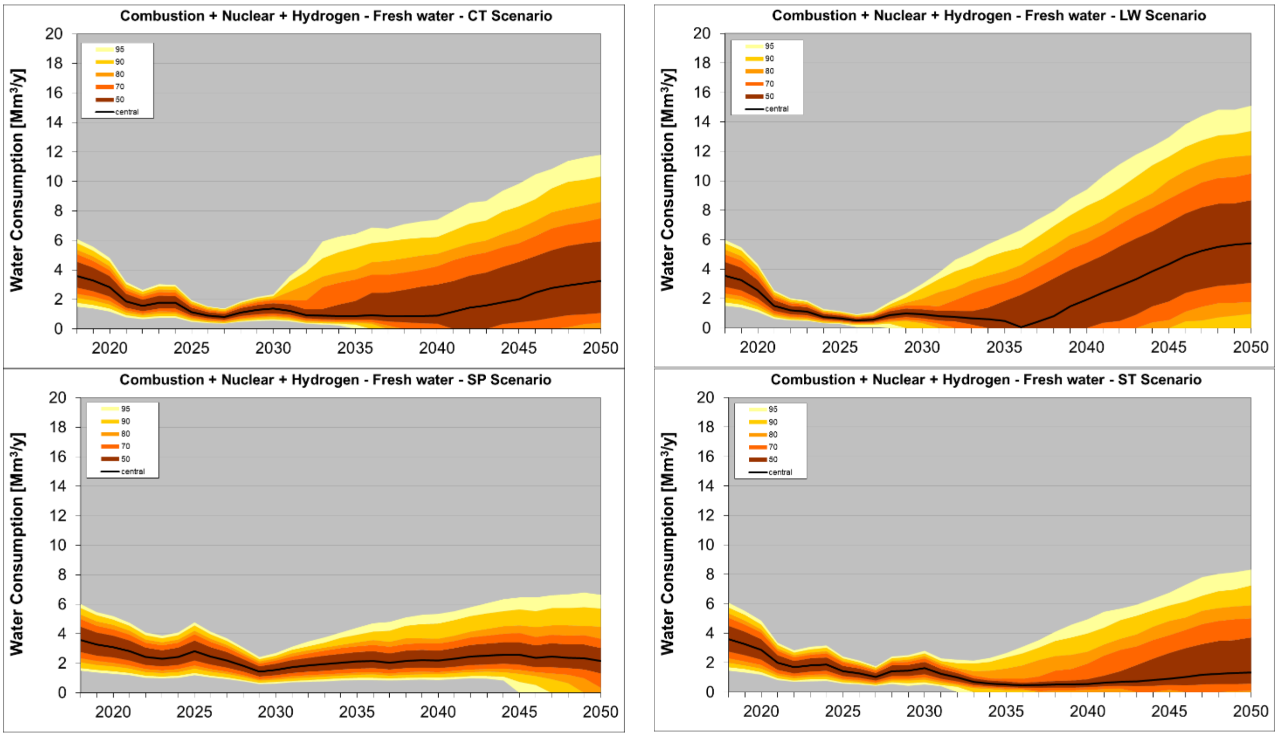



**Figure 32: same as Figure 30, but also including annual freshwater consumption by hydrogen production (electrolysis and steam methane reforming) under FES20 scenarios in WRSE.**

Total freshwater use for energy production is predicted to reach up to 14Mm$^3$/y by 2050 from a baseline of up to 6Mm$^3$/y. Whilst the demand from generation is predicted to reduce that from hydrogen production increases such that all the four scenarios the demand in 2050 equals or exceeds that for the baseline. For two of the scenarios (CT & LW) the range of consumptive use exceed the baseline from around 2035 onwards.

The total predicted annual freshwater consumption in 2050 for energy production and each element of the total (CCGT, BECCS, hydrogen etc) is plotted below for the four scenarios:

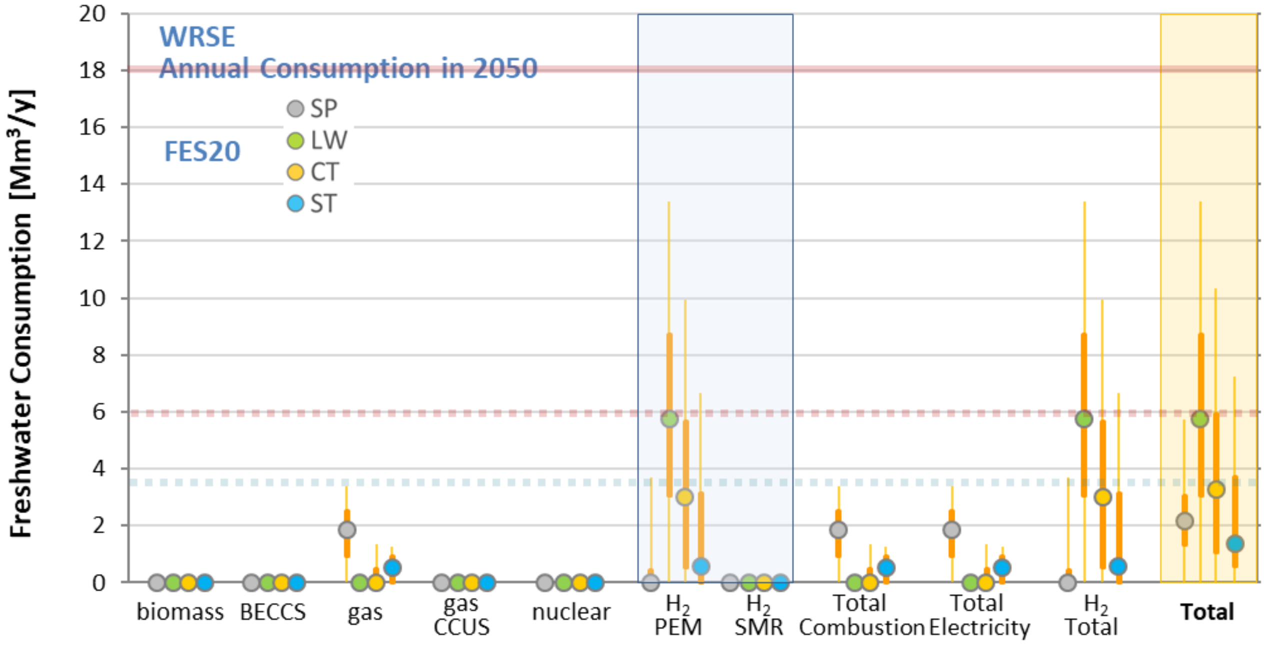



**Figure 33: WRSE annual freshwater consumption by power producers in 2050, modelled using FES20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the 25th-75th (boxes) and 5th-95th (whiskers) percentile ranges. To place these values into context, the chart also reports (horizontal dotted blue line) the freshwater consumption estimated by the model for the reference year 2018. Equivalent results, as obtained in Gasparino (2012) for the then baseline 2010, are also illustrated (with the inclusion or exclusion of contributions from coal-fired plant: solid and dotted red lines, respectively)**

The median annual freshwater consumption in 2050 for energy production ranges between 1.4 to 5.8Mm$^3$/y with up to 1.9Mm$^3$/y for combustion generation. The 95%ile consumption for combustion generation is up to 3.4Mm$^3$/y and for the energy sector it is up to 13.4Mm$^3$/y.

The range of annual freshwater consumption at 2050 is greater than the 2018 baseline and for all except the SP scenario which does not achieve Net Zero by 2050 it is greater than the 2010 baseline that excludes coal (red dotted line in Figure 33).

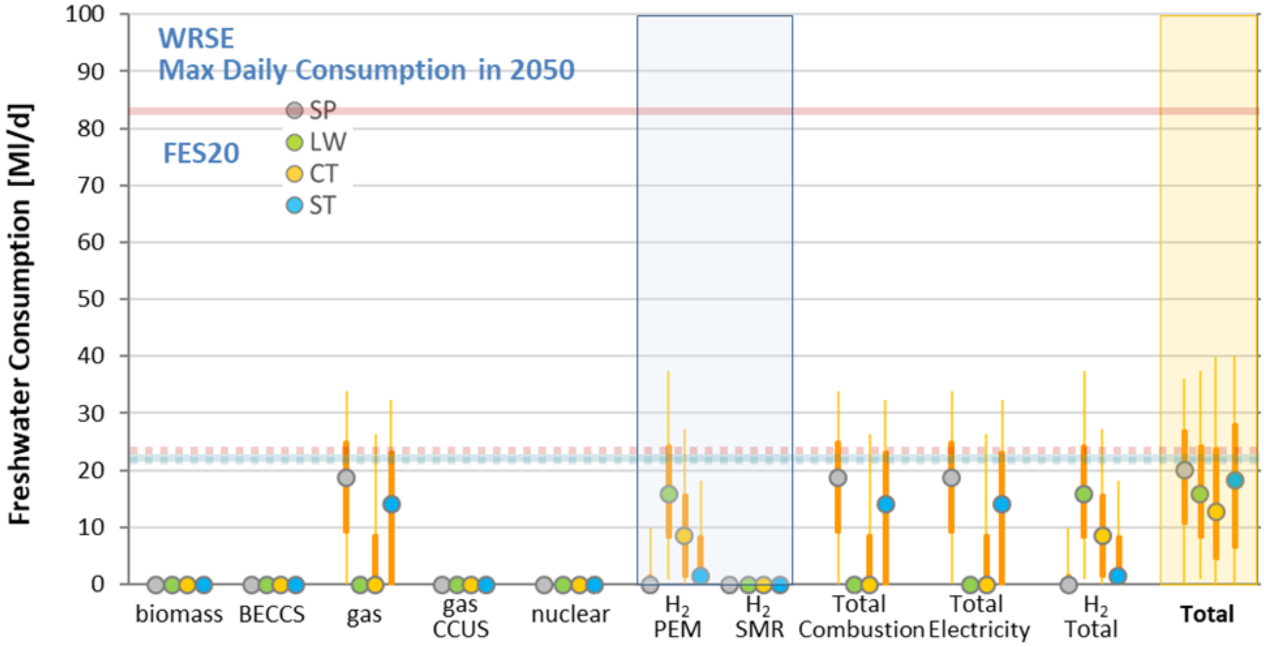



**Figure 34: WRSE same as Figure 33, but for the modelled maximum daily freshwater consumption in 2050.**

The median daily freshwater consumption in 2050 for energy production ranges between 12.7 to 19.9Ml/y with up to 18.6Ml/y for combustion generation. The 95%ile consumption is up to 34Ml/d for combustion generation and up to 40Ml/d for the energy sector.

The range of daily maximum freshwater consumption at 2050 is greater than the 2018 baseline and the 2010 baseline without coal fired generation. For three of the four scenarios the range of daily maximum consumption for electricity production at 2050 s greater than the 2018 baseline with and the 2010 baseline without cola fired generation.

The equivalent freshwater consumption pathways to 2050 in WRSE for the four CCC20 scenarios follow:

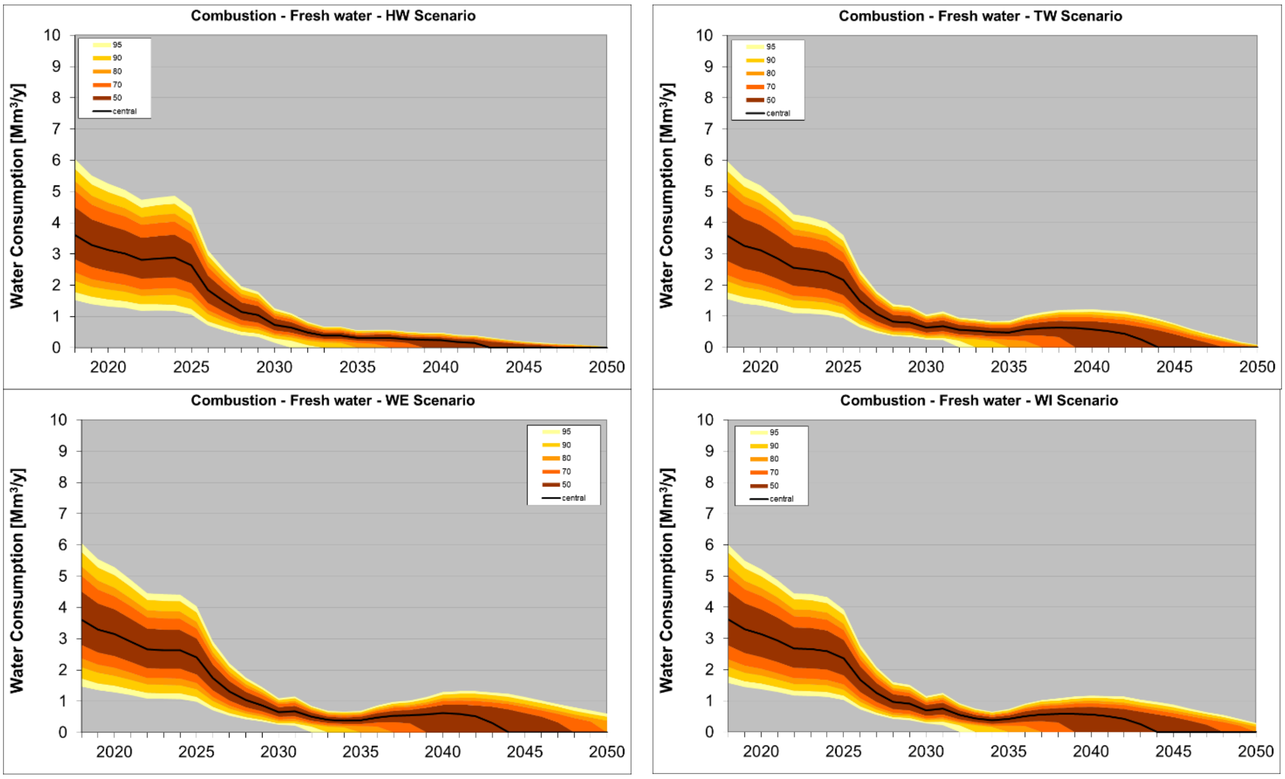



**Figure 35: WRSE: annual freshwater consumption by generation by combustion plant (coal + biomass + gas- and hydrogen-fired CCGTs), as projected under each of the four CCC20 (WE: bottom left; HW: top left, WI: bottom right and TW: top right). Uncertainty is illustrated by showing confidence intervals around the Monte Carlo modelled central value (median). The outer uncertainty envelope illustrates the 95th percentile of the sampled values (see Appendix D of JEP (2021) for more details).**

The CCC20 scenarios show a reduction in water consumption by combustion generation plant with some limited use in 2050.

The predicted use to produce hydrogen under the CCC20 scenarios follows. As with FES20 the lack of a CCUS cluster close to the WRSE region sites results in there being no SMR hydrogen production predicted.

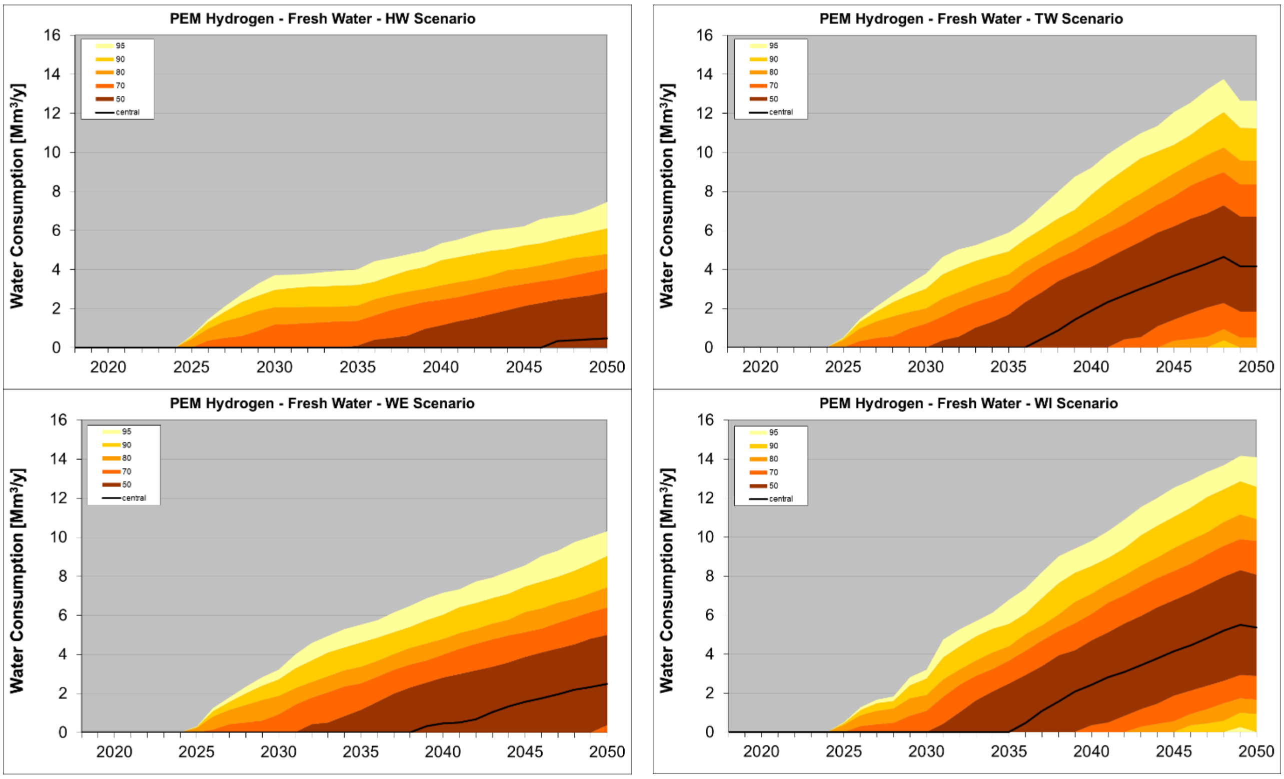



**Figure 36: same as Figure 15, but for the freshwater annually consumed to produce hydrogen by electrolysis for the CCC20 scenarios in WRSE.**

In the CCC20 scenario the production of hydrogen by electrolysis takes off around 2025 to 2030 and reaches a peak between 2035 to 2045 depending on the scenario.

The predicted total freshwater consumption for energy production (generation plus hydrogen) is plotted below:

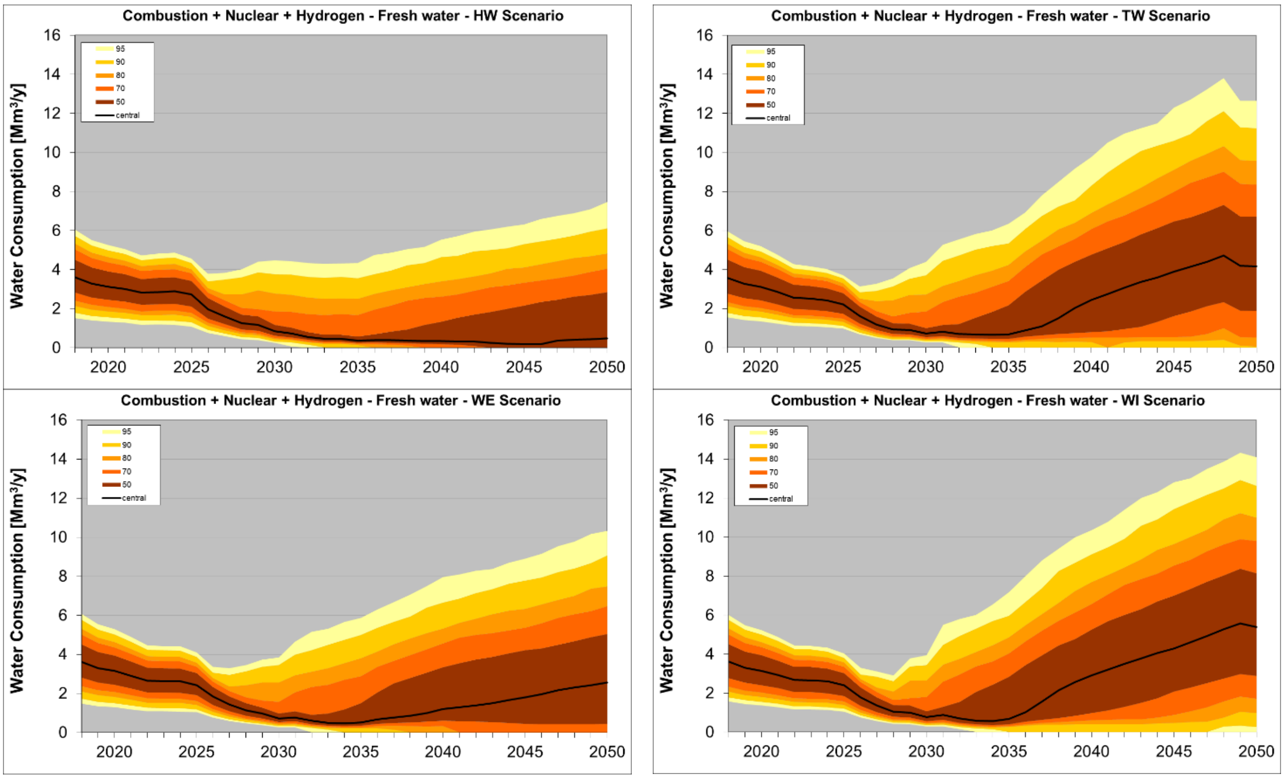



**Figure 37: WRSE: annual freshwater consumption for energy production by generation plant plus hydrogen production, as projected under each of the four CCC20 (WE bottom left, HW top left, WI bottom right, TW top right) scenarios.**

Total freshwater use for energy production is predicted to reach up to 14Mm$^3$/y by 2050 from a baseline of around 6Mm$^3$/y. Whilst the demand from generation is predicted to reduce that from hydrogen production increases such that under three of the four scenarios the demand in 2050 is similar to or greater than for the baseline.

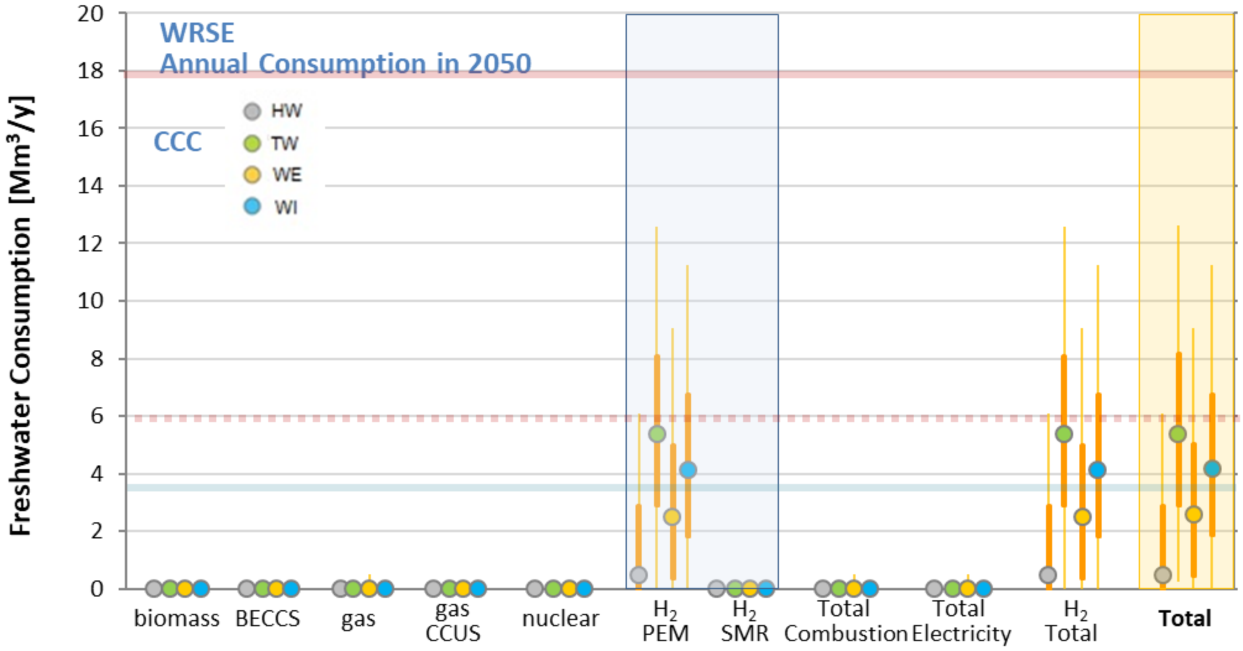



**Figure 38: WRSE annual freshwater consumption by power producers in 2050, modelled using CCC20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the 25th-75th (boxes) and 5th-95th (whiskers) percentile ranges. To place these values into context, the chart also reports (horizontal solid blue line) the freshwater consumption estimated by the model for the reference year 2018. Equivalent results, as obtained in Gasparino (2012) for the then baseline 2010, are also illustrated (with the inclusion or exclusion of contributions from coal-fired plant: solid and dotted red lines, respectively)**

On an annual basis the production of hydrogen is the largest consumptive water use for energy production predicted by the model for WRSE in 2050. The median total consumptive use for energy production ranges between 0.5 to 5.4Mm$^3$/y. The 95%ile for combustion is up to 0.5Mm$^3$/y and for the energy sector (electricity plus hydrogen production) it is up to 12.6Mm$^3$/y.

Under the CCC20 scenarios the annual freshwater consumption for energy production exceeds the 2010 baseline for all scenarios and equals or exceeds the 2010 baseline without coal generation.

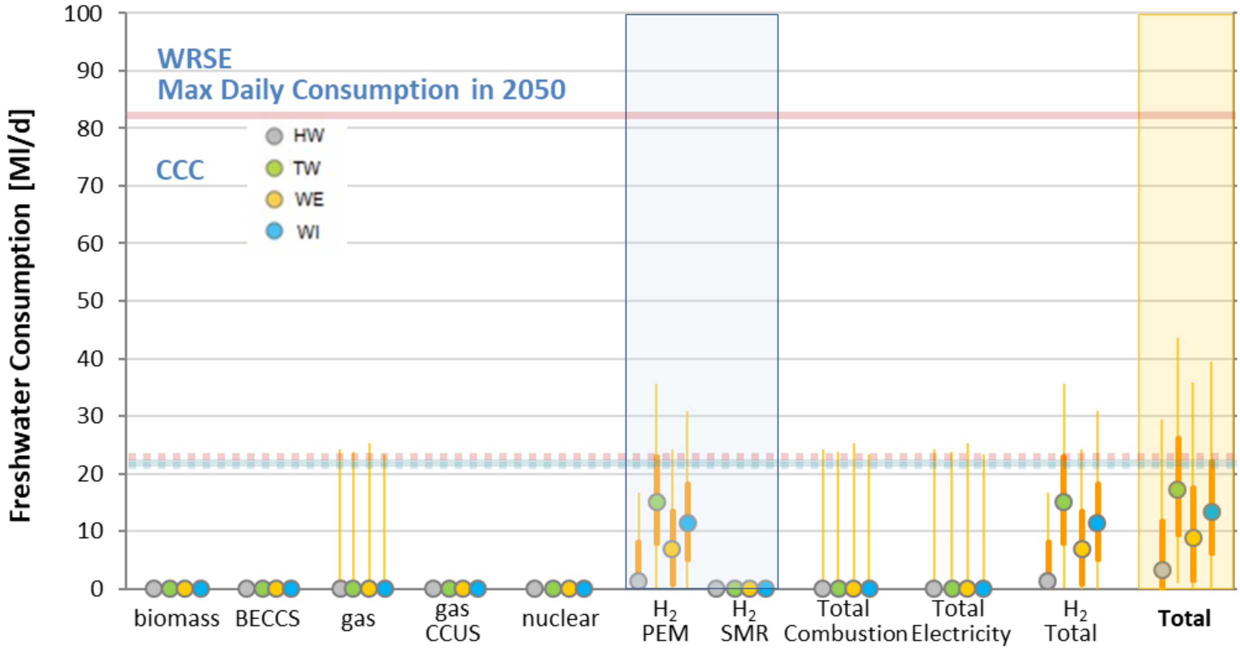



**Figure 39: WRSE same as Figure 38, but for the modelled maximum daily freshwater consumption in 2050.**

The maximum daily freshwater consumption data plotted as Figure 39 shows the majority of freshwater use to be for the production of hydrogen. In the model the maximum daily use is effectively a system stress event when plant providing capacity are called on to generate because other sources are unavailable. Hydrogen production is assumed to be constant (because of the availability of storage) and hence there is not a change in the modelled daily use for electrolysis in these stress events. The median predicted daily consumptive use for energy production in WRSE in 2050 is 3.2 to 17.3Ml/d. The 95%ile consumption for combustion generation is up to 25.4Ml/d with up to 43.6Ml/d for electricity plus hydrogen production combined.

The range of daily maximum freshwater consumption at 2050 exceeds the 2018 baseline with coal and the 2010 baseline without coal for all scenarios. The range of daily maximum water consumptions for electricity generation are similar to the 2018 baseline with cola and the 2010 without coal.

### 4.3.1 High Quality Water use in WRSE at 2050

The same model used to predict cooling water use has been used to predict high quality water use within the WRSE region for the FES 20 and CCC20 scenarios. Note that the freshwater consumption results plotted above include the high quality and cooling water use in hydrogen production and therefore the high quality water use in hydrogen production results below are not additive. The high quality water use was not included in the modelling of freshwater use in electricity generation and so the high quality water is an additional consumption to the previous results.

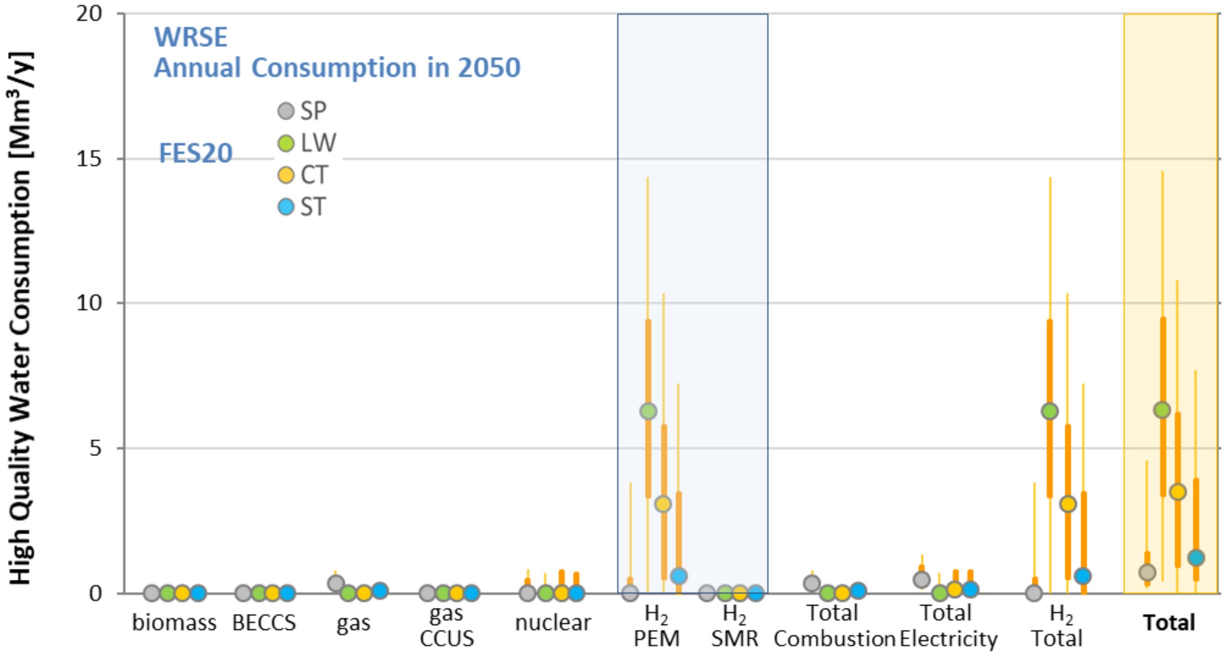



**Figure 40: WRSE annual high quality water consumption by power producers in 2050, modelled using FES20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the 25th-75th (boxes) and 5th-95th (whiskers) percentile ranges.**

As for the cooling water use the largest volume of high quality water in 2050 under the FES20 scenarios is used within hydrogen production. The median use for electricity production (combustion plus nuclear) is up to 0.4Mm$^3$/y with a median use between 0.7 and 6.3Mm$^3$/y for total energy (electricity plus hydrogen) production. The total high quality water use (95%ile) for energy production ranges up to 14.6Mm$^3$/y. There is some use by CCGTs in the SP scenario and for nuclear generation in all scenarios. The 95%ile consumption for thermal generation is up to 1.3Mm$^3$/y.

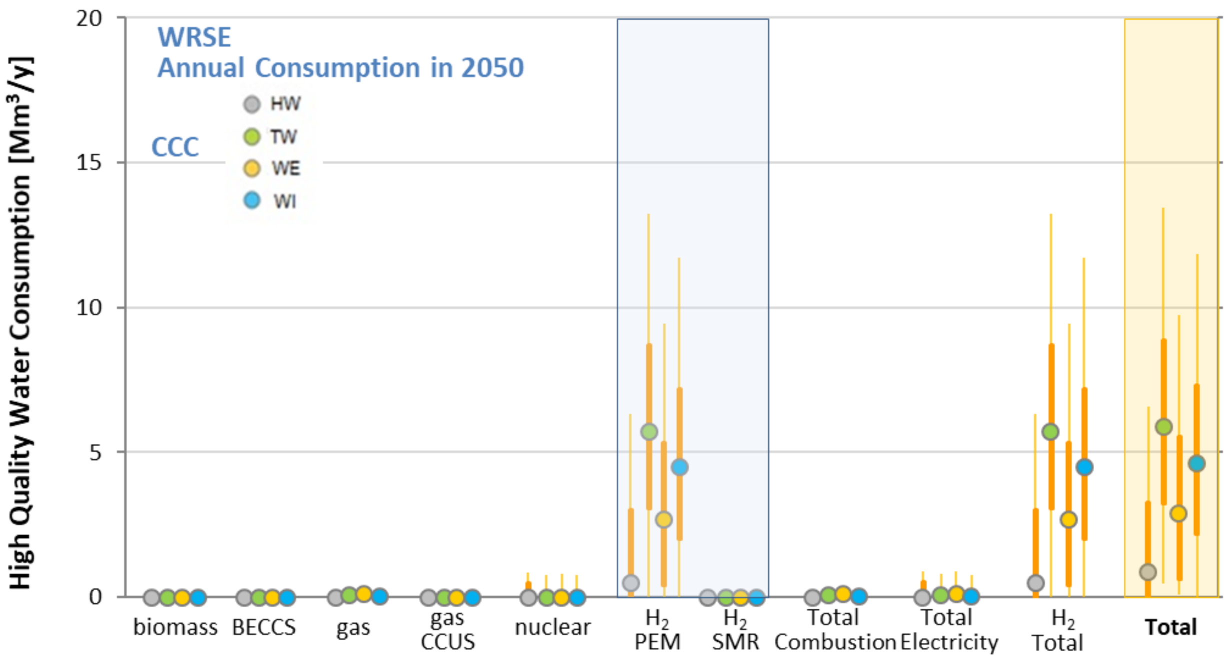



**Figure 41: same as Figure 40, but for the modelled annual high quality water consumption in 2050 under CCC20 scenarios.**

As for the cooling water use the largest volume of high quality water in 2050 under the CCC20 scenarios is used within hydrogen production. The median use for electricity production (combustion plus nuclear) is up to 0.1Mm$^3$/y. The 95%ile high quality water use by the energy (electricity plus hydrogen production) sector ranges up to 13.4Mm$^3$/y and up to 0.9Mm3/y for the thermal (combustion & nuclear) sector.

### 4.3.2 Summary Freshwater consumption WRSE

- Freshwater consumption for energy production in both FES20 & CCC20 reduces until 2025 to 2030 after which it increases
- Consumption for energy production under FES20 & CCC20 can be greater than both 2010 (without coal) & 2018 (with coal) baselines.
- The range of daily maximum consumption for electricity production is equal or greater than the 2018 (with coal) and 2010 (without coal) baselines
- Development of hydrogen (as in Project Cavendish) could increase use
- With only a single freshwater generation site the model will be sensitive to site specific developments
- FES20 Annual energy use: median up to 6Mm$^3$/y, 95%ile up to 13Mm$^3$/y
- FES20 Annual electricity use: median up to 2Mm3/y, 95%ile up to 3Mm$^3$/y
- FES20 Daily energy use: median up to 20Ml/d, 95%ile up to 36Ml/d
- FES20 Daily electricity use: median up to 19Ml/d, 95%ile up to 34Ml/d
- CCC20 Annual energy use: median up to 5Mm$^3$/y, 95%ile up to 13Mm$^3$/y
- CCC20 Annual electricity use: 95%ile up to 0.5Mm$^3$/y
- CCC20 Daily energy use: median up to 17Ml/d, 95%ile up to 44Ml/d
- CCC20 Daily electricity use: 95%ile up to 25Ml/d
- High Quality Water: Electricity production 95%ile up to 1.3Mm$^3$/y

### 4.4 Modelled Freshwater Consumption: pathways to 2050 Water Resource West (WRW)

Water Resource West (**Figure 1**) covers the west of England from the Scottish border to the Severn estuary. It has a border with each of the other regions. In addition to several coastal and estuarine sites the region includes the Derwent and upper Trent which both have existing and potential freshwater cooled power plant.

The predicted consumptive use of freshwater by combustion plant under the FES20 scenarios are plotted as **Figure 42** below:

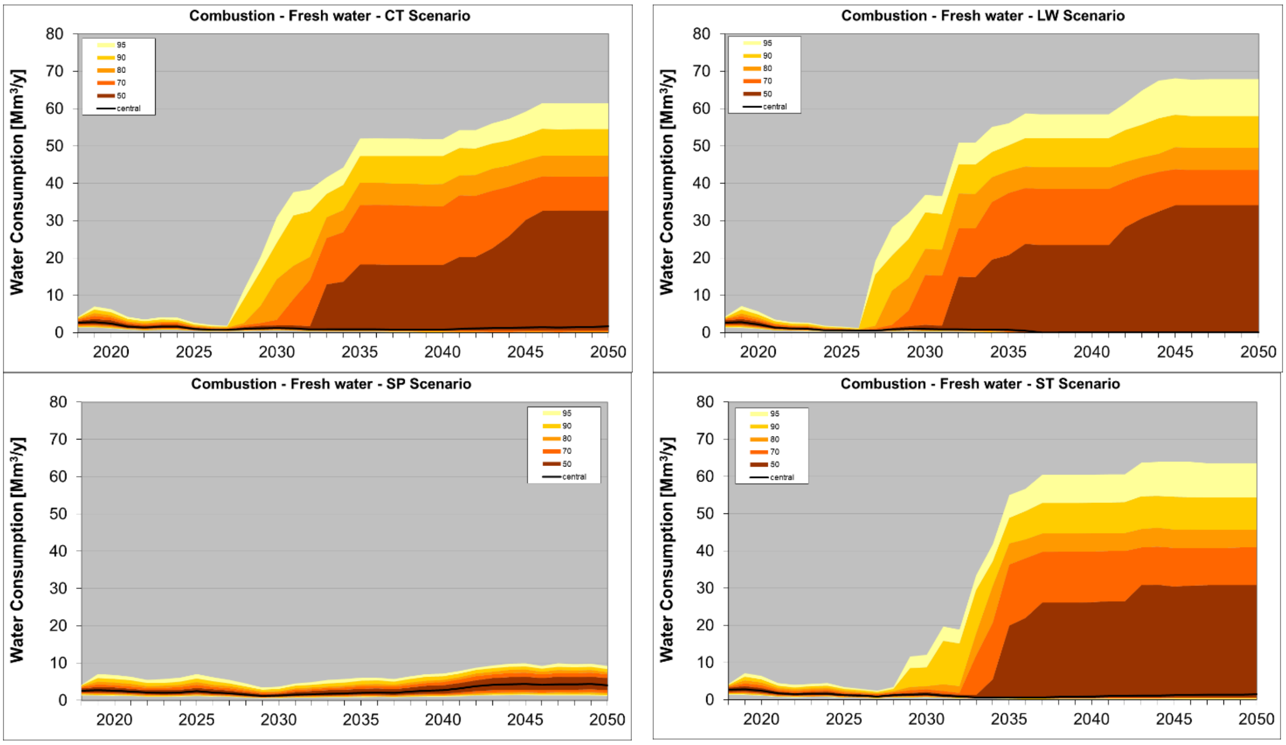



**Figure 42: WRW: annual freshwater consumption by generation by combustion plant (coal + biomass + gas- and hydrogen-fired CCGTs), as projected under each of the four FES20 (SP: bottom left; CT: top left, ST: bottom right and LW: top right). Uncertainty is illustrated by showing confidence intervals around the Monte Carlo modelled central value (median). The outer uncertainty envelope illustrates the 95th percentile of the sampled values (see Appendix D of JEP (2021) for more details).**

The FES20 scenarios show a reduction in water consumption by combustion plant to 2025 to 2030 and thereafter the range of predicted freshwater consumption increases. For all scenarios the consumptive use of freshwater for combustion generation increases above baseline consumption by 2050 and for three it is much greater than the baseline by the early 2030s.

Within the geographic boundary of the WRW region there are no potential freshwater nuclear sites. Some sites within WRW are close enough to a CCUS cluster for SMR hydrogen production to be selected by the model. The predicted annual consumptive use for hydrogen production follows.

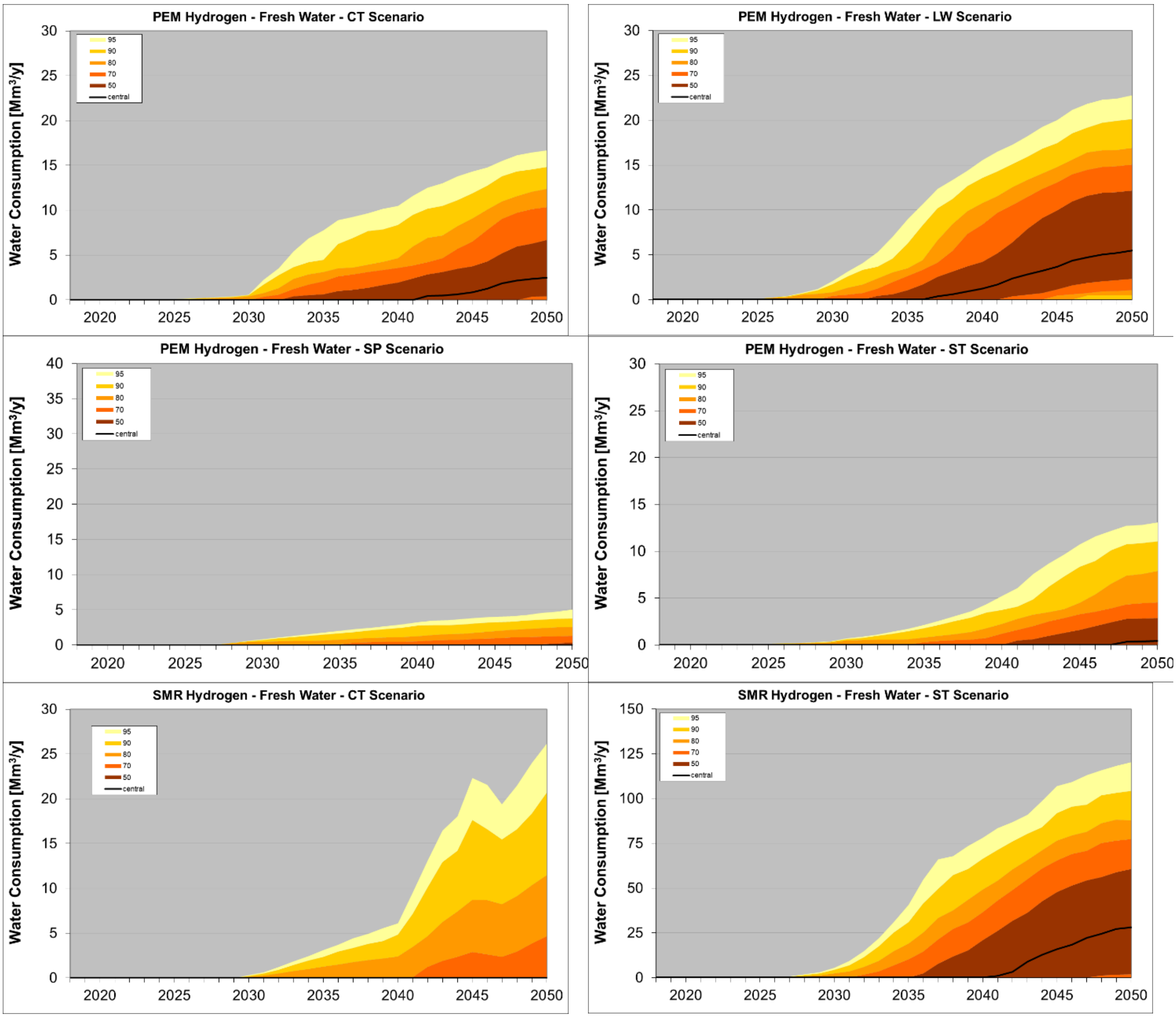



**Figure 43 WRW: same as Figure 42, but for the freshwater annually consumed to produce hydrogen by electrolysis (top and middle charts) and steam methane reforming (bottom charts: in this case the results are only illustrated for CT and ST, i.e. the two FES20 with non - zero SMR hydrogen production – note change of scale for SMR ST).**

All the FES scenarios include some PEM hydrogen production within the WRW region but only the CT and ST scenarios include steam methane production of hydrogen. From around 2030 onwards consumptive use of water for hydrogen increases and it can be of similar or greater (ST SMR use) magnitude to that used for generation.

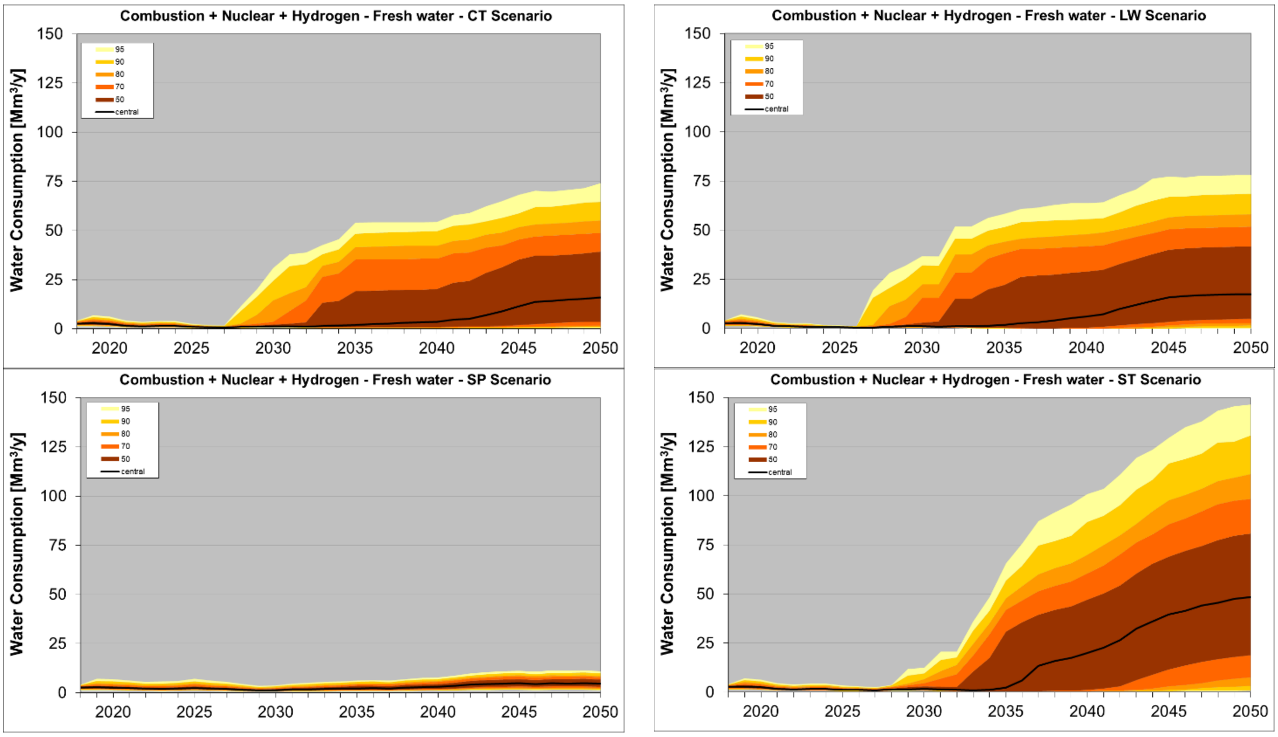



**Figure 44: same as Figure 42, but also including annual freshwater consumption by hydrogen production (electrolysis and steam methane reforming).**

For all scenarios the use for energy production (generation plus hydrogen) after an initial reduction from between 2025 to 2030, The rate of increase varies but for most scenarios the range of consumptive use is greater than the 2018 baseline from about 2030 onwards. The 2050 consumptive is generally much greater than the baseline.

The predicted annual and daily maximum use at 2050 for the four FES20 scenarios are plotted below.

The total predicted annual freshwater consumption in 2050 for energy production and each element of the total (CCGT, BECCS, hydrogen etc) is plotted below for the four scenarios:

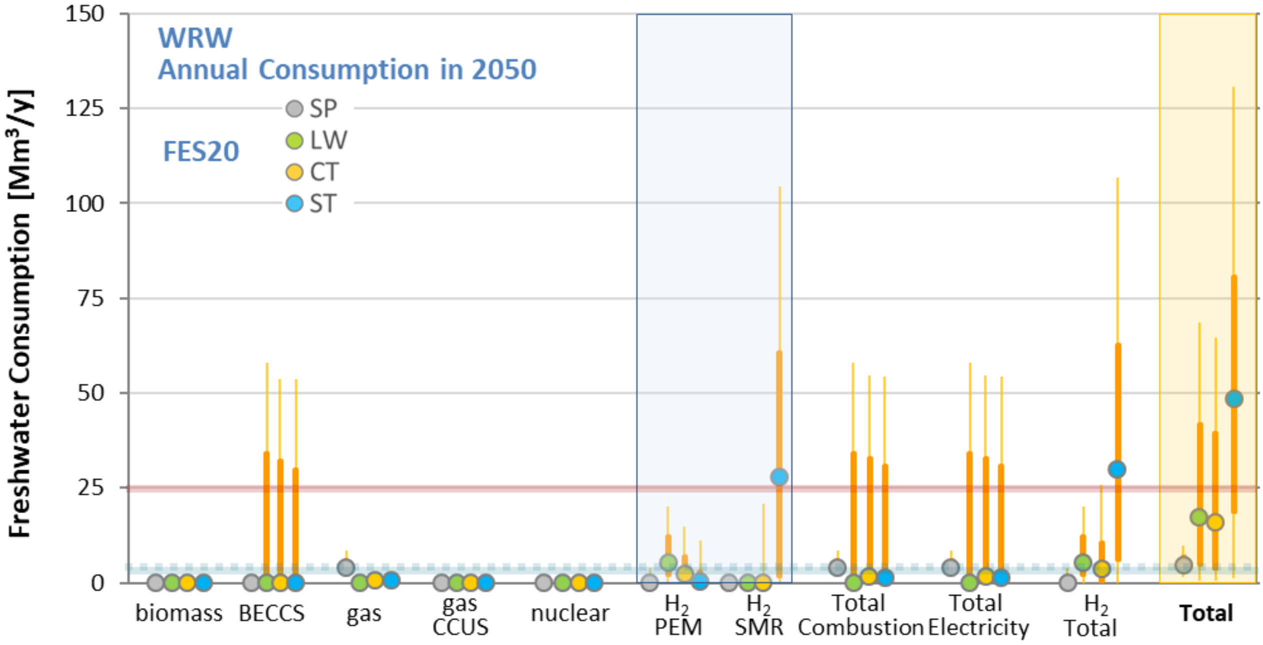



**Figure 45: WRW annual freshwater consumption by power producers in 2050, modelled using FES20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the 25$^{th}$-75$^{th}$ (boxes) and 5$^{th}$-95$^{th}$ (whiskers) percentile ranges. To place these values into context, the chart also reports (horizontal solid & dotted blue line) the freshwater consumption estimated by the model for the reference year 2018 (solid with and dotted without coal). Equivalent results, as obtained in Gasparino (2012) for the then baseline 2010, are also illustrated (with the inclusion or exclusion of contributions from coal-fired plant: solid and dotted red lines, respectively)**

At 2050 under the FES20 scenarios the median of the annual total consumptive use of freshwater for energy production is between 5 and 48Mm$^3$/y with up to 4Mm$^3$/y required for combustion plant. The 95%ile consumptive use for electricity production is up to 55M$^3$/y with up to 131Mm$^3$/y for the electricity and hydrogen production combined.

For three of the four FES20 scenarios the annual freshwater consumption for energy production in WRW is greater than the 2010 baseline with coal generation included. For all scenarios the consumption I greater than the 2018 baseline with coal included.

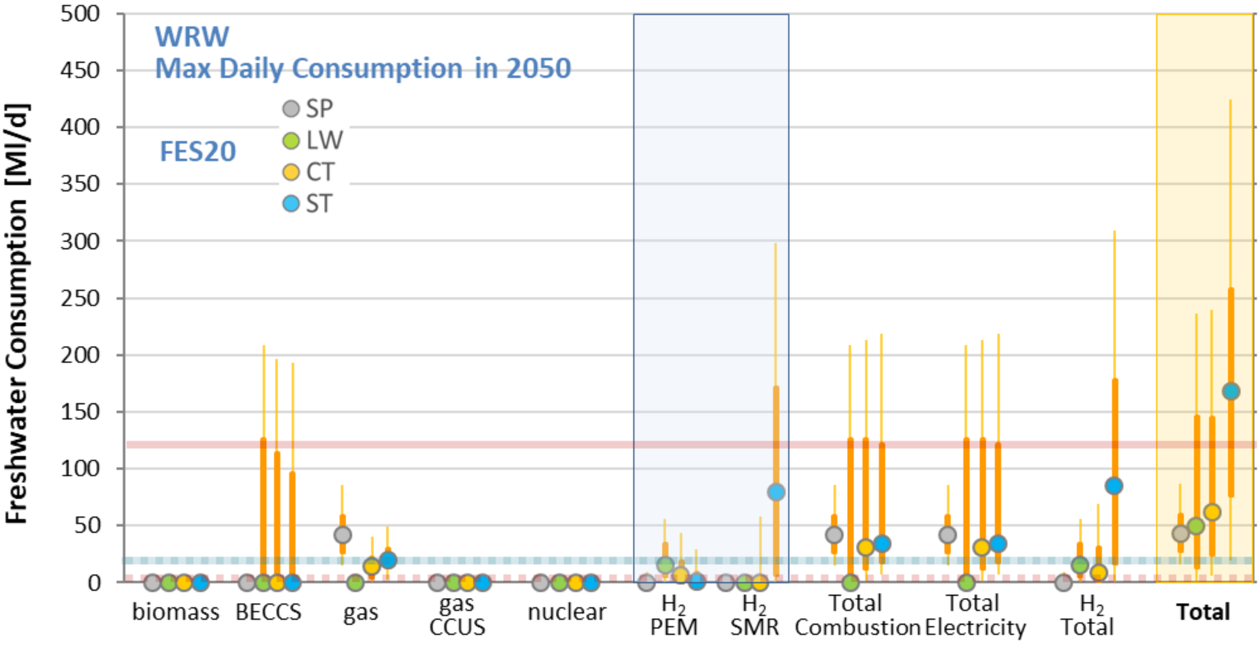



**Figure 46: same as Figure** 45**, but for the modelled maximum daily freshwater consumption in 2050.**

At 2050 under the FES20 scenarios the median of the daily maximum consumptive use of freshwater for energy production is between 43 and 167Ml/d with up to 42Ml/d required for combustion plant. The 95%ile consumptive use for electricity production is up to 219Ml/d with up to 424Ml/d for the energy sector.

The daily maximum freshwater consumption in WRW at 2050 are greater than the 2010 & 2018 baselines.

The equivalent freshwater consumption pathways to 2050 for the four CCC20 scenarios in WRW follow:

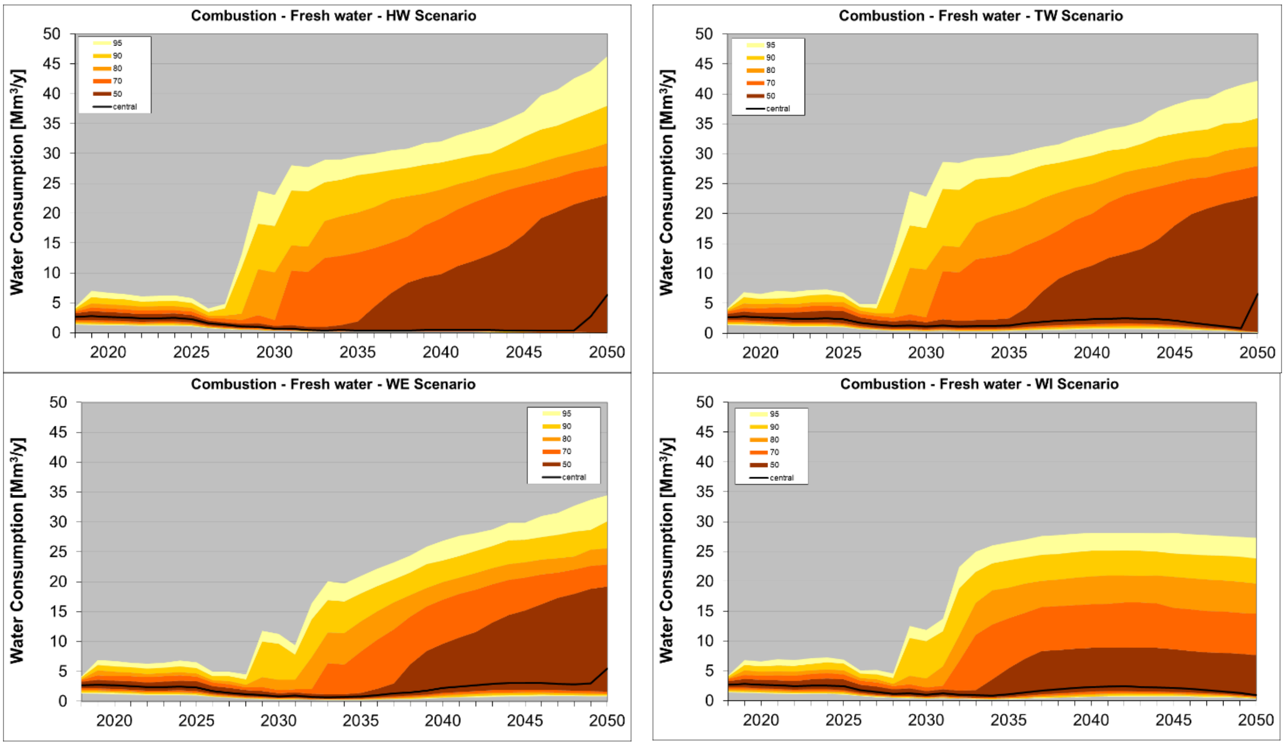



**Figure 47: WRW: annual freshwater consumption by generation by combustion plant (coal + biomass + gas- and hydrogen-fired CCGTs), as projected under each of the four CCC20 (WE: bottom left; HW: top left, WI: bottom right and TW: top right). Uncertainty is illustrated by showing confidence intervals around the Monte Carlo modelled central value (median). The outer uncertainty envelope illustrates the 95th percentile of the sampled values (see Appendix D of JEP (2021) for more details).**

The CCC20 scenarios are similar to the FES20 in that they show a reduction in water consumption by combustion generation plant until about 2025 thereafter there is an increase in water demand. For all scenarios the consumptive use reduces from the 2018 baseline to between 2025 and 2030. Thereafter the use increases with all of the scenarios having much higher range of consumption than at the baseline.

The predicted use for the production of hydrogen follows. Hydrogen is predicted to be needed from both PEM and SMR under all four CCC20 scenarios.

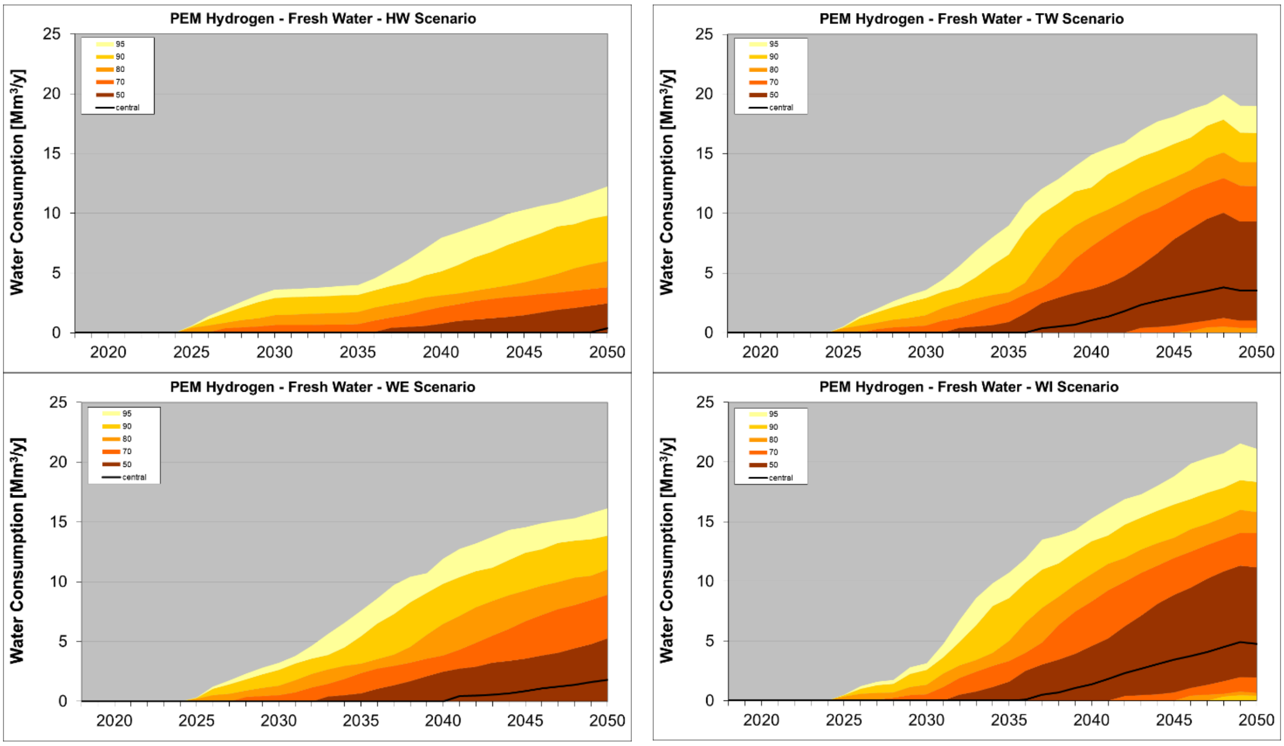



**Figure 48: same as Figure 47, but for the freshwater annually consumed to produce hydrogen by electrolysis for the CCC20 scenarios in WRW.**

The consumptive freshwater use in electrolysis is predicted to increase under all CCC20 scenarios from around 2025 to a maximum annual use just before the end of the simulation (at 2047 for TW and 2029 for WI) or increasing until 2050 (HW & WE).

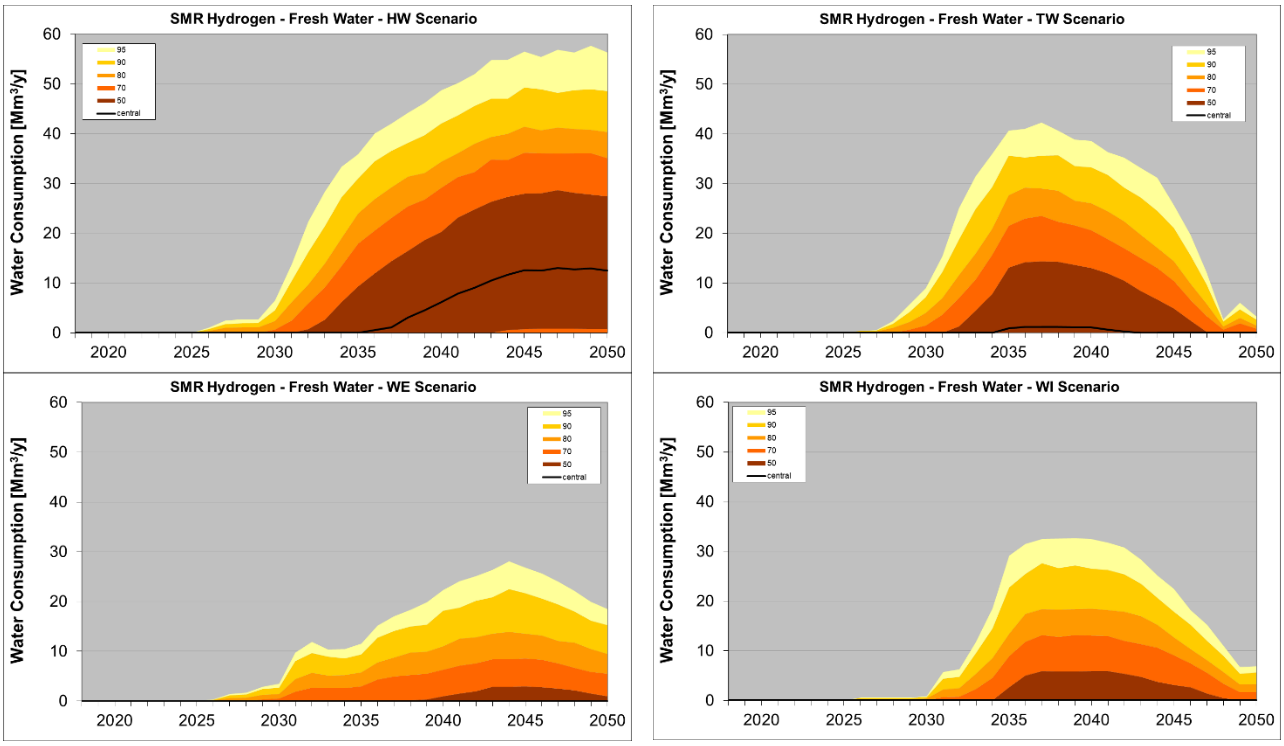



**Figure 49: same as Figure 48, but for the freshwater annually consumed to produce hydrogen by SMR for the CCC20 scenarios in WRW.**

Under the CCC20 scenarios consumptive use of freshwater is predicted to begin from around 2025 with growth tending to increase from 2035. SMR use begins to reduce after a peak between 2035 to 2048 depending on scenario. The rate of reduction varies so that for TW, WE & WI use has notably reduced in 2050 while for HW the reduction from the peak is less pronounced.

The modelled freshwater demand for energy production (combustion plus hydrogen) follows:

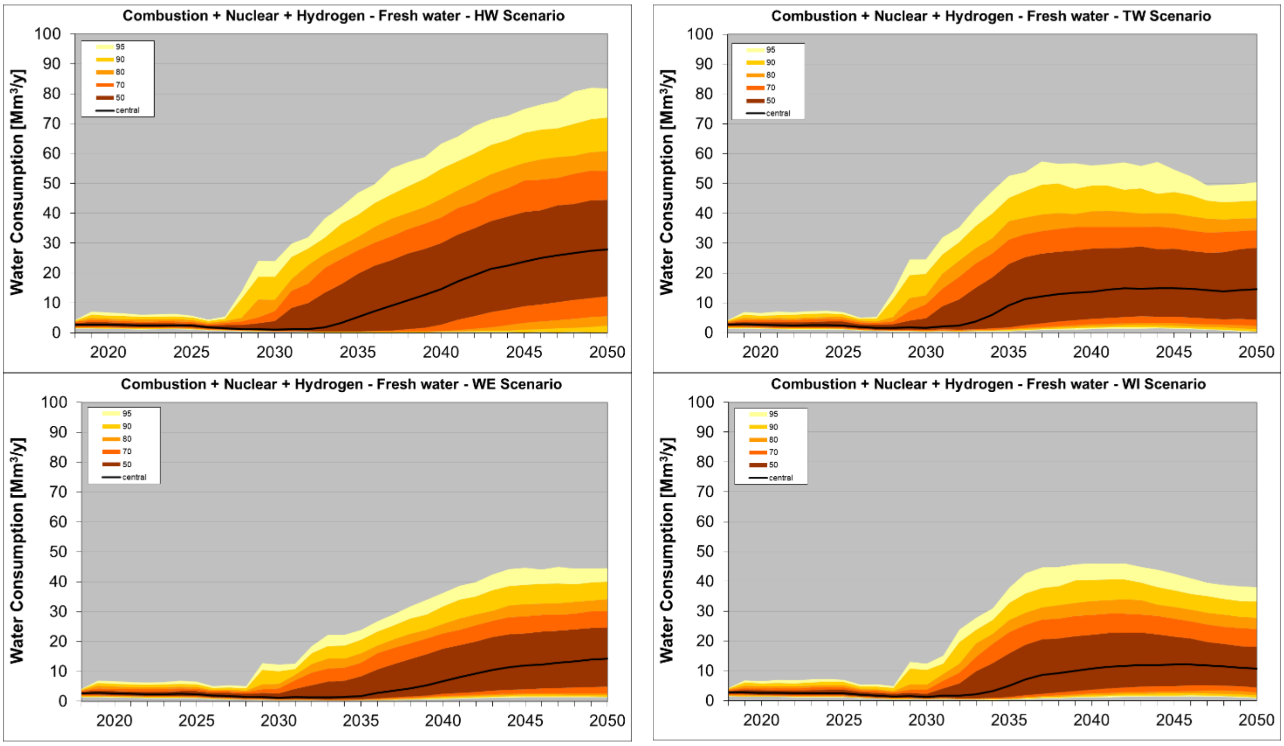



**Figure 50: WRW: annual freshwater consumption for energy production by generation plant plus hydrogen production, as projected under each of the four CCC20 (WE bottom left, HW top left, WI bottom right, TW top right) scenarios.**

Under all four CCC20 scenarios after an initial reduction until about 2025 consumptive freshwater use is predicted to increase. The rate of increase varies between scenarios but for all the use in 2050 is greater than in the baseline. Total water use for energy production is predicted to reach to over 70Mm$^3$/y.

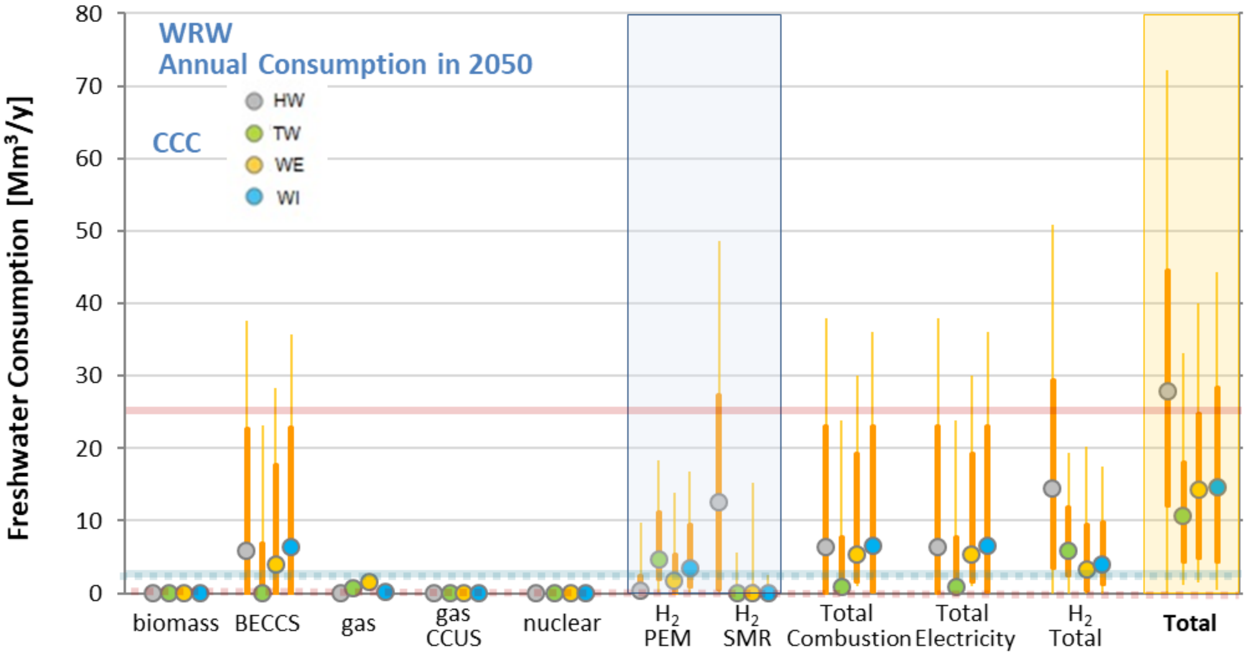



**Figure 51: WRW annual freshwater consumption by power producers in 2050, modelled using CCC20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the 25$^{th}$-75$^{th}$ (boxes) and 5$^{th}$-95$^{th}$ (whiskers) percentile ranges. To place these values into context, the chart also reports (horizontal solid & dotted blue line) the freshwater consumption estimated by the model for the reference year 2018 (solid with and dotted without coal). Equivalent results, as obtained in Gasparino (2012) for the then baseline 2010, are also illustrated (with the inclusion or exclusion of contributions from coal-fired plant: solid and dotted red lines, respectively)**

Under the CCC20 scenarios the median total consumptive use of freshwater in 2050 varies between 11 to 28Mm$^3$/y with a combustion median of between 1 and 6Mm$^3$/y. The 95%ile consumptive use for electricity production is up to 38M$^3$/y with up to 72Mm$^3$/y for the energy sector.

The range of annual freshwater consumption for energy production in 2050 exceeds that of the 2018 and 2010 baseline with coal generation included. The range of annual consumption for electricity generation is greater than the 2018 baseline (as is the median for three of the four). For all but one scenario the range of consumption for electricity generation is greater than the 2010 baseline with coal included.

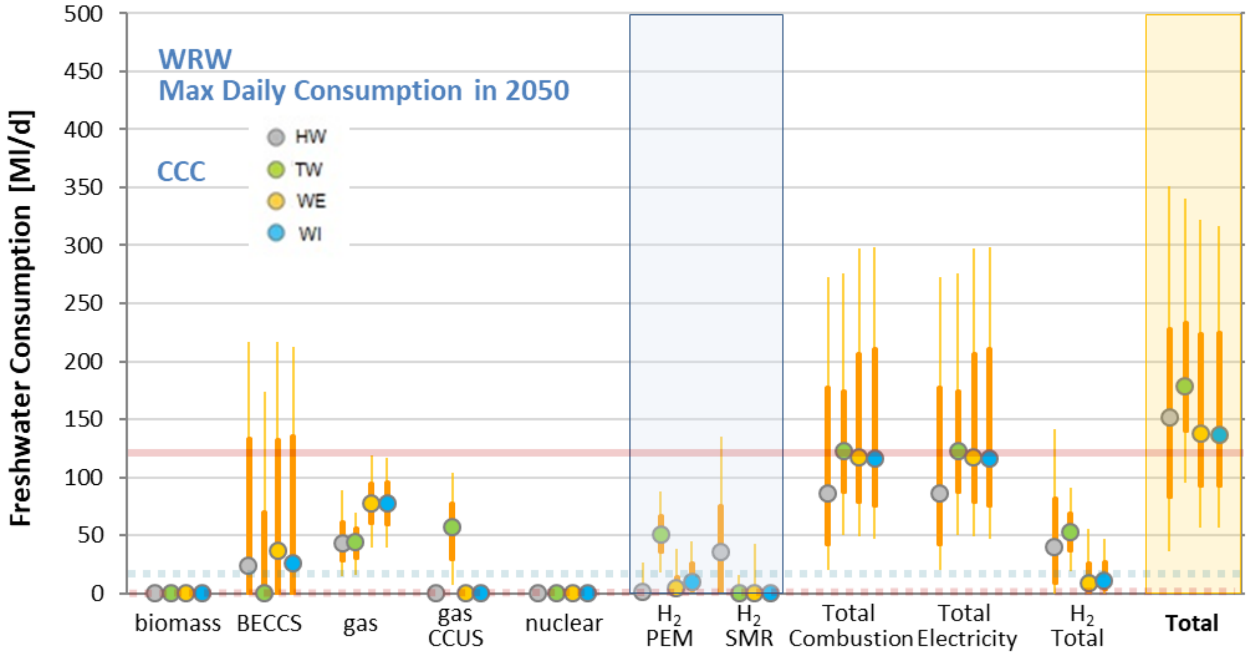



**Figure 52: same as Figure 51, but for the modelled maximum daily freshwater consumption in 2050.**

Under the CCC20 scenarios the median daily maximum consumptive use of freshwater in 2050 varies between 137 to 178Ml/d with a combustion median of between 86 and 123Ml/d. The 95%ile consumptive use for electricity production is up to 299Mm$^3$/y with up to 351Mm$^3$/y for the energy sector.

The median daily maximum freshwater consumption at 2050 for electricity generation and energy production is greater than the 2018 baseline and the 2010 baseline.

### 4.4.1 High Quality Water use in WRW at 2050

The same model used to predict cooling water use has been used to predict high quality water use within the WRW region for the FES20 and CCC20 scenarios. Note that the freshwater consumption results plotted above include the high quality and cooling water use in hydrogen production and therefore the high quality water use in hydrogen production results below are not additive. The high quality water use was not included in the modelling of freshwater use in electricity generation and so the high quality water is an additional consumption to the previous results.

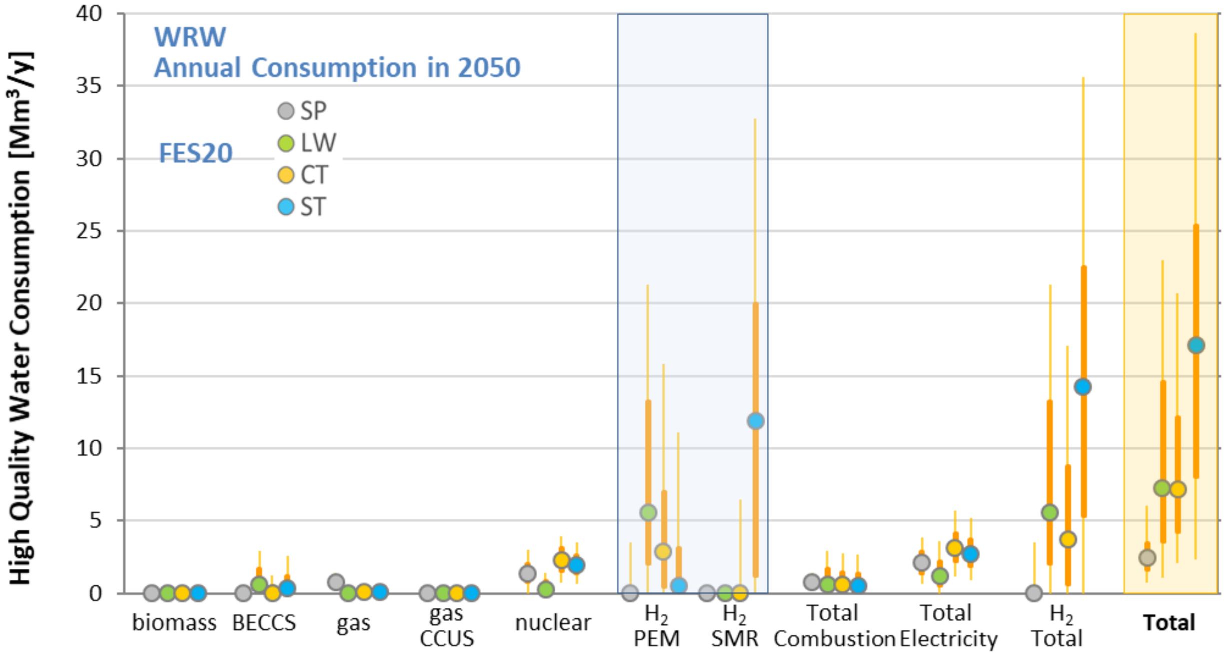



**Figure 53: WRW annual high quality water consumption by power producers in 2050, modelled using CCC20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the 25$^{th}$-75$^{th}$ (boxes) and 5$^{th}$-95$^{th}$ (whiskers) percentile ranges.**

As for the cooling water use the largest volume of high quality water in 2050 under the majority of the FES20 scenarios is used within hydrogen production. The median use for electricity production (combustion plus nuclear) is 1 to 3.7Mm$^3$/y and 2.4 to 17.1Mm$^3$/y for total energy production. The 95%ile high quality water use ranges up to 38.6Mm$^3$/y for the energy sector and is up to 5.7Mm$^3$/y for electricity generation.

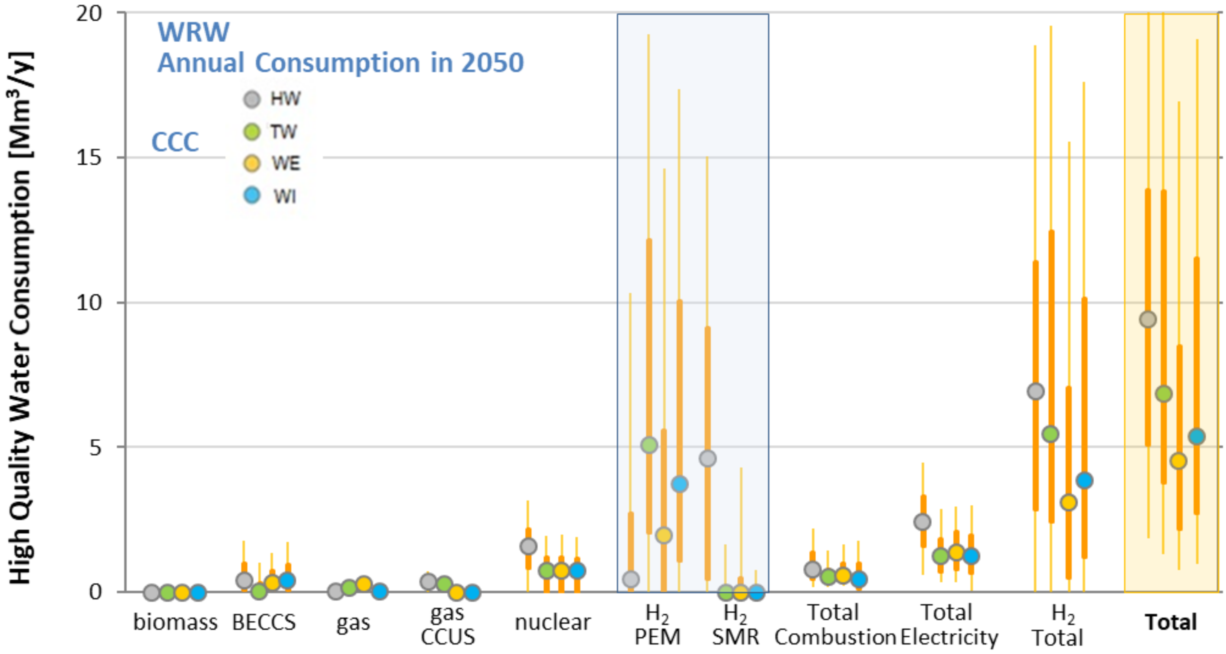



**Figure 54: same as Figure 40, but for the modelled annual high quality water consumption in 2050 under CCC20 scenarios.**

As for the cooling water use the largest volume of high quality water in 2050 under the CCC20 scenarios is used within hydrogen production. The median use for electricity production (combustion plus nuclear) is 1.3 to 2.4Mm$^3$/y with a median use between 4.5 and 9.4Mm$^3$/y in total. The 95%ile consumption of high quality water use for energy production ranges up to 21Mm$^3$/y with up to 4.5Mm$^3$/y for electricity generation.

### 4.4.2 Summary Freshwater consumption WRW

- Freshwater consumption for energy production in both FES20 & CCC20 reduces until 2025 to 2030 after which it increases
- Consumption for energy & electricity production under FES20 & CCC20 can be greater than both the 2010 and 2018 baselines
- FES20 has BECCS, CCGT and hydrogen production at 2050 consuming freshwater
- CCC20 has BECCS, CCGT (with and without CCUS) and hydrogen production at 2050 consuming freshwater
- FES20 Annual energy use: median up to 48Mm3/y, 95%ile up to 131Mm$^3$/y
- FES20 Annual electricity use: median up to 4Mm3/y, 95%ile up to 55Mm$^3$/y
- FES20 Daily energy use: median up to 168Ml/d, 95%ile up to 424Ml/d
- FES20 Daily electricity use: median up to 42Ml/d, 95%ile up to 219Ml/d
- CCC20 Annual energy use: median up to 28Mm$^3$/y, 95%ile up to 72Mm$^3$/y
- CCC20 Annual electricity use: median up to 7Mm$^3$/y, 95%ile up to 38Mm$^3$/y
- CCC20 Daily energy use: median up to 178Ml/d, 95%ile up to 351Ml/d
- CCC20 Daily electricity use: median up to 123Ml/d, 95%ile up to 298Ml/d
- High Quality Water: Electricity production 95%ile up to 5.7Mm$^3$/y

### 4.5 Modelled Freshwater Consumption: pathways to 2050 West Country Water Resources (WCWR)

None of the modelled power plant sites within the WCWR region use freshwater for cooling and therefore freshwater use by the power sector under the 2050 pathways is limited to hydrogen production. This is a simplification because as previously discussed power plant in addition to cooling water require a source of high quality water, for use in boiler and other services, which is typically provided by a PWS - NHHD supply. If the NHHD supply is sourced from the region's rivers there is then an indirect use of freshwater by both seawater and dry cooled generators.

The predicted annual consumptive use for hydrogen production in WCWR for the FES20 scenarios follows. The region is too distant from a cluster for the model to assign SMR hydrogen production and so the only hydrogen is from electrolysis.

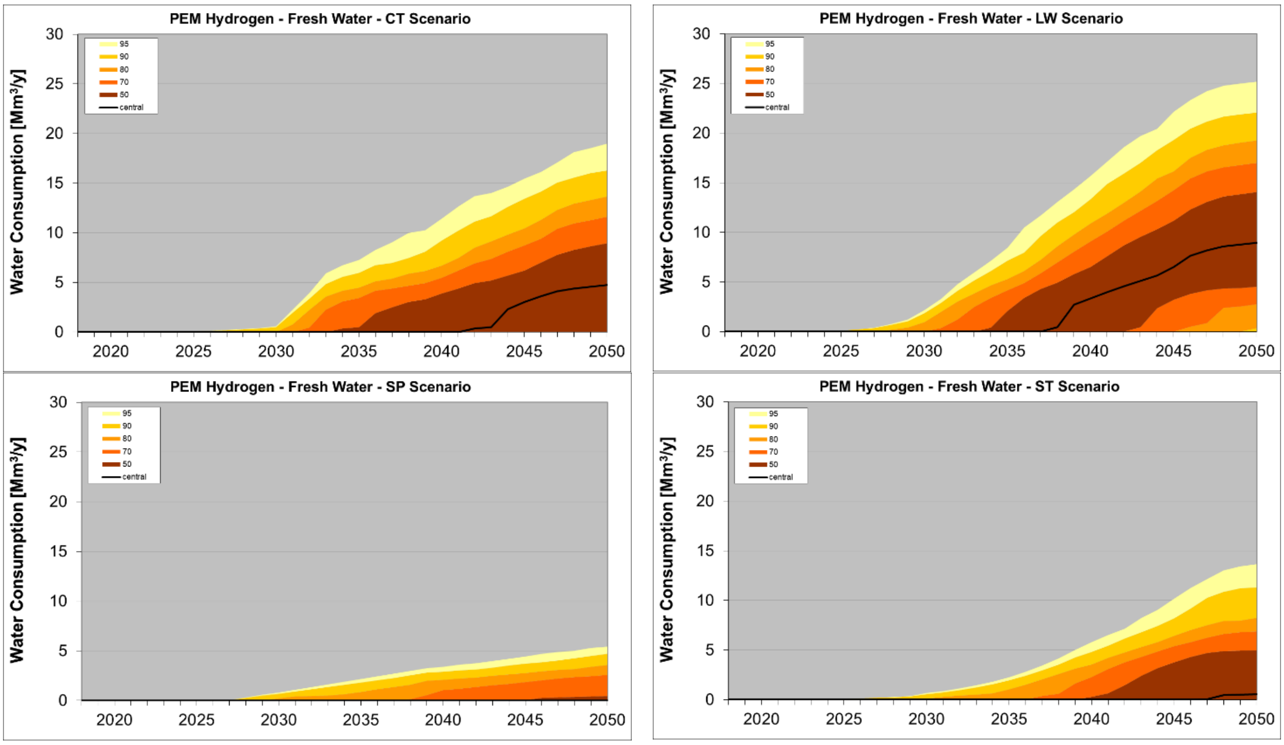



**Figure 55: WCWR freshwater annually consumed to produce hydrogen by electrolysis for the FES20 scenarios.**

The use for hydrogen production varies between scenario being predicted to begin between 2025 and 2030 with use increasing until the end of the simulation in 2050.

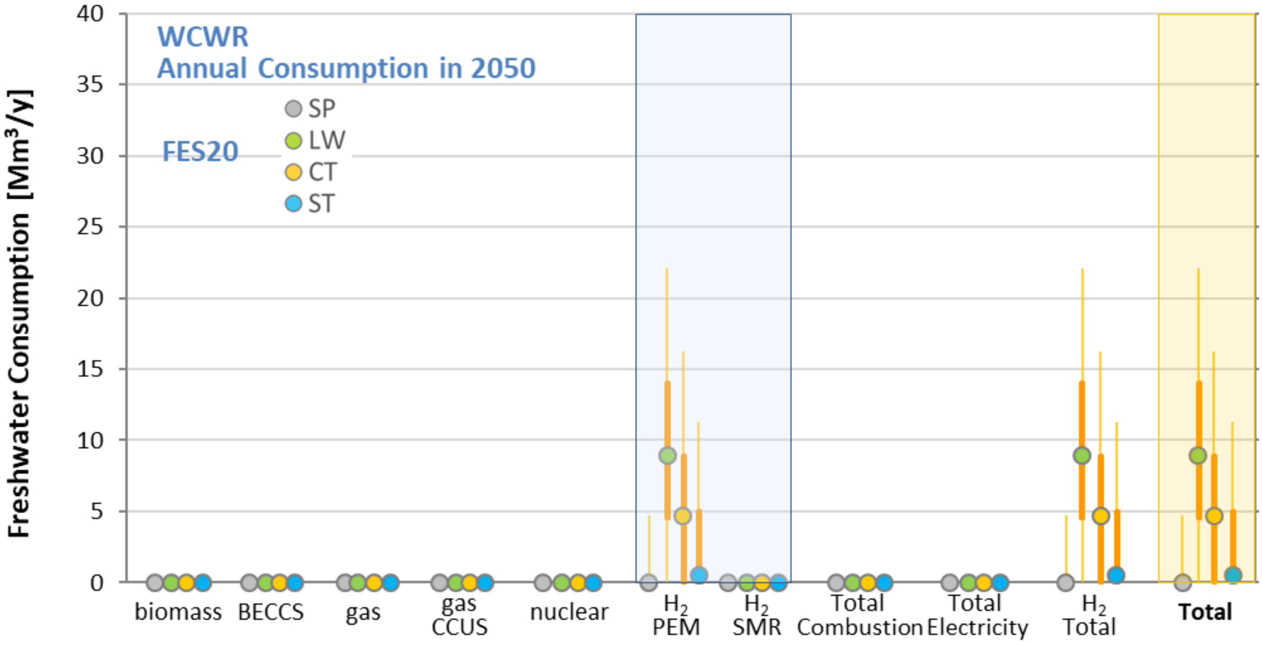



**Figure 56: WCWR annual freshwater consumption by power producers in 2050, modelled using FES20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the 25$^{th}$-75$^{th}$ (boxes) and 5$^{th}$-95$^{th}$ (whiskers) percentile ranges. To place these values into context, the chart also reports (horizontal solid blue line) the freshwater consumption estimated by the model for the reference year 2018 (solid blue). Equivalent results, as obtained in Gasparino (2012) for the then baseline 2010, are also illustrated (with the inclusion or exclusion of contributions from coal-fired plant: solid and dotted red lines, respectively)**

The median annual consumptive use of water for energy production in 2050 for WCWR is up to 9Mm$^3$/y with a 95%ile of up to 22Mm$^3$/y. As with the rest of the modelling this figure excludes indirect use of freshwater via public water supplies. As there is no freshwater cooled energy production assumed for WCWR before hydrogen production begins the consumptive use at 2050 is greater than the baseline.

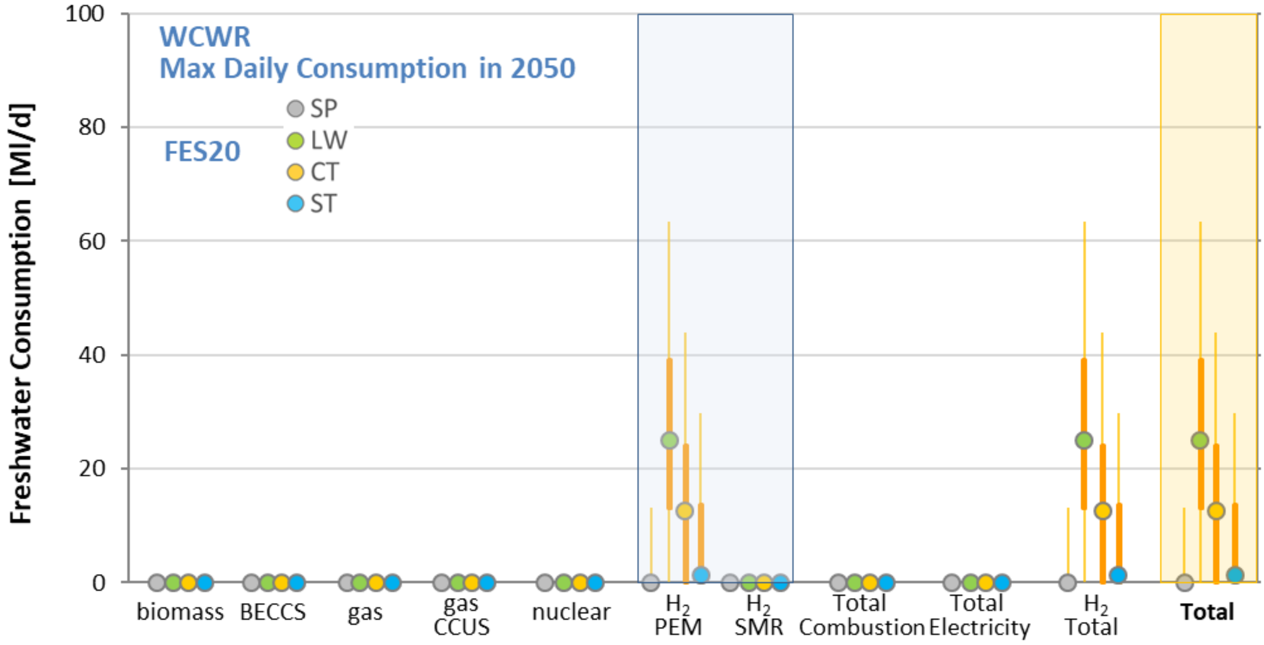



**Figure 57: same as Figure** 56**, but for the modelled maximum daily freshwater consumption in 2050.**

The daily use of freshwater for energy production within WCWR in 2050 is up to 25Ml/y with a 95%ile consumption of 63Mm$^3$/y.

The predicted consumptive use of freshwater for the production of hydrogen under the CCC20 scenarios follows. As with FES20 the lack of a cluster within the WRSE region results in there being no predicted SMR hydrogen production.

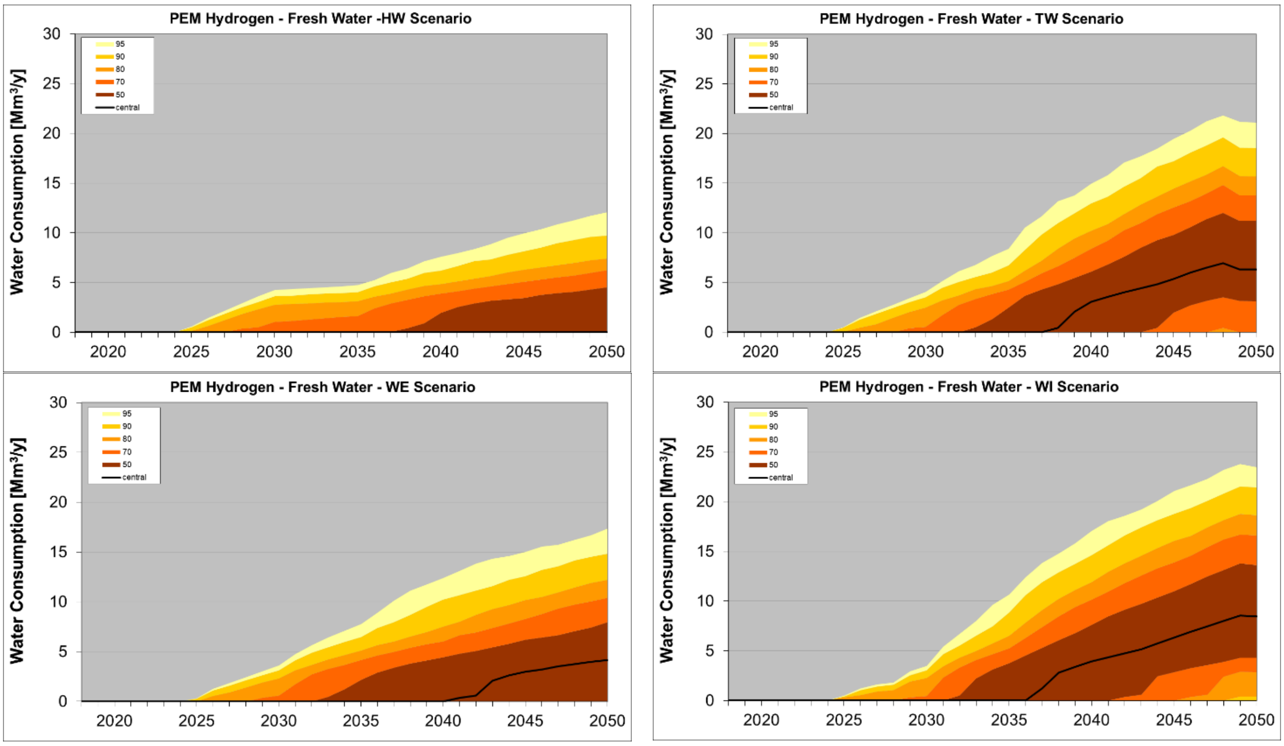



**Figure 58: WCWR freshwater annually consumed to produce hydrogen by electrolysis for the FES20 scenarios.**

In the CCC20 scenario the production of hydrogen by electrolysis takes off around 2025 to 2030 and either continues to increase (HW & WE) or reaches a peak around 2048 (TW & WI).

The annual and daily consumptive use in WCWR in 2050 under the CCC20 scenarios follow:

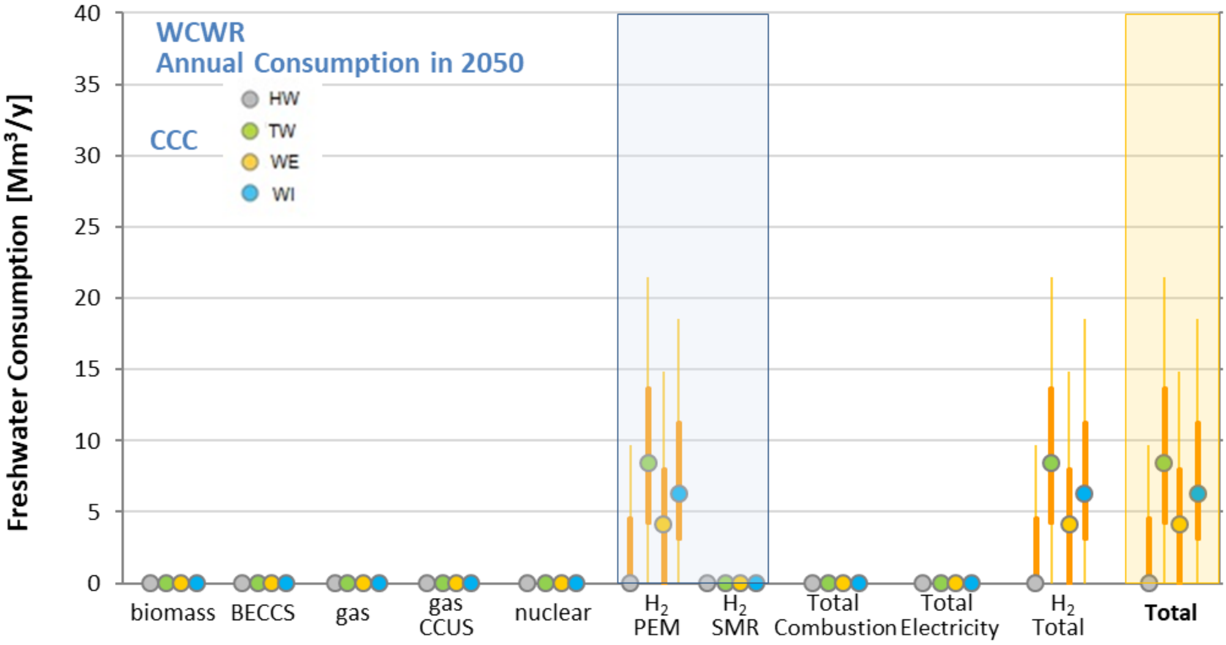



**Figure 59: WCWR annual freshwater consumption by power producers in 2050, modelled using CCC20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-**

**fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the 25th-75th (boxes) and 5th-95th (whiskers) percentile ranges. To place these values into context, the chart also reports (horizontal solid blue line) the freshwater consumption estimated by the model for the reference year 2018 (solid blue). Equivalent results, as obtained in Gasparino (2012) for the then baseline 2010, are also illustrated (with the inclusion or exclusion of contributions from coal-fired plant: solid and dotted red lines, respectively)**

The median use for hydrogen production in WCWR is up to 9Mm$^3$/y with the 95%ile use being 21Mm$^3$/y. Freshwater use in energy production in the WCWR is predicted to be greater in 2050 under most scenarios than in the baseline year of 2019. This is because there is initially no direct use of freshwater in the model and because the scenarios predict a need for hydrogen production to begin in the region with consumption increasing until 2050.

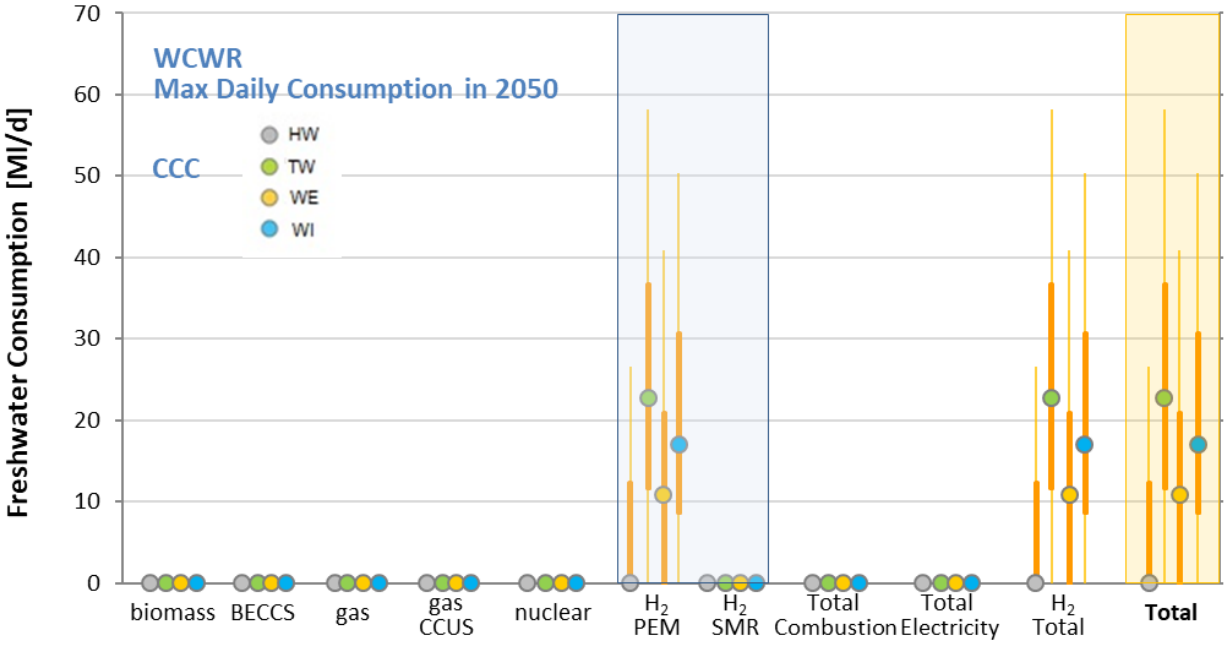



**Figure 60: same as Figure 59, but for the modelled maximum daily freshwater consumption in 2050.**

The median predicted daily consumptive use of freshwater in 2050 under the CCC20 scenarios is up to 22.7Ml/d. The 95%ile consumption for energy production in WCWR is 58.2Ml/d at 2050.

### 4.5.1 High Quality Water use in WCWR at 2050

The same model used to predict cooling water use has been used to predict high quality water use within the WCWR region for the FES 20 and CCC20 scenarios. Note that the freshwater consumption results plotted above include the high quality and cooling water use in hydrogen production and therefore the high quality water use in hydrogen production results below are not additive. The high quality water use was not included in the modelling of freshwater use in electricity generation and so the high quality water is an additional consumption to the previous results.

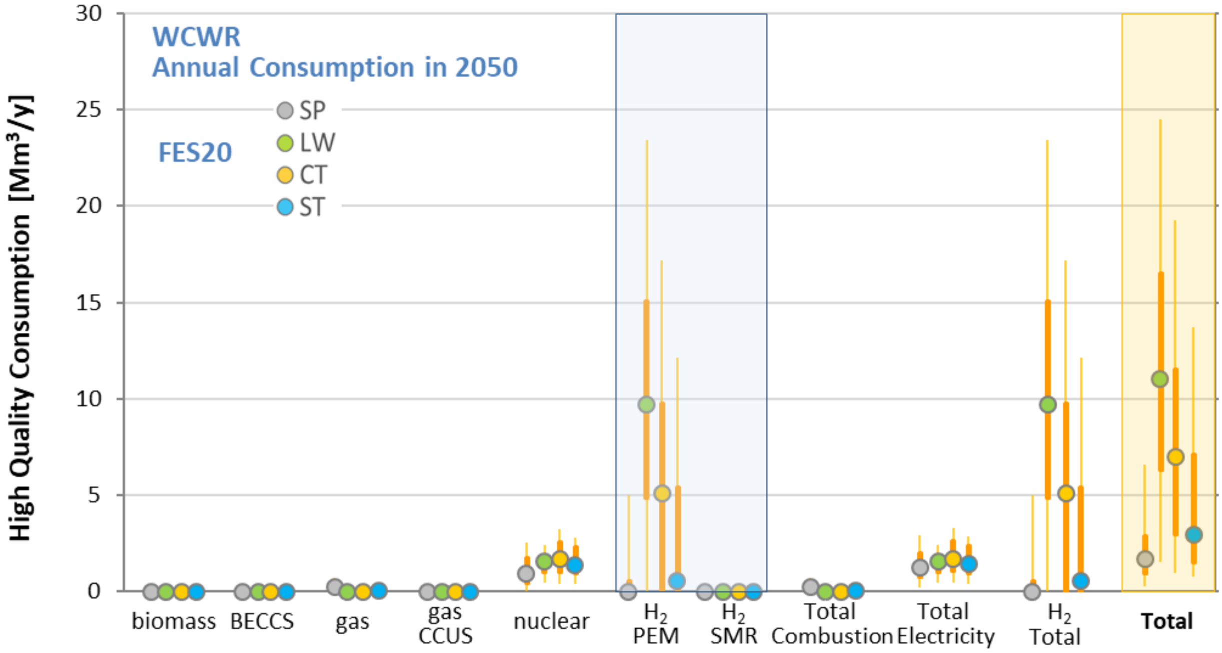



**Figure 61: WCWR annual high quality water consumption by power producers in 2050, modelled using FES20. 'Total Combustion' refers to: conventional biomass and gas-fired plant, CCUS-fitted biomass and gas-fired plant and hydrogen-fired CCGTs). 'Total Electricity' also includes contributions by nuclear plant. The chart reports the medians (dots) and the 25$^{th}$-75$^{th}$ (boxes) and 5$^{th}$-95$^{th}$ (whiskers) percentile ranges.**

There is no freshwater cooling use in WCWR but the high quality water use shows nuclear stations in operation and under the SP scenario some unabated CCGT (air cooled). The largest volume of high quality water in 2050 under the majority of the FES20 scenarios is used within hydrogen production. The median use for electricity production (combustion plus nuclear) is 1.3 to 1.7Mm$^3$/y with a 95%il consumptive use of 3.2Mm$^3$/y. The 95%ile high quality water use in energy production ranges up to 24Mm$^3$/y.

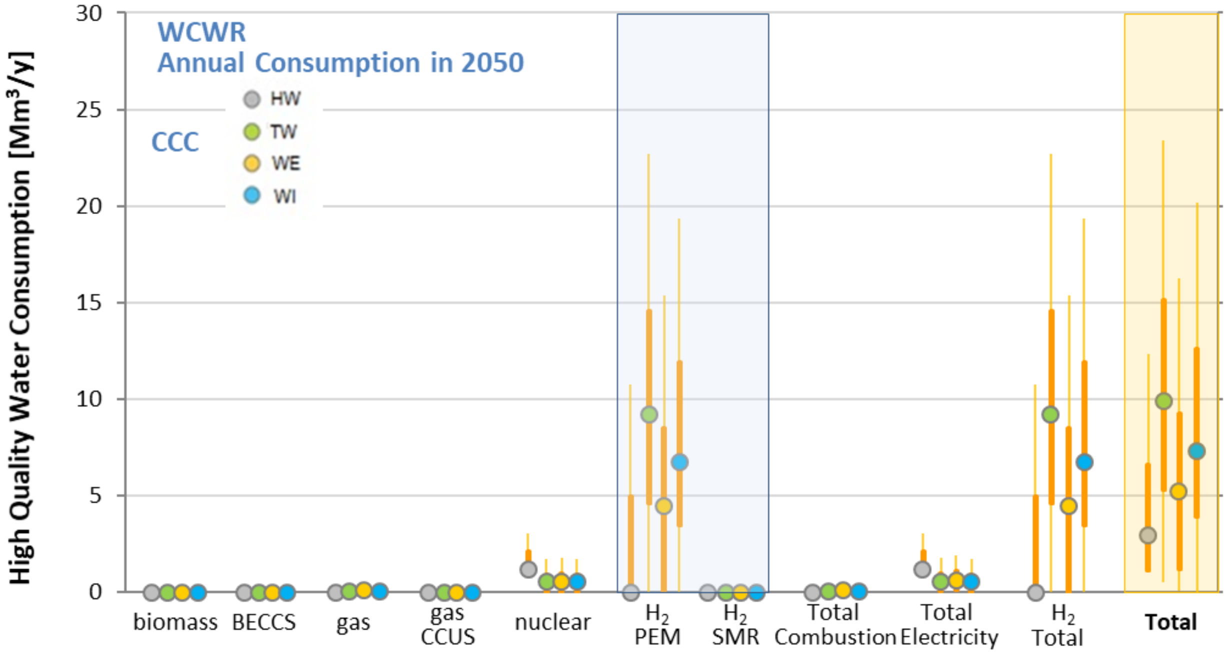



**Figure 62: same as Figure 40, but for the modelled annual high quality water consumption in 2050 under CCC20 scenarios.**

There is no freshwater cooling use in WCWR but the high quality water use shows nuclear stations in operation and some unabated air cooled CCGT operation in 2050. The largest volume of high quality water in 2050 under the majority of the FES20 scenarios is used within hydrogen production. The median use for electricity production (combustion plus nuclear) is 0.6 to 1.2Mm$^3$/y with a 95%ile consumption of 3.1Mm$^3$/y. The 95%ile high quality water use ranges up to 23.4Mm$^3$/y for energy (electricity plus hydrogen) production.

### 4.5.2 Summary Freshwater consumption WCWR

- No current freshwater cooled sites therefore 2050 consumption is greater than baseline
- Both CCC20 & FES20 only have hydrogen production at 2050 consuming freshwater for cooling
- FES20 use for energy production in 2050: median up to 9Mm$^3$/y, 95%ile up to 22Mm$^3$/y
- FES20 daily use for energy production: median up to 25Ml/d, 95%ile up to 63Ml/d
- CCC20 use for energy production in 2050: median up to 8Mm$^3$/y, 95%ile up to 21Mm$^3$/y
- CCC20 daily use for energy production: median up to 23Ml/d, 95%ile up to 58Ml/d
- High Quality Water: Electricity production 95%ile up to 1.3Mm$^3$/y

# 5 Conclusions

The main findings of the report can be summarized as follows:

There is considerable uncertainty in future energy sector potential water need at regional geographic scale. This is due to the uncertainty in the overall approach to the objective of carbon net-zero by 2050 within the generation and other sectors. Whilst a carbon net-zero position is the UK legal position as of 2020, there is the possibility that decarbonisation may prove to occur faster or slower than 2050. This modelling study has used eight scenarios from FES20 & CCC20 each of which has a different balance of energy plant over the years until 2050. These differences in generation and energy production between scenarios at a UK scale are reflected in the freshwater consumption at UK and regional scales. There is also uncertainty that arises from the model's sampling from the range of water consumptions observed at actual power plant.

Some uncertainty in the outcomes arises because the model uses a rule set to convert the energy mix of each of the eight Net Zero pathway scenarios used into an electricity and hydrogen production fleet. This process of defining a future energy production fleet is repeated a large number of times to sample the potential outcomes that satisfy the Net Zero pathway. The rules allow SMR hydrogen production, BEECS and CCUS fitted CCGTs only for a set of sites considered close enough to one of the five CCUS industrial hubs. This limits the potential cooling water demand in regions where sites are distant from one of the five clusters because some future generation options required by a scenario are unavailable. In addition as SMR production of hydrogen has a large freshwater demand any increase in the number of CCUS clusters will result in greater demand within a region. WRSE is an example of a region where consideration of SMR production away from the five CCUS hubs has been considered (Project Cavendish ENA (2020)).

Within a region the uncertainty will tend to be greater than at GB scale (JEP 2021) as a sub set of the total GB options are available with fewer potential sites at which the energy production required by the scenario can occur.

The rule set also only considers the water use at a site that is directly attributable to energy production. Some operators may have in place or have plans for multi-use of existing site licenses for uses such as water sharing or supplies to third parties. Examples of third party uses could include use in industrial processes such as data centres or for drinking water supplies. The rule set does not cover these cases and therefore the circumstances and hence water use at a specific site should be confirmed for water resource planning purposes.

For all regions the model predicts an initial reduction in freshwater consumption followed by an increase after 2025 to 2030 as hydrogen production ramps up. In general the range of use post 2035 often exceeds that in the 2018 baseline year for the current modelling study. The range of 2050 consumption in the current modelling is also often greater than the baseline in the 2010 baseline used in earlier modelling by Gasparino (2012) particularly when compared to the 2010 baseline without coal fired generation.

The model has been used to predict freshwater consumption by energy producers. For thermal power plant this is for cooling purposes. In practise thermal power plant also require a source of high quality water. This can be derived from a river or a non-household water supply or potentially a desalination plant at a coastal or estuarine site. If the water is taken from a non-household supply it is likely to be an additional, indirect, freshwater consumptive use at the site. For regions where the model has no freshwater cooled sites this could be the dominant freshwater use by thermal plant.

The freshwater consumption for each region are summarised below.

## 5.1 Summary of the Regional Water Use Results

### 5.1.1 Summary Freshwater consumption WRE

- Freshwater consumption for energy production in both FES20 & CCC20 reduces until 2025 to 2030 after which it increases
- Consumption for energy production & electricity generation under FES20 & CCC20 can be greater than 2018 & 2010 baselines
- FES20 has BECCS, CCGTs and hydrogen at 2050
- CCC20 has BECCS, CCGT (with and without CCUS) and hydrogen at 2050
- FES20 Annual energy use: median up to 62Mm$^3$/y, 95%ile up to 153Mm$^3$/y
- FES20 Annual electricity use: median up to 11Mm3/y, 95%ile up to 69Mm$^3$/y
- FES20 Daily energy use: median up to 214Ml/d, 95%ile up to 455Ml/d
- FES20 Daily electricity use: median up to 62Ml/d, 95%ile up to 240Ml/d
- CCC20 Annual energy use: median up to 46Mm$^3$/y, 95%ile up to 91Mm$^3$/y
- CCC20 Annual electricity use: median up to 20Mm3/y, 95%ile up to 54Mm$^3$/y
- CCC20 Daily energy use: median up to 237Ml/d, 95%ile up to 437Ml/d
- CCC20 Daily electricity use: median up to 160Ml/d, 95%ile up to 349Ml/d
- High Quality Water: Electricity production 95%ile up to 5Mm$^3$/y

### 5.1.2 Summary Freshwater consumption WReN

- Freshwater consumption for energy production in both FES20 & CCC20 reduces until 2025 to 2030 after which it increases
- Consumption for energy & electricity production under FES20 & CCC20 can be greater than the 2018 & 2010 baselines
- FES20 has BECCS, CCGTs, nuclear and hydrogen at 2050
- FES20 Annual energy use: median up to 108Mm$^3$/y, 95%ile up to 201Mm$^3$/y
- FES20 Annual electricity use: median up to 29Mm3/y, 95%ile up to 76Mm$^3$/y
- FES20 Daily energy use: median up to 330Ml/d, 95%ile up to 610Ml/d
- FES20 Daily electricity use: median up to 115Ml/d, 95%ile up to 310Ml/d
- CCC20 Annual energy use: median up to 63Mm$^3$/y, 95%ile up to 116Mm$^3$/y
- CCC20 Annual electricity use: median up to 23Mm3/y, 95%ile up to 63Mm$^3$/y
- CCC20 Daily energy use: median up to 256Ml/d, 95%ile up to 480Ml/d
- CCC20 Daily electricity use: median up to 148Ml/d, 95%ile up to 354Ml/d
- High Quality Water: Electricity production 95%ile up to 7Mm$^3$/y

### 5.1.3 Summary Freshwater consumption WRSE

- Freshwater consumption for energy production in both FES20 & CCC20 reduces until 2025 to 2030 after which it increases
- Consumption for energy production under FES20 & CCC20 can be greater than both 2010 with coal) & 2018 (no coal) baselines.
- The range of daily maximum consumption for electricity production is equal or greater than the 2018 (with coal) and 2010 (without coal) baselines
- Development of hydrogen (as in Project Cavendish) could increase use
- With only a single freshwater generation site the model will be sensitive to site specific developments
- FES20 Annual energy use: median up to 6Mm$^3$/y, 95%ile up to 13Mm$^3$/y

- FES20 Annual electricity use: median up to 2Mm3/y, 95%ile up to 3Mm$^3$/y
- FES20 Daily energy use: median up to 20Ml/d, 95%ile up to 36Ml/d
- FES20 Daily electricity use: median up to 19Ml/d, 95%ile up to 34Ml/d
- CCC20 Annual energy use: median up to 5Mm$^3$/y, 95%ile up to 13Mm$^3$/y
- CCC20 Annual electricity use:  95%ile up to 0.5Mm$^3$/y
- CCC20 Daily energy use: median up to 17Ml/d, 95%ile up to 44Ml/d
- CCC20 Daily electricity use: 95%ile up to 25Ml/d
- High Quality Water: Electricity production 95%ile up to 1.3Mm$^3$/y

### 5.1.4 Summary Freshwater consumption WRW

- Freshwater consumption for energy production in both FES20 & CCC20 reduces until 2025 to 2030 after which it increases
- Consumption for energy & electricity production under FES20 & CCC20 can be greater than both the 2010 and 2018 baselines
- CCC20 has BECCS, CCGT and hydrogen production at 2050 consuming freshwater
- CCC20 has BECCS, CCGT (with and without CCUS) and hydrogen production at 2050 consuming freshwater
- FES20 Annual energy use: median up to 48Mm3/y, 95%ile up to 131Mm$^3$/y
- FES20 Annual electricity use: median up to 4Mm3/y, 95%ile up to 55Mm$^3$/y
- FES20 Daily energy use: median up to 168Ml/d, 95%ile up to 424Ml/d
- FES20 Daily electricity use: median up to 42Ml/d, 95%ile up to 219Ml/d
- CCC20 Annual energy use: median up to 28Mm$^3$/y, 95%ile up to 72Mm$^3$/y
- CCC20 Annual electricity use:  median up to 7Mm$^3$/y, 95%ile up to 38Mm$^3$/y
- CCC20 Daily energy use: median up to 178Ml/d, 95%ile up to 351Ml/d
- CCC20 Daily electricity use: median up to 123Ml/d, 95%ile up to 298Ml/d
- High Quality Water: Electricity production 95%ile up to 5.7Mm$^3$/y

### 5.1.5 Summary Freshwater consumption WCWR

- No current freshwater cooled sites therefore 2050 consumption is greater than baseline
- Both CCC20 & FES20 only have hydrogen production at 2050 consuming freshwater for cooling
- FES20 use for energy production in 2050: median up to 9Mm$^3$/y, 95%ile up to 22Mm$^3$/y
- FES20 daily use for energy production: median up to 25Ml/d, 95%ile up to 63Ml/d
- CCC20 use for energy production in 2050: median up to 8Mm$^3$/y, 95%ile up to 21Mm$^3$/y
- CCC20 daily use for energy production: median up to 23Ml/d, 95%ile up to 58Ml/d
- High Quality Water: Electricity production 95%ile up to 1.3Mm$^3$/y

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